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Landslides modifying drainage divides in mountainous areas and their classification: a case study from the Polish Outer Carpathians

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Landslides change terrain morphology, often causing destruction of road infrastructure and other kinds of construction. Ever-increasing attention is drawn to the detection, identification, and classification of landslides. However, the influence of landslides on mountain-range migration has been more or less overlooked. The application of a digital elevation model (DEM) and successive DEM modelling derivatives have allowed determination of the influence of landslides on drainage divide modification. The Polish Outer Carpathians were here analysed for landslides, to distinguish landslide forms that modified drainage divides in mountainous areas and then to classify them. This analysis was performed based on data from airborne laser scanning using geographic information system tools. Accordingly, 510 landslides have been recognized as modifying drainage divides and were subsequently classified into three proposed landslide types (I–III).

Key words: LiDAR ALS, DEM, landslides detection, drainage divide migration.

INTRODUCTION

Landslides and their causes draw much attention from researchers. Studies generally concentrate on four key landslide aspects:

– landscape-recognition methodology employed in areas susceptible to the development of landslide processes (Crosta and Agliardi, 2003; Federico et al., 2012; Sarda and Pandey, 2019; Sharma et al., 2020);
– causes of landslide occurrence (Radbruch-Hall and Varnes, 1976; Alexander, 1992; Kirschbaum et al., 2010);
– socio-economic effects of landslides and their impact on people's lives (Petley, 2012; Jaedicke et al., 2014; Zumpano et al., 2018);
– landslide classification.

Landslide subdivision is conducted according to various criteria, usually based on:

– types of movements in a rock massif in association with landslide-forming material typology (Varnes, 1958; Nemčok et al., 1972; Cruden and Varnes, 1996; Dickau et al., 1996; Hungr et al., 2014);
– degree of downslope activity (WP/WLI, 1993; Cruden and Couture, 2011);
– downslope movement rate (WP/WLI, 1995; Cruden and Couture, 2011);
– scale of associated socio-economic losses (Caldera and Wirasinghe, 2022).

Much less attention has been drawn to the impact of landslides on terrain morphology, mountain-slope evolution, and changes in catchment hydrological parameters, all of which influence the development of the hydrographic network, magnitude of retention and outflow, and water and sediment fluxes in river systems (e.g., Korup et al., 2006, 2010; Safran et al., 2011; Fan et al., 2012; Jin et al., 2021; Davies and Moretti, 2022).

Recent, albeit limited, interest in the influence of landslides on the modification of drainage divides has concentrated on the evolution of river systems and the role of fluvial erosion in landslide formation (Dahlquist et al., 2018; Chenn et al., 2021; Cebulski, 2022; Kukulak et al., 2022; Zhou et al., 2022). Recognition of the phenomenon of drainage-divide migration is of particular importance in mountainous areas where high-energy processes contribute to relief, higher slope gradients, and often the geological settings that favour landslide development (Agliardi et al., 2001; Długosz, 2011; Chalupa et al., 2018; Görüm, 2018; Sikora, 2018, 2022). In the Carpathians (Fig. 1), there have been no studies of the modification of drainage divides, even though this area is particularly susceptible to landsliding because of specific geologic characters such as differential mechanical instability due to sandstone-shale alternations (Ostaficzuk, 1999; Margielewski, 2002; Baroň et al., 2004, 2005; Rączkowski, 2007).

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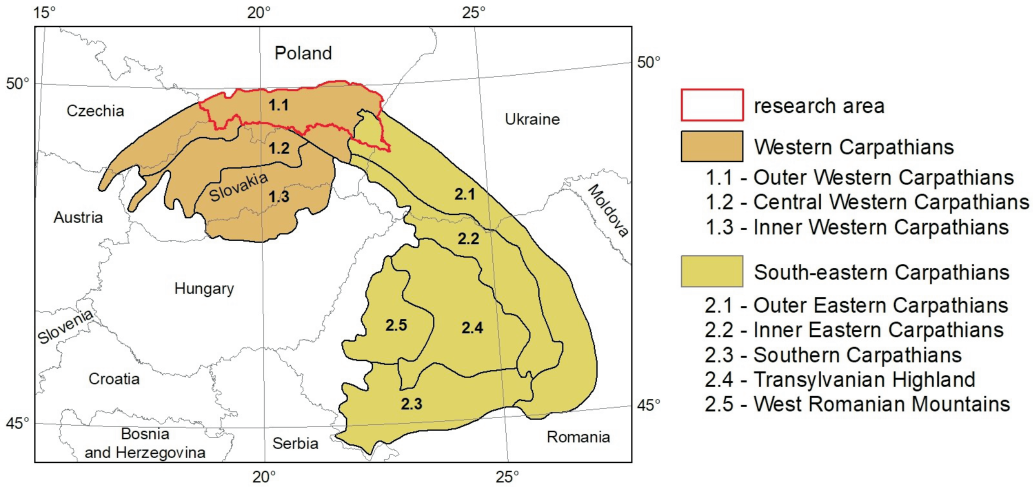


