STUDIA GEOMORPHOLOGICA CARPATHO-BALCANICA
vol. LVI–LVII 2022–2023: 31–50 PL ISSN 0081-6434

JAROSŁAW CEBULSKI

QUANTITATIVE CHANGES IN NEAR-CHANNEL LANDSLIDES CAUSED BY FLUVIAL EROSION IN THE LIGHT OF HIGH-RESOLUTION DEM

Abstract: The article deals the issue of near-channel landslide activity in two regions (Rożnowskie Foothills and Beskid Niski Mountains) in the Polish Outer Carpathians. The main objective of the research was to determine the volume of material removed from the studied landslides in the period from their occurrence to 2012 and to compare these results with the volume of material removed from landslides during the period of detailed research in 2014–2017. The ALS data was used to prepared to the DoDs analysis DoD analysis with theoretical landslide surfaces and to determine the volume of material removed from the occurrence of landslides to 2012. Detailed TLS surveys (10 measurement series) were carried out from April 2014 to November 2017, resulting in nine Digital Elevation Models (DEMs) of Difference (DoDs), illustrating quantitative and spatial changes within the investigated landslides. It was found that near-channel landslides, under the influence of ongoing fluvial erosion, exhibit continuous activity with varying intensity, depending on the hydrometeorological conditions. During flood events, the movements within the entire landslide area were activated. Conversely, in periods between floods, there was a constant removal of material from the toe of the landslides. During flood events, the material carried away by streams accounted for 60% to 90% of the volume of material removed throughout the research period. The volume of material removed from the landslide in 4 years of survey ranges from 14 to 107% of the material removed from the landslide since its occurrence to 2012.

Keywords: landslide, fluvial erosion, landslide-channel coupling, terrestrial laser scanning, LiDAR data, Polish flysch Carpathians

INTRODUCTION

Landslides have a significant impact on shaping the surface of slopes (Bober 1984; Starkel 1996; Rączkowski 2007) and, in many cases, valley (Korup 2004; Lévy et al. 2012). The coupling between hillslopes and river channels is a fundamental aspect of geomorphic system functioning (Crozier 1986; Harvey 2002; Wistuba et al. 2015). The relief of the Polish Outer Carpathians is strongly formed by landsliding processes. Over an area of 19,600 km^2, more than 70,000 landslides and 6,500 landslide-prone areas have been inventoried, which in many parts of them make up 30 to 40% of the surface area of slopes (Marciniec et al., 2019). This area is particularly predisposed to the formation of new and rejuvenation of old landslides due to its geological structure. Alternately lying down layers of sandstones and marl shales form the so-called “flysch,” which predisposes this area to the occurrence of numerous landslides (Rączkowski, Mrozek 2002; Margielewski 2006). Tectonic elements such as discontinuity surfaces, thrust types, faults, and fractures also have a significant influence on landslide formation (Bober 1984). A significant portion of Carpathian landslides have contact with the river channel, including near-channel landslides.

High precipitation affects landslides by saturating the colluvium with water, altering the physico-chemical properties of the soil, and leading to significant slope loading (Gil, Długosz 2006). In the case of landslides in direct contact with a channel, the activation of the landslide is not only influenced by the amount of precipitation but also by the water level in the stream, which erodes the slope both vertically and laterally (Dauksza, Kotarba 1973; Lévy et al. 2012; Kukulak, Augustowski 2016). The combination of these two factors (infiltration of rainwater into the colluvium and fluvial erosion) makes near-channel landslides more susceptible to activation than landslides without direct contact with the river channel (Costa, Schuster 1988; Korup 2004; Lévy et al. 2012; Yenes et al. 2015; Fuller et al. 2016). The rainfall thresholds that trigger activation of near-channel landslides may also be lower than for landslides without contact with the channel (Ziętara 1968; Gil 1997).

To determine the speed, type of movement and volume of colluvial material removed by streams, it is necessary to monitoring the surfaces of selected landslide areas using geodetic methods, particularly LiDAR (Light Detection and Ranging) technology. Geodetic measurements, which can be conducted on the ground, from the air, or via satellite, are also essential in landslide research, particularly for measuring the rates of colluvial movement (Refice et al. 2000; Travelletti, Malet 2012). The increasingly popular LiDAR technology, including terrestrial laser scanning (TLS), enables the creation of high-resolution Digital Elevation Models (DEMs), which are used to study geomorphic processes, including landslides (Abellán et al. 2009; Oppikofer et al., 2009; Travelletti, Malet 2012). An analysis of the obtained DEMs (Digital Elevation Models) using GIS (Geographic Information System) software allows for accurate determination of landslide boundaries, finding their morphometric parameters, and describing the land cover. Generating hillshade and slope maps enables the analysis of the surface of landslides and the identification of colluvial packets, characterized by different degrees of activity within these landslides (Oppikofer et al. 2009; Travelletti, Malet

2012; Fidelus-Orzechowska et al. 2018). On the basis of two or more DEMs created based on measurements carried out at intervals, it is possible to perform an analysis called DEM of Difference (DoD). This analysis allows for the determination of quantitative and spatial changes within the studied area (Betts et al. 2003; Oppikofer et al. 2009; Jaboyedoff et al. 2012; Jones, Preston 2012; Travelletti, Malet 2012; McColl et al. 2017; Rączkowska et al. 2018; Tyszkowski, Cebulski 2019; Hendrickx et al. 2020; Rączkowska, Cebulski 2022).

Limitations of DoD analysis result from the fact that the LiDAR data comes from measurements made several or a dozen or so years ago (measurements for the Polish Carpathians were made in 2012–2013), but the analysed forms (landslides in this case) had usually been created earlier. Therefore, the analysed DEM shows the actual state of pre-existing landslides while the DEM for the period before landslide formation is missing. Such DEM can be artificially created in GIS software, based on the current LiDAR data, although it should be borne in mind that it will not represent the actual DEM from the time before landside formation, but only a theoretical surface of the slope. A comparison of two DEMs (current terrain's surface and theoretical terrain's surface from the period before landslide formation) enables quantitative and spatial determination of changes resulting from landslide creation (Cebulski 2018).

The main goal of the research was variation in dynamic of landslides functioning in contact with river channels. This goal was achieved based on partial objectives, including: (i) determining the quantitative and spatial changes within the landslide surfaces from their formation until 2012; (ii) compare the volume of material removed by streams since the landslides occurred until 2012 with the volume of material removed by streams in the period 2014–2017; (iii) forecasting the activity of the studied landslides.

STUDY AREA

For detailed studies were selected five near-channel landslides located in the Polish Outer Carpathians. The research covered the Beskidy Mts. and Carpathians Foothills (Fig. 1), due to the diversity of geological structure and terrain relief as the main factors influencing the course of landslide processes. Three landslides are located within the Rożnowskie Foothills (Boczkówka, Żabno, Leszczyny) (Fig. 2), where the terrain has the character of low mountains (Fig. 1). The other two landslides (Bodaki, Sękówka) (Fig. 2) are located in the Beskid Niski Mts., where the terrain has the character of middle mountains.