Fig. 1. Sub-divisions of the Carpathians (after Kondracki, 1978)

The application of traditional landscape-detection methodology including field surveys, analysis of aerial and satellite photographs, topographic map analysis, and hydrographic networks is difficult in the Outer Carpathians due to the large morphological variability and the occurrence of dense vegetation. A significant advance in Carpathian landslide studies has stemmed from the application of high-resolution digital elevation models (DEMs), generated upon a cloud of points obtained from airborne laser scanning (ALS). This method has been successfully used around the world for over twenty years (Carter et al., 2001; Jaboyedoff et al., 2012) and allows a comprehensive analysis of landslide forms, e.g. landslide detection on steep and densely vegetated slopes, their identification and classification, and analysis of morphometric features. It has also enabled better understanding of landslide processes (e.g., Ardizzone et al., 2007; Borkowski et al., 2011; Wojciechowski et al., 2012; Pirasteh and Li, 2018; Pawłuszek et al., 2019; Wódka, 2019; Demurtas et al., 2021), as well as monitoring and observations of landslide activity based on differential models (Palenzuela et al., 2015; Pellicani et al., 2019; Wódka, 2022). In Poland, the use of LiDAR data (Light Detection and Ranging) accelerated fieldwork as regards landslide recognition. These methods were used in the SOPO project (landslide counteracting system) implemented by the Polish Geological Institute – National Research Institute. The project identified landslides and areas at risk of mass wasting, to create an effective system warning against slope movements and helping to counteract their negative effects (Grabowski, 2008; Grabowski et al., 2008; Ozimkowski et al., 2010; Mrozek et al., 2013; Mrozek and Laskowicz, 2014). Application of LiDAR data has increased the degree of landslide detection in the Carpathians, including landslides modifying drainage divides (LMDD).

In this paper we:

- work out a methodology allowing the detection of LMDD based on LiDAR ALS data;
- determine the influence of landslide processes on the modification of drainage divides;
- propose a LMDD classification;
- recognize the scale of LMDD influence on the migration of drainage divides in the Polish Outer Carpathians.

STUDY AREA

The Carpathians extend for 1300 km from the vicinity of Vienna, Austria, to Romania's Iron Gate on the Danube (Fig. 1). The Outer Carpathians in Poland are composed mainly of flysch successions, including shales, sandstones and conglomerates whose age ranges from the Upper Jurassic to the Lower Miocene. During the Alpine orogeny, these deposits were detached from their basement and transported northwards onto deposits of the Carpathian Foredeep, resulting in nappes thrusted over each other (Oszczypko, 2006; Oszczypko et al., 2008). The study area is located within two Carpathian sub-provinces, the Outer Western Carpathians and the Outer Eastern Carpathians, which are themselves subdivided into 30 mesoregions (Fig. 2) that are assigned to three relief types: 1) medium mountains; 2) piedmonts and low mountains; and 3) basins (Kondracki, 2009). These areas are characterized by large relief variability; the highest mountain – Babia Góra in the Beskid Żywiecko-Orawski – reaches 1725 m a.s.l., whereas the lowest topography – the Kotlina Sądecka – is located at 280–300 m a.s.l.

MATERIAL AND METHODS

The Polish Outer Carpathians (Fig. 2), covering an area of 18.7 thousand km^2, were the subject to detailed analysis including:

- identification of landslides modifying drainage divides;
- delineating the boundaries of these landslides;
- determining the present-day and pre-landslide position of the drainage divide.

These aims were achieved with application of Geographic Information System (GIS) tools. The analysis was made in *ArcGIS 10.8* and *Relief Visualization Toolbox 2.2.1.* software, in metric rectangular coordinates of the European Terrestrial Reference System (ETRS) 1989 (PL1992). The analysis was subdivided into four stages:

- spatial data integration;
- generating drainage divides (2a) and landslide detection (2b);

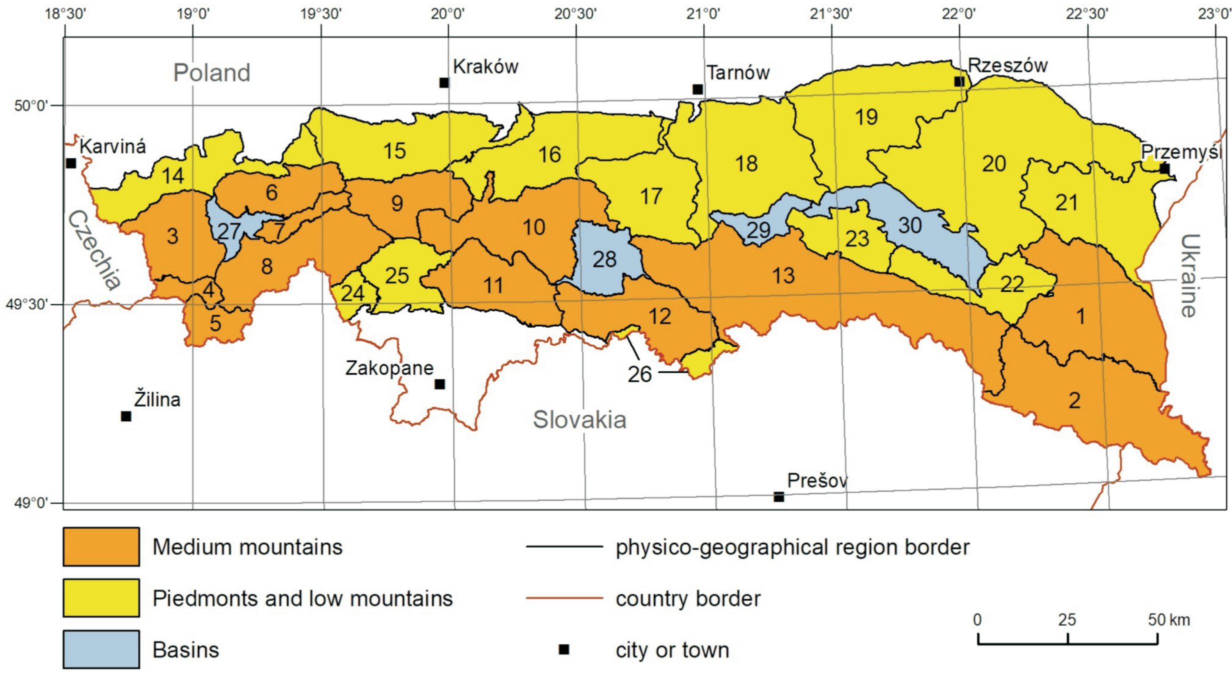


Fig. 2. Physico-geographical regions of the Polish Outer Carpathian (after Kondracki, 2009, modified by Solon et al., 2018)

- landslide selection;
- classification of landslides modifying drainage divides (Fig. 3).

STAGE 1 – SPATIAL DATA INTEGRATION

The first stage included spatial data integration. To achieve this, the LiDAR data applied were obtained from the Head Office of Geodesy and Cartography (Republic of Poland) from two intervals: 1) 2011–2014, which was collected in the frame of the Information System of National Protection Against Extraordinary Risks Project (ISOK Project); and 2) 2019–2023, which derived from the Centre for Spatial Analysis of Public Administration Project (CAPAP Project). Based on LiDAR ALS point clouds with a resolution of 4–12 points/m^2, a digital elevation model (DEM) was created. Then, for the test areas, rasters with spatial resolution of 0.5 x 0.5 m, 1 x 1 m, 5 x 5 m and 10 x 10 m were created. Based on the rasters generated, a raster with a resolution of 1 x 1 m was selected for further analysis, as it is the optimal resolution for generating drainage divides and landslide detection in areas with a very high relief variability and with large elevation differences, such as in mountainous areas.