The Polish Outer Carpathians are a sequence of tectonic units (nappes) that are thrust one over another, comprising folded series of sandstone, shale, and

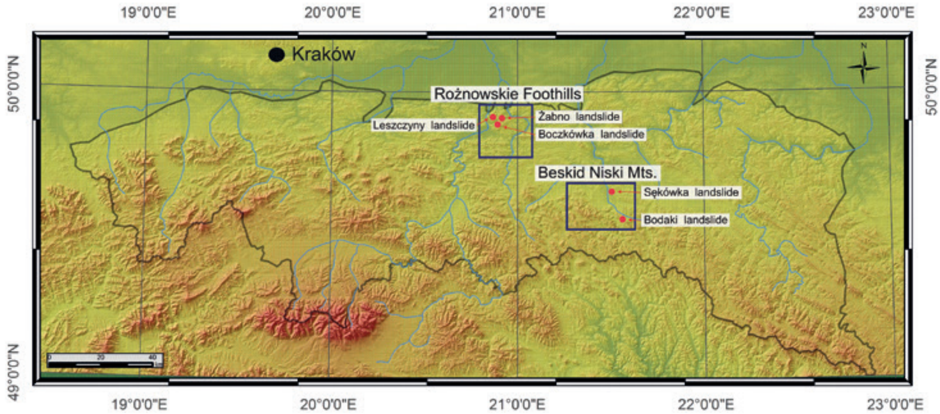

Fig. 1. Location of study area

marl (Oszczypko et al. 2008). The Foothills part of Carpathians is formed of the Skole series are Upper Cretaceous. Inoceramian beds developed in the form of sandstone and shale, siliceous marl, and bioturbated marl (fucoid marl) as well as thick-bedded sandstone and conglomerate interbedded with shale the Leszczyny sandstone member (Marciniec et al. 2014).

These layers are less resistant to erosion, which also results in smaller terrain elevations. The Beskid part of the Carpathians is composed of thick Magura layers consisting of sandstones, shales, and Upper Cretaceous-Paleocene fucoid marls, as well as Paleocene-Eocene red and green shales (Kopciowski et al. 2014). These layers are more resistant to erosion than the Skole series rocks that make up the foothills of the Carpathians.

The following criteria were employed while selecting landslides for analysis: (i) the landslide should remain in direct contact with the stream channel – a riverside landslide; (ii) there should be presence of fresh elements of inner-landslide relief, confirming its activity in recent years; (iii) only scarce vegetation growing on the landslide surface, so that it would be possible to use laser scanning techniques to monitor the surface; (iv) similar surface area; (v) location in close proximity to a meteorological station

DATA AND METHODS

TERRESTRIAL AND AIRBORNE LASER SCANNING (TLS AND ALS DATA)

TLS measurements were performed using a long-range impulse scanner (Riegl VZ-4000) with a spatial data acquisition speed of about 222,000 points·s^{-1}. The precision of the scanner was 10 mm, and its accuracy was 15 mm. We used a Global Navigation Satellite System (GNSS) receiver (TRIMBLE R4)

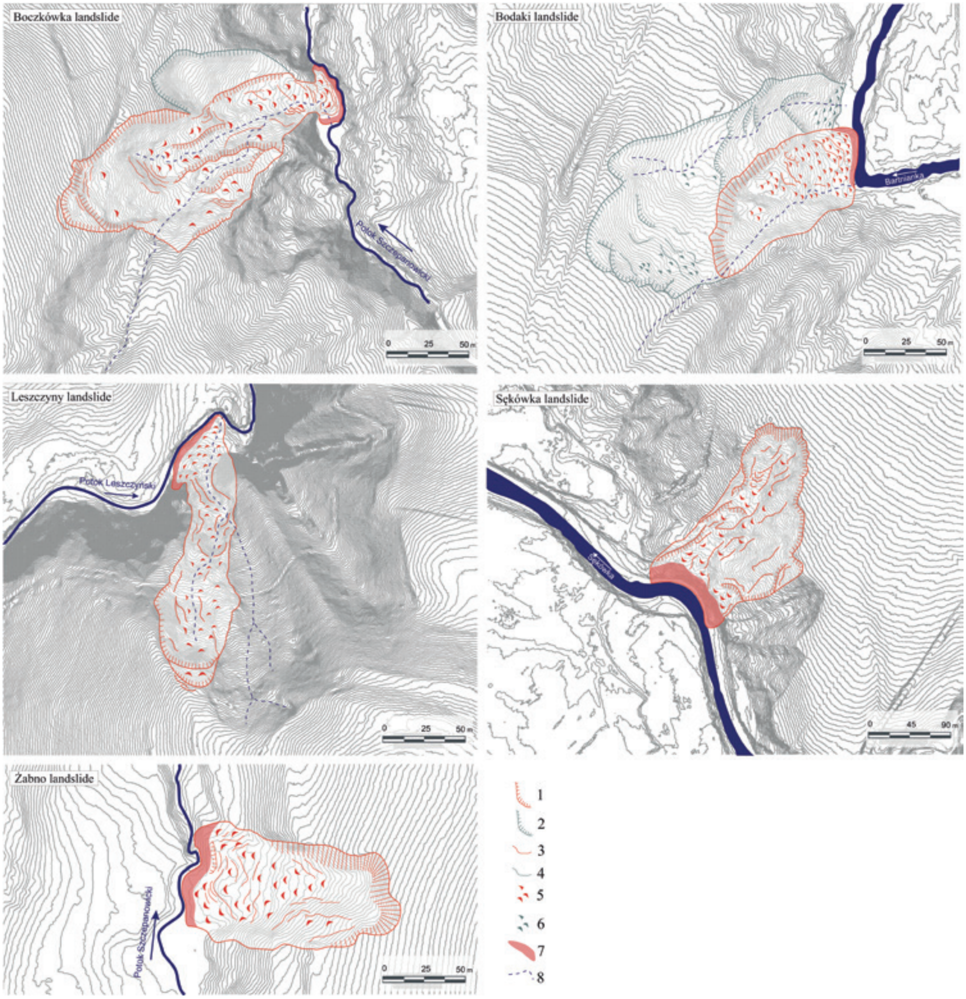

Fig. 2. Geomorphological sketches of selected landslides and photographs of landslide toes; 1 – active scarp, 2 – inactive scarp, 3 – active longitudinal and transverse fissures, 4 – inactive longitudinal and transverse fissures, 5 – active colluvial ridges, 6 – inactive colluvial ridges, 7 – toe of the landslide, 8 – intermittent stream; contour lines are marked every 0.5 m

using Real Time Kinematic (RTK) corrections from the ASG-EUPOS system for identifying geospatial locations. The data from the GNSS receiver were averaged, and then the scanner location was assessed (accuracy better than 1 cm). Point clouds derived from TLS were then processed using RiSCAN PRO software including the Multi-Station Adjustment (MSA) module, which can generate planes from point clouds and then aligns them based on similarity and spatial distribution (Fig. 3). The resulting poly-data objects were used by the RIEGL Multi-Station Adjustment Tool for automatic fine alignment using a best-fit iterative least-squares iteration. Data prepared in this manner for a particular survey were exported to Las.1.2. format and then analyzed using ArcGiS 10.2.2 (Fig. 3). The point clouds were converted into high-resolution terrain models (0.05 m grid), followed by differential DoD analysis, which then allowed to determine both spatial and quantitative changes across the landslide surface.