STAGE 2 – GENERATING DRAINAGE DIVIDES (2A) AND LANDSLIDE DETECTION (2B)

These activities were performed independently on the same input data generated in stage 1 – i.e., a DEM with a spatial resolution of 1 × 1 m.

The drainage divides were generated by subjecting the DEM to the infilling process; this consisted of removal of the pits on the surface of the area analysed which were formed during LiDAR data interpolation (Planchon and Darboux, 2001). Such data were next used for constructing flow-direction maps. The D8 single flow-direction method was used to construct the map; it assumes water flow from each raster cell to only one of the eight cells surrounding it, towards the largest terrain slope. Water flowing between the cells forms the flow lines, and cells located below along the flow path accumulate water from cells occurring above. This allowed the construction of a flow-accumulation map, in which each raster cell is attributed to the number of cells that supply it (Jenson and Domingue, 1988; Urbański, 2011; Radecki-Pawlik et al., 2015; Scherler and Schwanghart, 2020). Next the pour point was determined; this allowed the creation of a drainage divide for a given point. A parallel landslide detection analysis was performed. This was enhanced by data for landslides acquired from the SOPO project. Data were specified basing on a meticulous landslide analysis, which was based on the following models generated from the DEM: 1) hillshade; 2) hillshade from multiple directions; 3) positive and negative openness; 4) sky-view factor; 5) and slope gradient (Yokoyama et al., 2002; Zakšek et al., 2011; Kokalj and Hesse, 2017; Kokalj and Somrak, 2019).

STAGE 3 – LANDSLIDE SELECTION

The next stage included identification of landslides whose ranges are located within contemporary drainage divides. In this case models generated in Stage 2b from DEM were applied. Within selected landslides it was possible to reconstruct the drainage divide before the landslide event (DDBL), this being based on the position of the mountain ridge and slope exposure. Using aspect and contour maps along with morphological