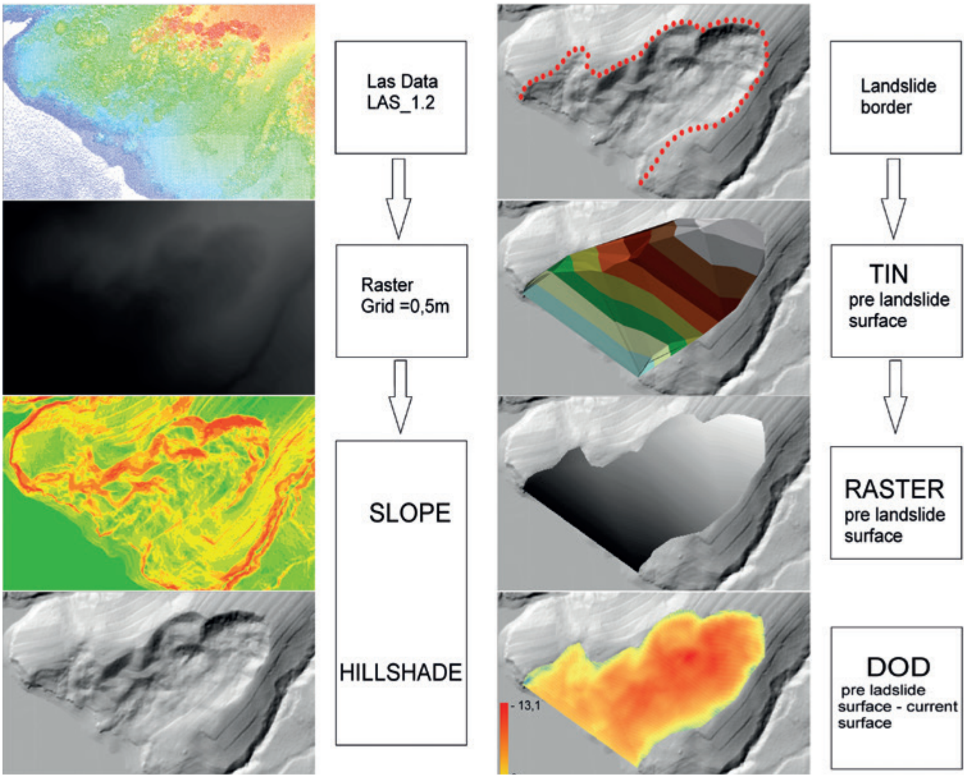

Fig. 3. Process of creation of a theoretical surface of a slope, before landslide formation

The 2012 ALSwas obtained from the National Protection Against Extreme Hazards (ISOK) project. The 2012 ALS 2012 was carried out using a RIEGL LMS-Q680i scanner with a density of 4 to 6 points·m^{-2} and pulse repetition frequencies of 300 kHz. The accuracy of the ALS model for 2012 ranged from 7 cm for woodland-free slopes to 15 cm for woodland slopes.

Quantitative and spatial changes within the chosen landslides were identified based on an analysis of appropriate DEMs of Difference (DoD). Ten measurements of the surface of each of the five studied landslides were performed using terrestrial laser scanning (TLS) in April 2014, June 2014, September

2014, November 2014, April 2015, November 2015, April 2016, November 2016, April 2017, and November 2017. The choice of April and November was the result of two key considerations: (1) absence of a well-developed plant cover that helped produce a more accurate DEM, (2) desire to examine landslide movements after the winter and summer seasons.

CREATING DoD MODEL WITH THEORETICAL SURFACE AREA

LiDAR data was transformed into a vector layer with a side length of 0.5 m in the ArcGis 10.2 software (Fig. 3). Next, a slope map and hillshade were created using the raster data. Thanks to this, it was possible to determine the spatial extent of the analyzed landslide. The next step was to generate the triangulated irregular networks (TINs) between points located on the boundary of landslides, which roughly corresponded to the theoretical surface existing in those places before landslide formation. Subsequently, the TINs were transformed into a raster with a resolution of 0.5 m. As there were two raster layers: (1) the current surface of the landslide and (2) the theoretical terrain's surface before landslide formation, the difference between these layers was calculated.

In order to determine spatial and quantitative changes caused by landslide formation, two high resolution DEMs were used. The first DEM was generated using the available LiDAR data (measurement on 19.08.2012) and it showed the current relief of the slopes. The extent of landslides and their basic parameters were determined based on this model. The surface from the period prior to landslide formation was generated artificially. To this end, triangulation between points located on the surface of the slope was conducted near the boundary with the landslide. The surface generated in this way was employed in the DoD analysis and compared to the actual DEM of the slope and the landslide (Fig. 3). In the case of landslides formed on linear – linear, linear – convex, linear – concave slopes, the total balance should have been equal to 0 or close to this value (Fig. 4). The cubic volume of the material removed from the landslide niche should have been in balance with the volume of the created landslide tongue, assuming that the material had not been removed beyond the landslide by erosion caused by river.

QUANTITATIVE AND SPATIAL CHANGES IN SELECTED LANDSLIDES

Using TLS instrument, spatial quantitative changes within 5 investigated landslides were determined during the period from April 2014 to November 2017. The obtained data allowed for identifying areas within the landslides

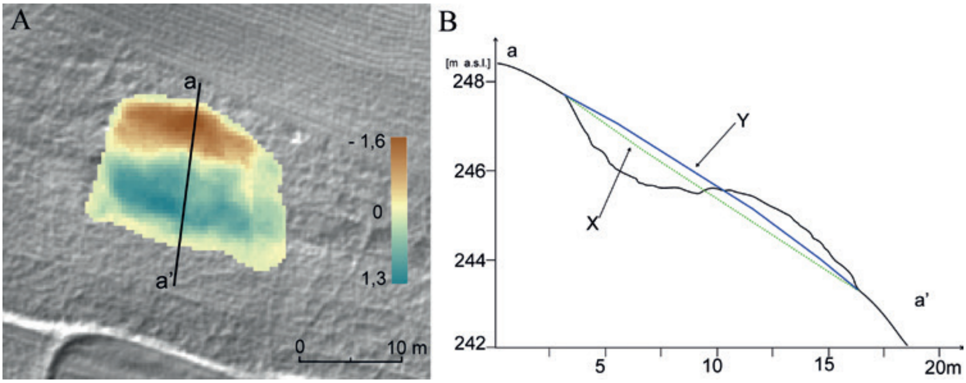

Fig. 4. Differential model of an example landslide. A – differential model (DoD) of the landslide, B – profile through the differential model, x – theoretical slope surface, y – actual slope surface

where the largest changes occurred. Additionally, a loss of colluvium within the landslides resulting from erosion and transport by flowing streams was recorded. These results (for the period of 2014–2017) were compared with the volume of material removed by the stream since the landslides formation until 2012 (DoD models with theoretical surface).

BOCZKÓWKA LANDSLIDE

The Boczkówka landslide became active in the summer of 2010 within a small denudation hollow (Fig. 2). The analysis of DoD between the landslide surface in 2012 and the theoretical surface showed that a total volume of 9,234 m^3 of material was removed from the Boczkówka landslide area by fluvial erosion (Table 1). Most likely, a significant portion of the removed material was composed of colluvium that slid into the stream channel in June 2010 (Fig. 5). The average lowering of the Boczkówka landslide surface was 1.08 m (Table 1), and the maximum difference between the 2012 terrain surface model and the theoretical model was 6.8 m (Fig. 5, Table 1).

Quantitative and spatial changes in the studied area were noted using TLS during the period April 2014 – November 2017. A total of 3,118 m^3 of colluvial material was removed from the landslide as a result of fluvial erosion in the study period (Fig. 6, Table 1), which had caused the surface of the landslide to lower by 0.37 m, on average (Fig. 6). Spatial changes were observed within the entire body of the landslide. The greatest changes occurred in the lower part of the foot of the landslide (Cebulski 2022).

The stream flowing through the colluvium of the Boczkówka landslide eroded a total of 3,118 m^3 of material during the four years of measurements

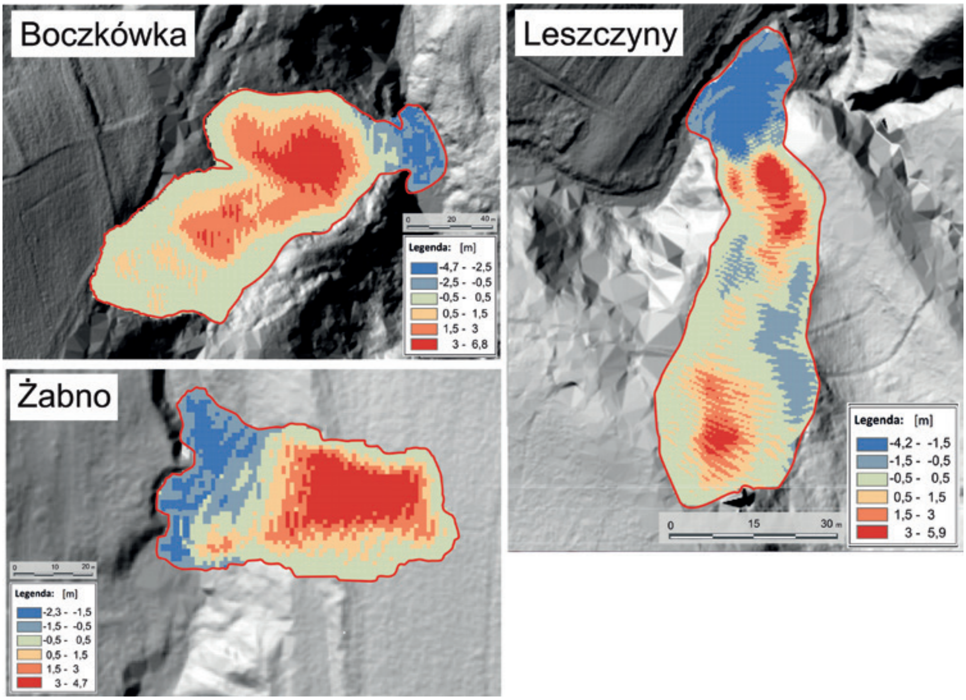

Fig. 5. DoD models of selected Rożnowskie Foothills landslides, between 2012 and the theoretical surface

Table 1.

Comparison of the volume of colluvium removed by fluvial processes since the development of landslides up to 2012, with that during the 4-year period of detailed measurements

	Volume of removed colluvia from landslide to 2012	Average lowering of the landslide surface to 2012	Volume of material removed during the research period April 2014 –November 2017	Average lowering of the landslide surface during the research period April 2014 –November 2017	Percentage of the volume of material removed in 4 years compared to the period since the landslide creation to 2012
	(m^3)	(m)	(m^3)	(m)	(%)
Boczkówka	9,234	1.08	3,118	0.37	34
Żabno	2,164	1.14	302	0.16	14
Leszczyny	2,810	1.17	645	0.27	23
Bodaki	2,916	0.85	3,117	0.91	107
Sękówka	9,186	1.05	1,741	.20	19

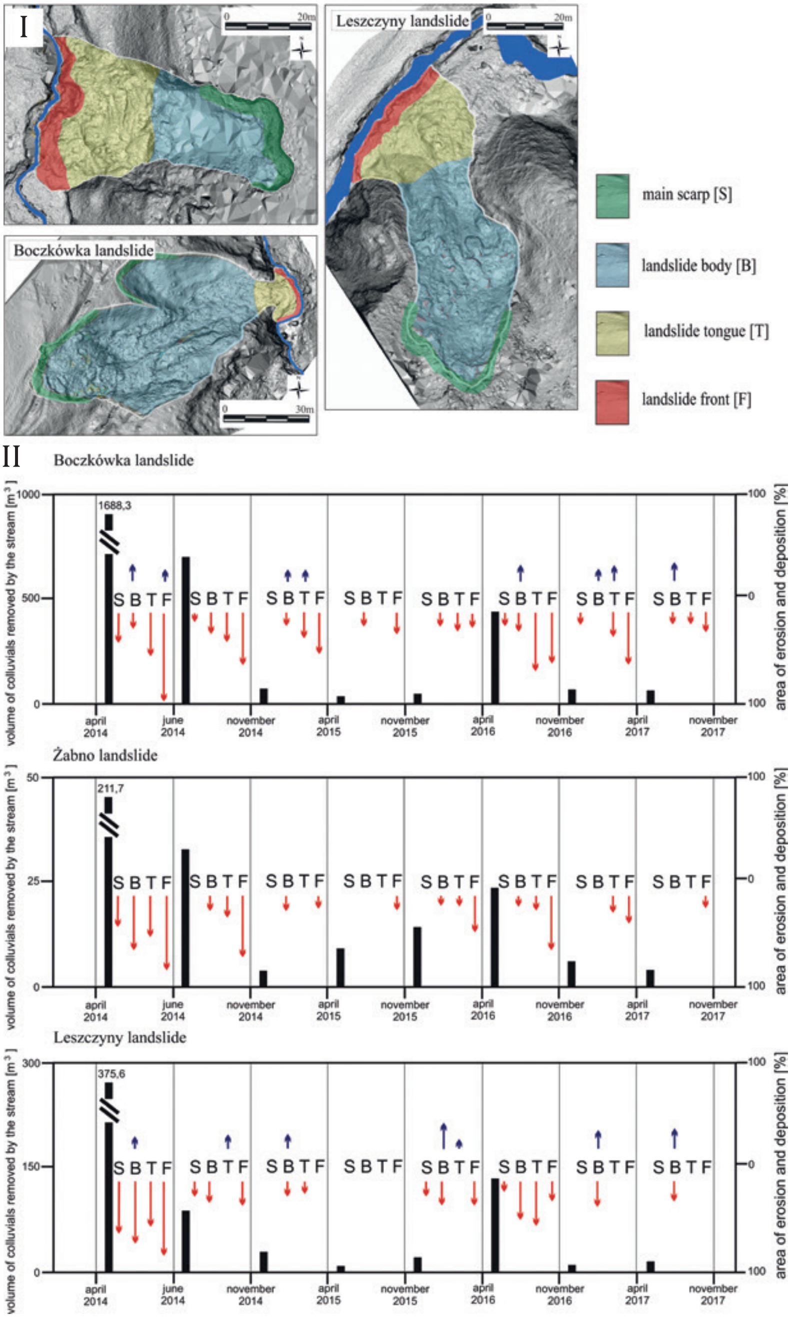

Fig. 6. Spatial and quantitative changes within Rożnowskie Foothills landslide surface during the research period (2014–2017). I – the extent parts of the landslides; II – quantitative changes: vertical bars – the volume of colluvium removed by the stream from the landslides, blue arrow – accumulation, red arrow – erosion, S – main scarp area, B – landslide body, J – landslide foot, F – landslide toe

(2014–2017). This value represents approximately 30% of the volume calculated based on the analysis of the DoD with the theoretical surface (Table 1).

ŻABNO LANDSLIDE

The Żabno landslide has been triggered in the summer of 2010 within a linear-linear slope. The DoD analysis between the terrain surface and the theoretical surface showed that a total volume of 2,164 m^3 of material was removed from the Żabno landslide area by fluvial erosion. Most likely, a significant portion of the removed material was composed of colluvium that slid into the stream channel in June 2010. The maximum lowering of the Żabno landslide surface was 4.7 m, while the maximum gain was 2.3 m (Fig. 5).