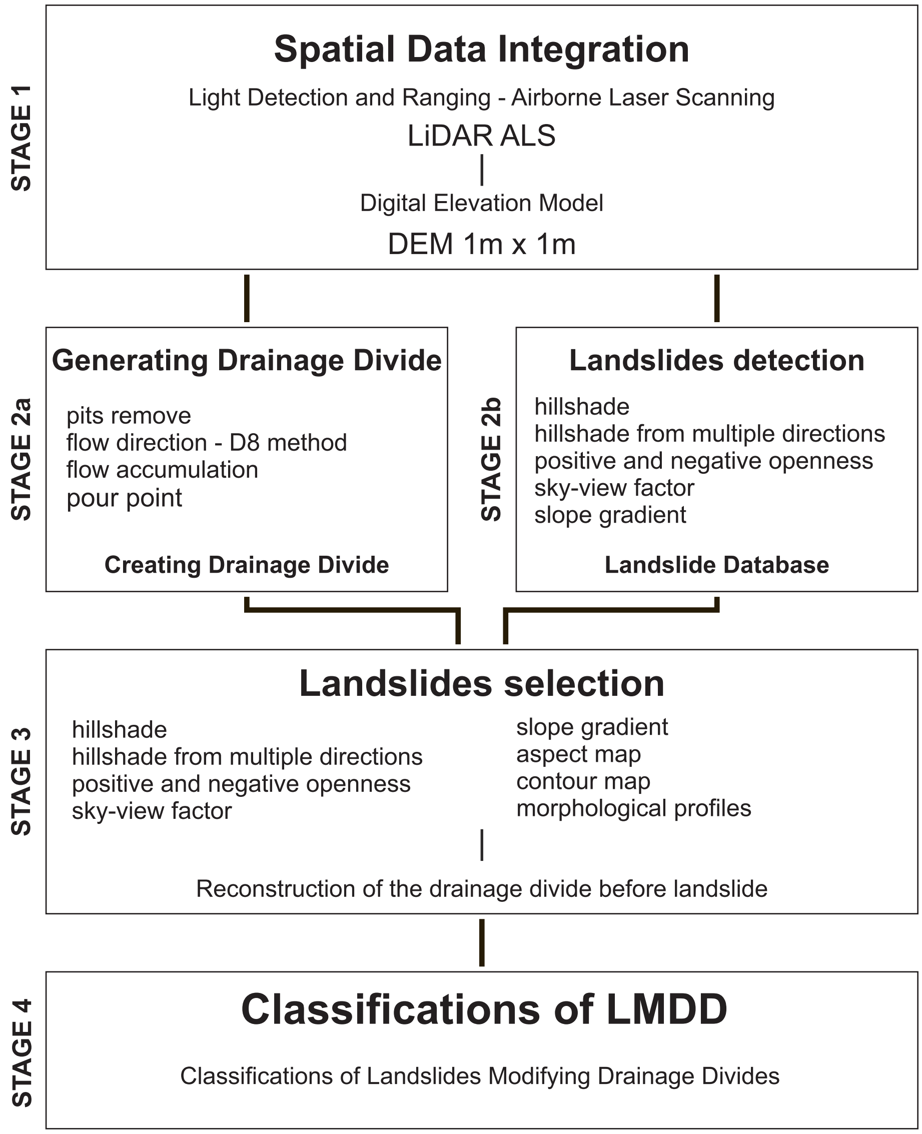


Fig. 3. Scheme of analytical stages

profiles, parts of the drainage divide that are adjacent to the developed landslide scarp or landslide tongue were then connected by a line (Fig. 4).

STAGE 4 – CLASSIFICATION OF LANDSLIDES MODIFYING DRAINAGE DIVIDES

Classification of landslides takes place after all actions described in stages 1–3, thereby detecting landslides modifying drainage divides. The proposed classification is based on landslide elements along which the modified drainage divide occurs – i.e., the landslide main scarp and the colluvium.

RESULTS

DRAINAGE DIVIDES MODIFIED BY LANDSLIDES

LiDAR ALS data analysis performed for the Polish Outer Carpathians allowed recognition of drainage divide modifications caused by landslide processes. The course of topographic drainage divides is modified within mountain ridges (Fig. 5A) that have been subjected to landslide processes. Displacement of rock material causes translocation and lowering of topographic points along which the primary drainage divide occurred, and thus modifies the line of a given drainage divide. The final typology of landslides will depend upon the localization of the modified drainage divide, which may either run along the main scarp – DDMLS (Fig. 5B), or be placed inside the colluvium – DDMLC (Fig. 5C). Analysis of course changes inside a landslide-modified drainage divide requires reconstruction of the drainage divide before the landslide (DDBL), as this allows the determination of changes to the DD position by using the following specific parameters (Figs. 5A and 6B):

1 – for DDMLS (Fig. 5B):

– ds_{max} – maximum distance measured horizontally between DDBL and DDMLS [m];

– Hs – elevation difference between DDBL and DDMLS.