The DoD analysis conducted for the Żabno landslide indicated that in the entire study period fluvial processes helped to remove a total of 302.7 m^3 of colluvial material (Table 1), which caused a lowering of the landslide's surface by an average of 0.16 m. The amount of material removed by the stream and magnitude of the average lowering of the ground surface within the Żabno landslide were the smallest out of the five studied landslides (Cebulski 2022).

The activation of the Żabno landslide in 2010 resulted in the removal of 2164 m^3, while the material removed over a 4-year period accounted for only 14% of the material removed in the period from the created landslide to 2012 (Table 1).

LESZCZYNY LANDSLIDE

The Leszczyny Landslide became active in the summer of 2010 within a small denudation hollow. The foot of the landslide moved into the channel of Leszczyński Stream, in effect blocking the flow of water and creating a small, landslide-dammed lake, which remained in existence 30 days. The DoD analysis between terrain models and theoretical surface showed that the area of Leszczyny landslide experienced the removal of material with a total volume of 2,810 m^3 due to fluvial erosion. The greatest surface lowering was observed within the landslide body, amounting to 3.9 m. The largest increase in height was observed within the landslide toe, amounting to 4.2 m (Fig. 5).

The Leszczyny landslide was also examined. A colluvium volume of 644.8 m^3 was removed from the landslide by fluvial erosion (Fig. 6, Table 1) acting throughout the study period (April 2014–November 2017). Changes were recorded across the whole surface of the landslide in the first measurement period (April – June 2014). In this time period, a colluvium volume of 375.6 m^3 (Fig. 6) was removed from the landslide, which constituted 59% of the amount of colluvium removed throughout the study period (Cebulski 2022).

The stream flowing through the colluvium of the Leszczyny landslide eroded a total of 645 m^3 of material during the four years of measurements (2014–2017). This value represents approximately 23% of the volume calculated based on the analysis of the DoD with the theoretical surface (Table 1).

BODAKI LANDSLIDE

The DoD analysis for the Bodaki landslide was performed separately for the entire form and for the part activated in autumn 2012, which was later monitored from 2014 to 2017 using the terrestrial laser scanning (Fig. 2). Analysis DoD between terrain models and theoretical surface showed that material with a total volume of 2,916 m^3 was removed from landslide by fluvial erosion of the Bartnianka stream, and the landslide surface decreased by an average of 0.85 m (Fig. 7, Table 1). The surface of the landslide tongue is on average 2.5 m above the previous land surface, and the maximum 2.9 m (Fig. 7).

The DoD analysis conducted for the Bodaki landslide indicated that in the entire study period fluvial processes helped to remove a total of 3,117 m^3 of colluvial material (Cebulski 2022). More than 61% of that volume was removed from the landslide in the first measurement period (April–June 2014), and 20% in April–November 2016. In the remaining measurement periods, including periods without high-water events (35 months total), removed material constituted only 19% (Fig. 8, Table 1) (Cebulski 2022).

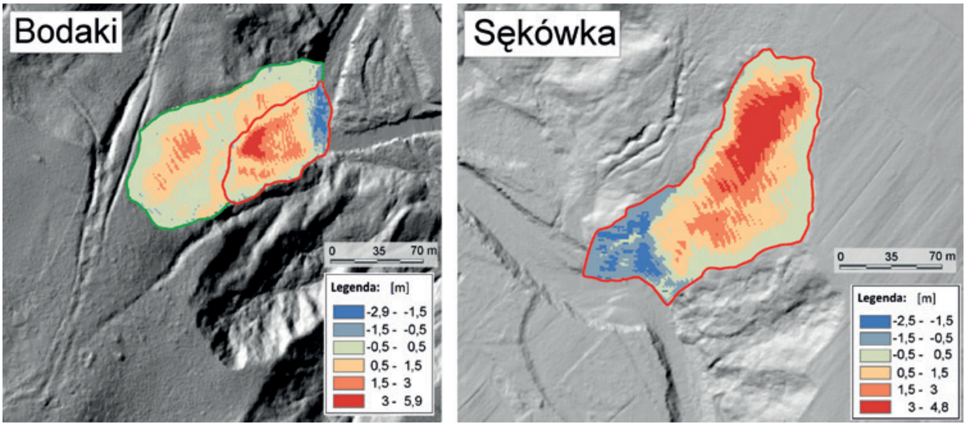

Fig. 7. DoD models of selected Beskid Niski Mts. landslides, between 2012 and the theoretical surface

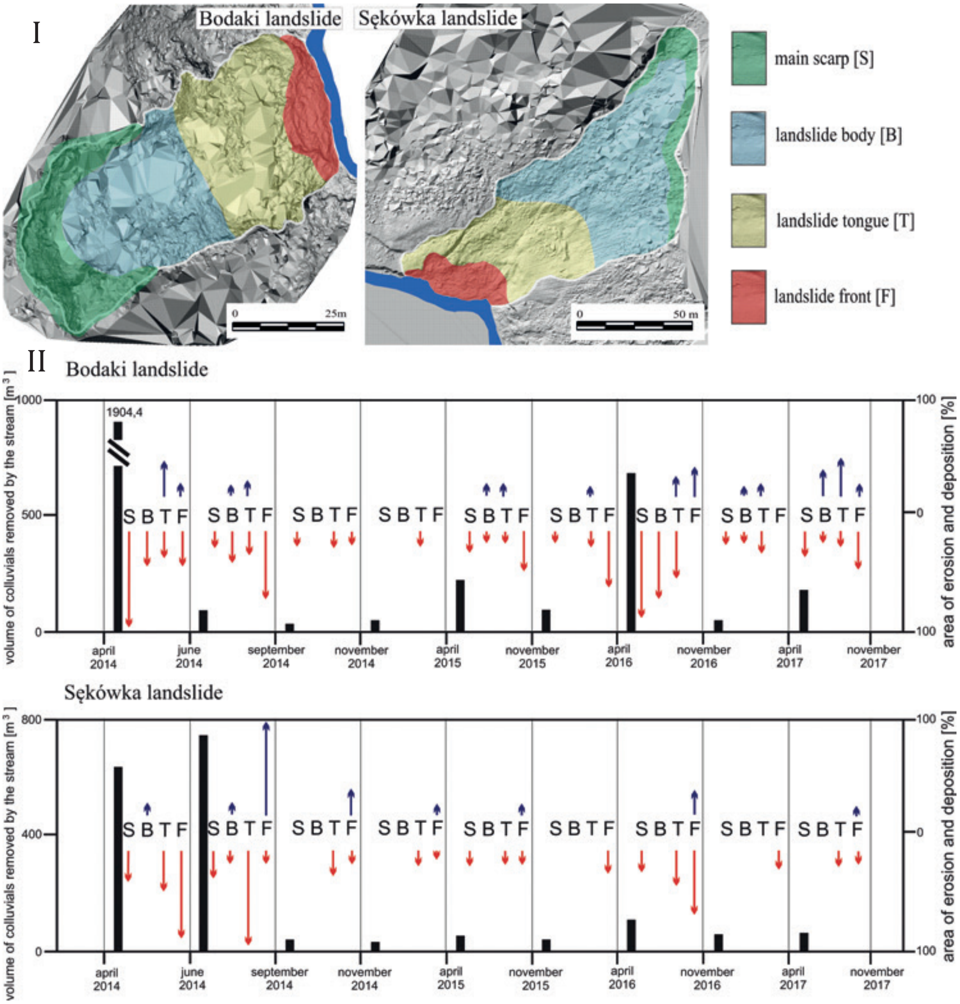

Fig. 8. Spatial and quantitative changes within Beskid Niski Mts. landslides surface during the research period (2014–2017). I – the extent parts of the landslides; II – quantitative changes: vertical bars – the volume of colluvium removed by the stream from the landslides, blue arrow – accumulation, red arrow – erosion, S – main scarp area, B – landslide body, J – landslide foot, F – landslide toe

From formation the Bodaki landslide, to 2012 material with a volume of 9,698 m^3 was removed by fluvial erosion. In 4-years period (2014–2017) of detailed measurements, the volume of removed colluvia amounted to 3,117 m^3 (Table 1). The volume of colluvia removed by the stream in 2014–2017, compared to the value achieved before 2012, was 31% (Table 1).