$$Hs = HDDBL - HDDMLS \text{ [m]} \qquad [1.1]$$

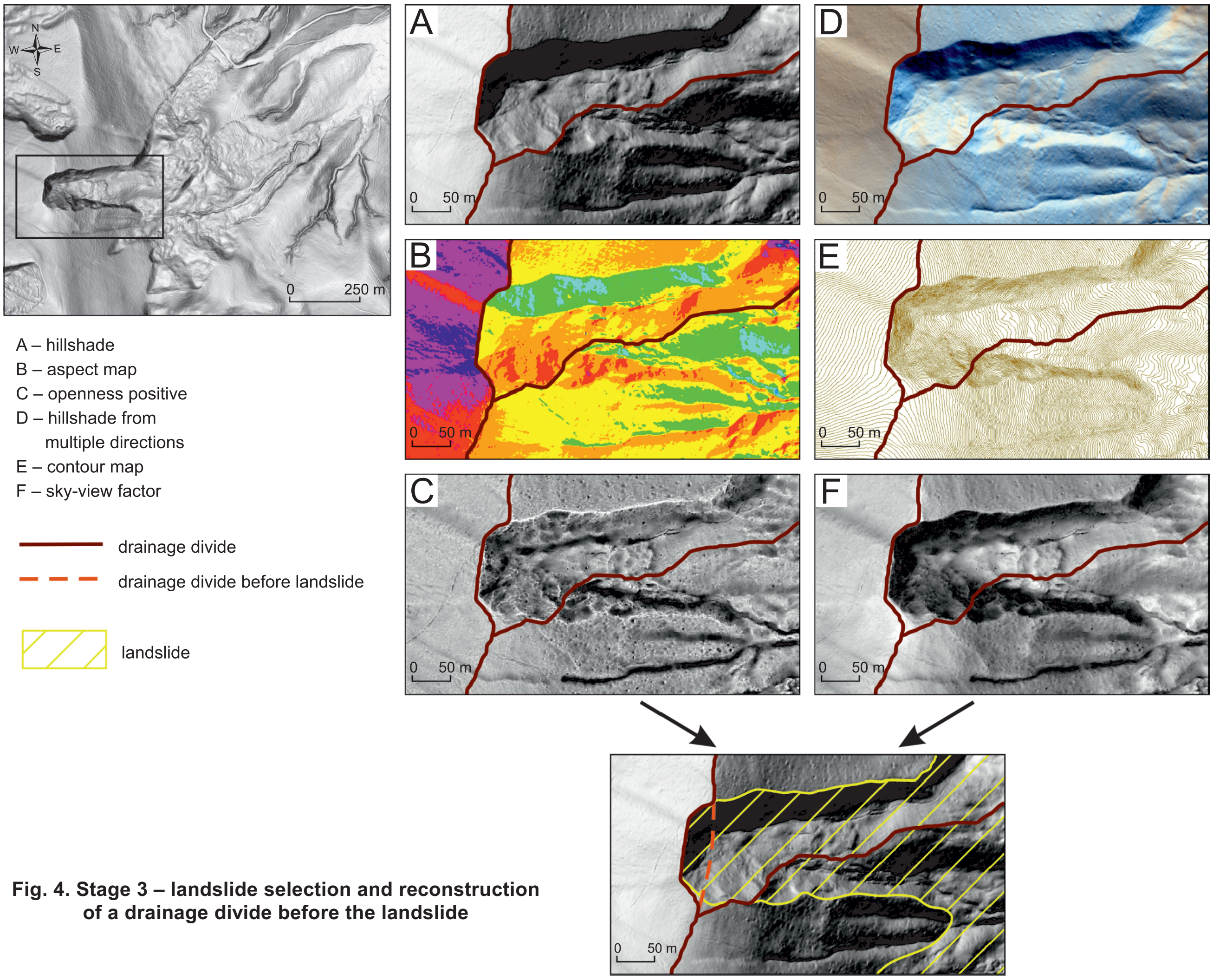


Fig. 4. Stage 3 – landslide selection and reconstruction of a drainage divide before the landslide

where: HDDBL – ordinate of point DDBL, HDDMLS – ordinate of point DDMLS (m a.s.l.).

2 – for DDMLC (Fig. 5C):
– dc_{max} – maximum distance measured horizontally between DDBL and DDMLC [m];
– Hc – elevation difference between DDBL and DDMLC.

$$Hc = HDDBL – HDDMLC \text{ [m]} \quad [1.2]$$

where: HDDBL – ordinate of point DDBL, HDDMLC – ordinate of point DDMLC (m a.s.l.).

CLASSIFICATIONS OF LANDSLIDES MODIFYING DRAINAGE DIVIDES

Inside the landslide, the drainage divide may be displaced in various directions, either towards the main scarp or towards the landslide front, occurring along the main scarp or within the colluvium. The term colluvium indicates the presence of both mixed and weathered lithologies. The position of the modified drainage divide is the basis of classifications of landslides modifying drainage divides (LMDD). Accordingly, three types of landslides were distinguished (Table 1):

1 – type I – landslides modifying drainage divides – scarp (LMDDS);
2 – type II – landslides modifying drainage divides – colluvium (LMDDC);
3 type III – landslides modifying drainage divides – mixed (LMDDM).

TYPE I – LANDSLIDES MODIFYING DRAINAGE DIVIDES – SCARP (LMDDS)

In this type, the modified drainage divide is located along the main scarp. The landslide causes the drainage divide to be displaced solely towards the main scarp of the landslide (A in Fig. 6). The maximum displacement of the drainage divide is described by parameter ds_{max} (Table 1).