SĘKÓWKA LANDSLIDE

Analysis DoD between terrain models and theoretical surface showed that material with a total volume of 9,186 m^3 was removed from landslide by fluvial erosion of the Sękówka stream, and the landslide surface decreased by an average of 1.05 m (Fig. 7, Table 1). The maximum lowering of the Sękówka landslide surface was 4.8 m, while the maximum gain was 2.5 m (Fig. 7).

The Sękówka landslide was measured 10 times – just like the Bodaki landslide. A colluvium volume of 1,741 m^3 was removed from the landslide by fluvial erosion (Fig. 6, Table 1) acting throughout the study period (April 2014 – November 2017). Significant changes were found in the toe of the landslide – as the volume of material removed from it was more than 400 m^3 (Cebulski 2022). In the period, June–September 2014, a volume of 776.2 m^3 of colluvium was removed from the Sękówka landslide, which constituted 45% of the material removed in the studied period (Fig. 8). Throughout the measurement period, the Sękówka landslide, unlike the Bodaki landslide, developed starting at the bottom only, which proves that fluvial erosion was more important than precipitation in the activation of this landslide (Cebulski 2022).

The stream flowing through the colluvium of the Sękówka landslide eroded a total of 1,741 m^3 of material during the four years of measurements (2014–2017). This value represents approximately 19% of the volume calculated based on the analysis of the DoD with the theoretical surface (Table 1).

DISCUSSION

The use of TLS technique allowed to generate DEMs showing the surface of landslides at a very high resolution. A DoD analysis was performed based on data for select time periods, and for the entire study period of 2014 to 2017 and for period form created landslides to 2012. The obtained results allowed to identify areas of the studied landslide that had undergone the greatest changes. Many papers have already been written on the use of multi-temporal TLS data to create DoDs for landslides (Ventura et al. 2011; Jaboyedoff et al. 2012; Stumvoll et al. 2021), debris flow (Rączkowska et al. 2018; Rączkowska, Cebulski 2022), and glacier activity (Hancock et al., 2018). This method is used to identify the most transformed areas with a very high accuracy (Ventura et al. 2011; Cucchiaro et al. 2019; Strzelecki et al. 2022), and quantitatively determine the magnitude of changes across terrain surfaces in intervals between measurements (Fidelus-Orzechowska et al. 2018; Rączkowska et al. 2018; Tyszkowski, Cebulski 2019; Stumvoll et al. 2021).

Creating detailed (DoDs) models to determine quantitative and spatial changes in the terrain surface caused by landslide processes is possible based on detailed DEMs created before and after the landslide activation (Stumvoll et al. 2021; Lévy et al. 2012). Detailed measurements using TLS on five Carpathian landslides during the period from 2014 to 2017 allowed for a very high level of accuracy in identifying spatial and quantitative changes during individual measurement periods. These changes were dependent on hydrometeorological conditions (sum of rainfall and stream water levels) (Cebulski 2022). The amount of colluvial material removed by fluvial processes in individual periods ranged from 1.6 m^3 to 1,904 m^3. The largest volumes of colluvial material were removed during high-water level events in May 2014 and October 2016 (Fig 6, 8). Significant spatial and quantitative changes were also observed during the periods right after high-water level events, especially in the period June–November 2014. Increased activity of the studied landslides, despite of low precipitation, can be explained by secondary movements (Rączkowski, Mrozek 2002; Soldati et al. 2018). In the periods when high-water levels occurred in the Carpathians, and entire area landslides became active, colluvial material removed by fluvial processes constituted 60% to 91% of the volume of material carried away in the entire study period. Fluvial processes continued to constantly remove material from landslides in periods between high-water events. Although this period lasted three times longer than the period with high-water levels, the material volume removed from the landslides constituted between 9% and 40% of colluvium removed in the four-year study period (Cebulski 2022). This showed that high-water level events play a dominant role in the removal of material from landslides by fluvial erosion. Other papers have already indicated as water levels increased, discharge in streams increased, and landslide toe lateral erosion intensified (Lévy et al. 2012; Caputa, Gorczyca 2021).

Determining the volume of material removed from a landslide by a river for landslides that formed before the first LiDAR measurements (in Polish Carpathian 2012) in a given area is achievable but with lower accuracy than when there are detailed DEMs from TLS (Cebulski 2018). To reconstruct the shape and surface of the slope where a landslide later occurred, it is needed to create a theoretical surface (Cebulski 2018; Płaczkowska et al. 2021). Quantitative results of DoD analysis for active landslides not in contact with streams oscillate around zero, as the volume of material detached from the area of the main scarp or the main body of the landslide is subsequently deposited across the foot and toe area (Cebulski 2018). Getting a result other than zero, in this situation, may indicate tension or compression of the material within the lower part of the landslide. A result different than zero may be due to an inaccuracy in the method – and more precisely due to DEM resolution

(Stumvoll et al. 2021). This inaccuracy decreases as the accuracy of DEMs increases. In the case of landslides remaining in contact with stream channels, which are the landforms out of which the material is eroded by streams, the value will always be less than zero, as the volume of the material removed by fluvial erosion is added to the fill and cut balance within the landslide.

Of the five selected Carphatian landslides, only in the case of the Żabno landslide it was found that it occurred within a linear-linear slope, which allowed for a very accurate calculation of the volume of material removed by the eroding stream between 2010 (date of landslide created) and 2012 (date of ALS-LiDAR measurements). This value amounted to 2,164 m^3, and the largest volume of removed material likely occurred immediately after the landslide formation and in the subsequent months. In other cases, the studied areas where landslides occurred or were activated did not have a linear-linear shape, which may have influenced the underestimation or overestimation of the volume of material removed by the river between the landslide occurrences and 2012. Although the applied method has certain limitations, the obtained results are still significantly more accurate than previous estimates for individual Carpathian landslides (Dauksza, Kotarba 1973; Gil, Kotarba 1977). Therefore, it is justified to use this method, being aware that the results may be subject to a slight error. The effectiveness of using this method has been confirmed by research on channel heads in the Bieszczady Mountains (Płaczkowska et al. 2021).

Comparison of the volume of material removed by streams in a 4-year period of detailed studies (2014–2017) and the volume of material removed since the formation of landslides until 2012 has been presented in Figure 9. Of the five studied landslides, only the Bodaki landslide during the period 2014–2017 had more material removed than during the period from its formation until 2012. In the other studied landslides, the amount of material removed by rivers from the landslide in the first period was significantly greater than in the second period. This distribution of removed material in different periods is influenced by the substantial delivery of material to the riverbed during the initial development of the landslide, i.e., during its formation and a few days thereafter. After such an event, the landslide stabilizes relatively. During the period 2014–2017, the frontal parts of the landslides were reactivated through fluvial erosion, and only in two instances (May 2014 and October 2016) did a larger portion of the landslides become active. Measurements and observations of the studied landslides allow us to determine three types of quantities removed by river erosion (Cebulski 2022). The first, during the formation of the landslide, involves significant transformations and material transport down the slope into the riverbed. This material is heavily saturated with water, making it plastic, and high water flow in the stream results

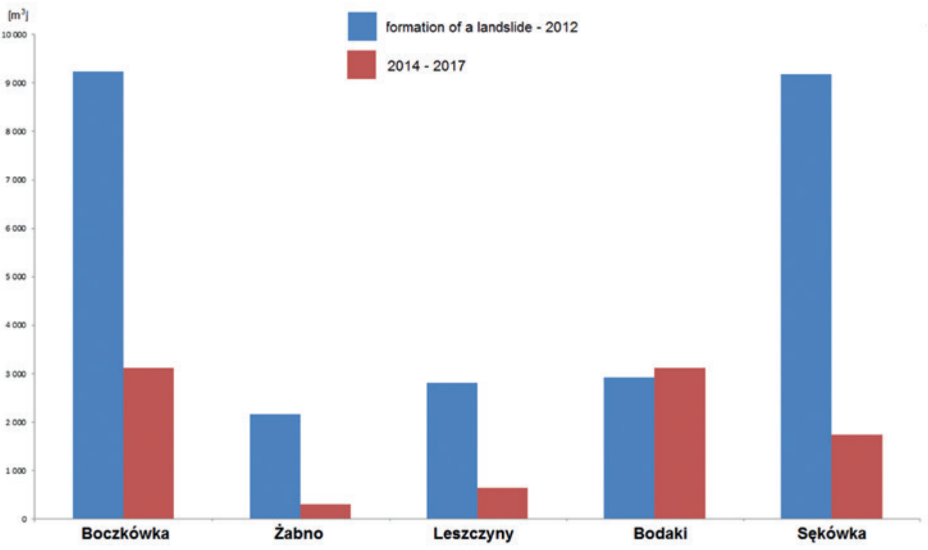

Fig. 9. Comparison of material removed from landslides by rivers in two study periods

in the rapid removal of debris from the landslide front. The highest intensity of this process occurs during the formation of the landslide and within a few hours to a dozen hours after its occurrence. After the landslide stabilizes, further removal of debris from the landslide occurs through fluvial erosion, as shown by the results of DoD measurements for selected landslides during the period 2014–2017. During periods without heavy rainfall and rising water levels in streams, material erosion from the landslide front is continuous. However, during flood events, a large amount of material is removed.

CONCLUSION

The use of LiDAR data, including TLS and ALS data with great effectiveness, allowed the DoD analysis to be carried out, resulting in a better understanding of the functioning of landslides near the channel. An important result of the use of these methods was the precise determination of the volume of material removed by streams from landslides from their formation until 2012 (the date of the ALS measurements in Polish Carpathian). The information obtained in this way may be useful in interpreting the activity of selected landslides in the past. Another important result was the precise determination of the spatial and quantitative changes in the surface of the studied landslides from 2014 to 2017. It was found that during periods without floods, material is removed from the toe of the landslide, and during floods, movements of colluvia are activated within the entire surface of the landslides. Combining the results of the DoDs analysis for the theoretical surface with the results of the DoDs analysis for the semi-annual comparison periods allowed a better understanding of the functioning of the near-channel landslides.

REFERENCES

Abellán A., Jaboyedoff M., Oppikofer T., Vilaplana J.M., 2009. *Detection of millimetric deformation using a terrestrial laserscanner: experiment and application to a rockfall event.* Natural Hazards and Earth System Sciences 9, 365–372.

Betts H.D., Trustrum N.A., De Rose R., 2003. *Geomorphologic changes in a complex gully system measured from sequential Digital elevation models, and implications for management*. Earth Surface Processes and Landform 28, 1043–1058.

Bober L., 1984. *Rejony osuwiskowe w polskich Karpatach fliszowych i ich związek z budową geologiczną region.* Biuletyn Instytutu Geologicznego 340, 115–158, (in Polish).

Caputa J., Gorczyca E., 2021. *The role of landslides in the evolution of a small mountain river valley (Polish Carpathians).* Episodes 44, 227–239.

Cebulski J., 2018. *Zastosowanie analizy DoD do oceny ilości usuniętego materiału osuwiska przez potok.* [in:] W. Bochenek, M. Kijowska-Strugała (eds.), *Zintegrowany Monitoring Środowiska Przyrodniczego. Ocena funkcjonowania i kierunków zmian środowiska przyrodniczego Polski na podstawie badań stacjonarnych.* Biblioteka Monitoringu Środowiska 32, Stacja Badawcza IGiPZ PAN, Szymbark, 83–88, (in Polish).

Cebulski J., 2022. *Impact of river erosion on variances in colluvial movement and type for landslides in the Polish Outer Carpathians.* Catena, 217, https://doi.org/10.1016/j.catena.2022.106415.

Costa J.E., Schuster R., 1988. *The formation and failure of natural dams.* Geological Society of America Bulletin 100, 1054–1068.

Crozier M.J., 1986. *Landslides: Causes, consequences and environment*. Croom Helm, London.

Cucchiaro S., Cazorzi F., Marchi L., Crema S., Beinat A., Cavalli M., 2019. *Multi-temporal analysis of the role of check dams in a debris-flow channel: Linking structural and functional connectivity.* Geomorphology 345, 106844, DOI:10.1016/j.geomorph.2019.106844

Dauksza L., Kotarba A., 1973. *An analysis of the influence of fluvial erosion in the development of a landslides slope (using the application of the queueing theory).* Studia Geomorphologica Carpatho-Balcanica 7, 91–109.

Fuller I.C., Riedler R.A., Bell R., Marden M., Glade T., 2016. *Landslide-driven erosion and slope–channel coupling in steep, forested terrain, Ruahine Ranges, New Zealand 1946–2011*. Catena 142, 252–268. DOI:10.1016/j.catena.2016.03.019

Fidelus-Orzechowska, J., Wrońska-Wałach, D., Cebulski, J., Żelazny, M., 2018. *Effect of the construction of ski runs on changes in relief in a mountain catchment (Inner Carpathians, Southern Poland).* Science of Total Environment 630, 1298–1308, https://doi.org/10.1016/j.scitotenv.2018.02.305.

Gil E., 1997, *Meteorological and hydrological conditions of landslides, Polish Flysh Carpathians.* Studia Geomorphologica Carpatho-Balcanica 31, 143–158.

Gil E., Długosz M., 2006. *Threshold values of rinfalls triggering selected deep-seated landslides in the Polish Flysch Carpathians*. Studia Geomorphologica Carpatho-Balcanica 40, 21–43.

Gil E., Kotarba A., 1977. *Model of slide slope evolution in flysch mountains (An example drawn from the Polish Carpathians).* Catena 4, 3, 233–248.

Hancock H., Prokop P., Eckerstorfer M., Hendrikx J., 2018. *Combining high spatial resolution snow mapping and meteorological analyses to improve forecasting of destructive avalanches in Longyearbyen, Svalbard.* Cold Regions Science and Technology 154, 120–132.