TYPE II – LANDSLIDES MODIFYING DRAINAGE DIVIDES – COLLUVIUM (LMDDC)

In this landslide type, the drainage divide is located solely within the colluvium. The modified DD may become displaced along its entire length towards the main scarp of the landslide (B in Fig. 6), towards the landslide front (C in Fig 6), or the displacement may take place in both directions – part of the DD is

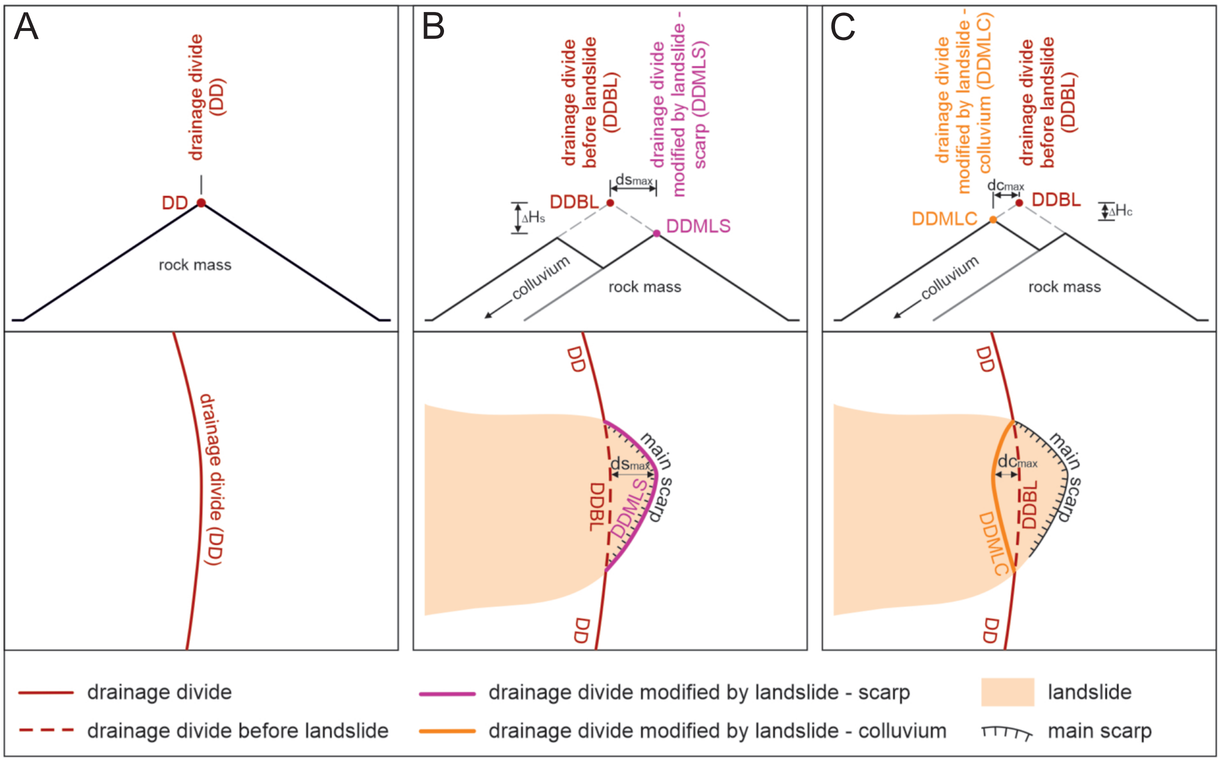


Fig. 5. Spatial parameters of drainage divides modified by landslides

shifted towards the main scarp and part towards the landslide front (D in Fig. 6). The maximum displacement of the drainage divide is determined by parameter dc_{max} (Table 1).

TYPE III – LANDSLIDES MODIFYING DRAINAGE DIVIDE – MIXED (LMDDM)

This is a mixed type, linking features of types I and II, in which the modified drainage divide is located partly along the main scarp and partly within the colluvium. The entire DD may become displaced towards the main scarp (E in Fig. 6) or part of the DD may become displaced towards the landslide front and the remaining part towards the main scarp (F in Fig. 6). The maximal DD displacement is determined by two parameters: 1) ds_{max}, which indicates the maximum displacement along the main scarp, and 2) dc_{max}, which points to the maximum displacement within the colluvium (Table 1).

Landslides are characterized by broad geomorphic dynamics and multi-stage development. Therefore, in distinctive stages, the DDML landslide may change its position from the main scarp to the colluvium and *vice versa*, changing the type of LMDD. Additionally, in each of the three landslide types (I–III), a modification of one or more drainage divides may take place. When a landslide is formed on a slope and overlaps only the ridge, the modification of just one drainage divide takes place (A–C in Fig. 7). However, when a landslide overlaps a peak or summit, the displacement occurs in at least two drainage divides (D–F in Fig. 7).