Hendrickx H., De Sloover L., Stal C., Delaloye R., Nyssen J., Frankl A., 2020. *Talus slope geomorphology investigated at multiple time scales from high- resolution topographic surveys and historical aerial photographs (Sanetsch Pass, Switzerland).* Earth Surface Processes and Landforms 45, 3653–3669.

Harvey A.M., 2002, *Effective timescales of coupling within fluvial systems,* Geomorphology, 44, 175–201.

Jaboyedoff M., Abellán A., Derron M.H., Loye A., Metzger R., Pedrazzini A., 2012. *Use of LIDAR in landslide investigations: a review.* Natural Hazards 61, 5–28.

Jones K.E., Preston N.J., 2012. *Spatial and temporal patterns of off-slope sedyment delivery for small catchments subject to shallow landslides within the Waipaoa catchment, New Zealand.* Geomorphology 141-142, 150–159.

Kopciowski R., Zimnal Z., Jankowski L., 2014. *Objaśnienie do Szczegółowej Mapy Geologicznej Polski 1:50 000, arkusz 1038 - Osiek Jasielski.* CAG Warszawa, (in Polish).

Korup O., 2004. *Landslide dam.* [in:] A. Goudie (ed.), *Encyclopedia of geomorphology.* Routlege, London, p. 1156.

Kukulak J., Augustowski K., 2016. *Landslides on river banks in the western part of Podhale (Central Carpathians, Poland).* Geological Quarterly 60, 561–571.

Lévy S., Jaboyedoff M., Locat J., Demers D., 2012. *Erosion and channel change as factors of landslides and valley formation in Champlain Sea Clays: The Chacoura River, Quebec, Canada.* Geomorphology 145-146, 12–18.

Marciniec P., Zimnal Z., Nescieruk P., 2014. *Objaśnienia do Szczeg*ółowej Mapy Geologicznej Polski *1:50 000, arkusz Wojnicz – 1000*. CAG Warszawa, (in Polish).

Marciniec P., Zimnal Z., Wojciechowski T., Perski Z., Rączkowski W., Laskowicz I., Nescieruk P., Grabowski D., Kułak M., Wójcik A., 2019. *Osuwiska w Polsce – od rejestracji do prognozy, czyli 13 lat projektu SOPO.* Przegląd Geologiczny 67, 5, 291–297, (in Polish).

Margielewski W., 2006. *Structural control and types of movements of rock mass in anisotropic rocks: case studies in the Polish Flysch Carpathians.* Geomorphology 77, 1-2, 47–68.

McColl S.T., Holdsworth C., Massey C., 2017. *Movement of a large, slow-moving landslide in the North Island, New Zealand, controlled by porewater pressure and river flow.* EGU General Assembly Conference Abstracts, 19.

Oppikofer, T., Jaboyedoff, M., Blikra, L., Derron, M.-H., Metzger, R., 2009. *Characterization and monitoring of the Åknes rockslide using terrestrial laser scanning.* Nat. Hazards Earth Syst. Sci. 9, 1003–1019, https://doi.org/10.5194/nhess-9-1003-2009.

Oszczypko, N., Ślączka, A., Żytko, K., 2008. *Regionalizacja tektoniczna Polski – Karpaty zewnętrzne i zapadlisko przedkarpackie.* Przegląd Geologiczny 56, 927–935, (in Polish).

Płaczkowska E., Cebulski J., Bryndza M., Mostowik K., Murawska M., Rzonca B., Siwek J., 2021. *Morphometric analysis of the channel heads based on different LiDAR resolutions.* Geomorphology 375, 107546, DOI:10.1016/j.geomorph.2020.107546

Rączkowska Z., Cebulski J., Rączkowski W., Wojciechowski T., Perski Z., 2018. *Using TLS for monitoring talus slope morphodynamics in the Tatra Mts.* Studia Geomorphologica Carpatho-Balcanica 51-52, 179–198.

Rączkowski W., 2007. *Landslide hazard in the Polish flysh Carpathians.* Studia Geomorphologica Carpatho-Balcanica 41, 61–76.

Rączkowski W., Mrozek T., 2002. *Activating of landsliding in the Polish Flysch Carpathians by the end of the 20th century.* Studia Geomorphologica Carpatho-Balcanica 36, 91–111.

Refice A., Bovenga, F., Wasowski, J., Guerriero, L., 2000. *Use of InSAR data for landslide monitoring: a case study from southern Italy.* [in:] *IGARSS 2000. IEEE 2000 International Geoscience and Remote Sensing Symposium. Taking the Pulse of the Planet: The Role of Remote Sensing in Managing the Environment.* 2504–2506. https://doi.org/10.1109/IGARSS.2000.859621.

Starkel L., 1996. *Geomorphic role of extreme rainfalls in the Polish Carpathians.* Studia Geomorphologica Carpatho-Balcanica 30, 21–38.

Strzelecki M.C., Duszyński F., Tyszkowski S., Zbucki L., 2022. *Limestone Sea Stacks (Rauks) Record Past Sea Levels and Rocky Coast Evolution in the Baltic Sea (Gotland and Fårö Islands, Sweden).* Frontiers in Earth Science 10, 895419, DOI:10.3389/feart.2022.895419

Soldati M., Barrows T.T., Prampolini M., Fifield K.L., 2018. *Cosmogenic exposure dating constraints for coastal landslide evolution on the Island of Malta (Mediterranean Sea).* Journal of Coastal Conservation 22, 831–844.

Stumvoll M.J., Schmaltz E. M,. Glade T., 2021. *Dynamic characterization of a slow-moving landslide system – Assessing the challenges of small process scales utilizing multi-temporal TLS data.* Geomorphology 389, https://doi.org/10.1016/j.geomorph.2021.107803

Travelletti J., Malet J.P., 2012. *Characterization of the 3D geometry of flow-like landslides: A methodology based on the integration of heterogeneous multi-source data.* Engineering Geology 128, 30–48.

Tyszkowski S., Cebulski J., 2019. *Practical aspects of landslides surveys using terrestrial laser scanning in diverse geomorphological terrains: case studies from Polish Carpathians and Lower Vistula Valley.* Zeitschrift für Geomorphologie 62, 2, 107–124.

Ventura G., Vilardo G., Terranova V., Bellucci Sessa E., 2011. *Tracking and evolution of complex active landslides by multi-temporal airborne LiDAR data: The Montaguto landslide (Southern Italy).* Remote Sensing of Environment 115, 12, DOI:10.1016/j.rse.2011.07.007

Wistuba M., Malik I., Wójcicki K., Michałowicz P., 2015. *Coupling between landslides and eroding stream channels reconstructed from spruce tree rings (examples from the Carpathians and Sudetes-Central Europe).* Earth Surface Processes and Landforms 40, 293–312.

Yenes M., Monterrubio S., Nespereira J., Santos G., Fernández-Macarro B., 2015. *Large landslides induced by fluvial incision in the Cenozoic Duero Basin (Spain).* Geomorphology 246, 263–276.

Ziętara T., 1968. *Rola gwałtownych ulew i powodzi w modelowaniu rzeźby Beskidów.* Prace Geograficzne Instytutu Geografii PAN 60, 5–116, (in Polish).

Jarosław Cebulski
Institute of Geography and Spatial Organization
Polish Academy of Sciences
31-018 Kraków, św Jana 22
e-mail:cebulski@zg.pan.krakow.pl