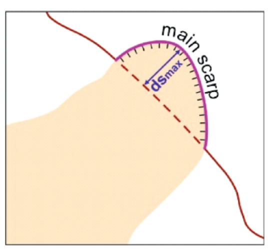
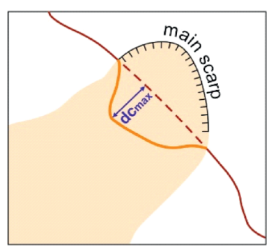
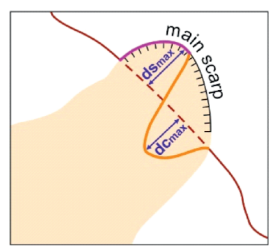
LANDSLIDES MODIFYING DRAINAGE DIVIDES IN THE POLISH OUTER CARPATHIANS

In the Polish Outer Carpathians, >50,000 landslides were analysed based on the methodology proposed here. The analyses were carried out on a model displayed at a scale of 1:10,000, and 510 landslides were discovered that changed the course of drainage divides. This number is not final, and may be changed by the use of other detection methods. The LMDD distribution was analysed within particular physico-geographical regions of the Outer Carpathians (Fig. 8) as distinguished by Kondracki (2009) and modified by Solon et al. (2018), because the unit boundaries were established based on geomorphological and geological data. The occurrence of landslides depends in part on the slope inclination and geological conditions.

The LMDD are randomly distributed; their largest accumulation was observed within units assigned to medium mountains, for which the average density is 0.047 LMDD/km^2. Two mountain ranges should be highlighted – the Bieszczady Zachodnie (no. 2) and the Beskid Śląski (no. 3; Figs. 2 and 8) – where the density is 0.094 and 0.092 LMDD/km^2, respectively. By contrast, in the Góry Sanocko-Turczańskie (no. 1), the density is only 0.006 LMDD/km^2, and in the Międzygórze Jabłon-

Table 1

Classification of landslides modifying drainage divides

Type of landslide	Type I	Type II	Type III
	Landslides modifying drainage divide – scarp (LMDDS)	**Landslides modifying drainage divide – colluvium (LMDDC)**	**Landslides modifying drainage divide – mixed (scarp and colluvium) (LMDDM)**
Location of the modified drainage divide	along the main scarp	within the colluvium	along the main scarp and within the colluvium
Parameter	ds_{max}>0 [m]	dc_{max} >0 [m]	ds_{max} >0 [m] dc_{max} >0 [m]
Parameter definition	Maximum distance measured horizontally between drainage divide before landslide (DDBL) and drainage divide modified by landslide – scarp (DDMLS)	Maximum distance measured horizontally between drainage divide before landslide (DDBL) and drainage divide modified by landslide – colluvium (DDMLC)	The same definition of ds_{max} as in type I and dc_{max} as in type II
Model			

drainage divide
drainage divide before landslide
drainage divide modified by landslide - scarp
drainage divide modified by landslide - colluvium
landslide
main scarp

kowsko-Koniakowskie (no. 4), LMDD were not even registered. Within piedmonts and low mountains (nos. 14–26), the average LMDD density is lower, at 0.013 LMDD/km^2. Within the Pogórze Popradzkie (no. 26), the average density is 0.077 LMDD/km^2 and is considerably above the average density for piedmonts and low mountains. This unexpected higher density probably results from the fact that only the northern part of this unit, neighbouring medium mountain ranges, occurs in Poland. In the Pogórze Jasielskie (no. 23) and the Działy Orawskie (no. 24), LMDD have not been registered (Figs. 2 and 8). In basins (nos. 27–30), the average density is only 0.005 LMDD/km^2, which is caused by the fact that the Kotlina Sądecka (no. 28) has a LMDD/km^2 of 0.019, and such forms were not observed in the remaining units. The distribution of LMDD within a particular region is variable. In regions 2, 8, 12, and 21 a large LMDD concentration was observed in small areas, whereas in other units, the distribution is more widespread.

In the study area, all three LMDD types were observed. The percentage contribution of the particular types is different; the most common was type I, which contributes to 67% of the forms analysed (Fig. 9). The distribution of particular landslide types within specific mesoregions is variable and depends on

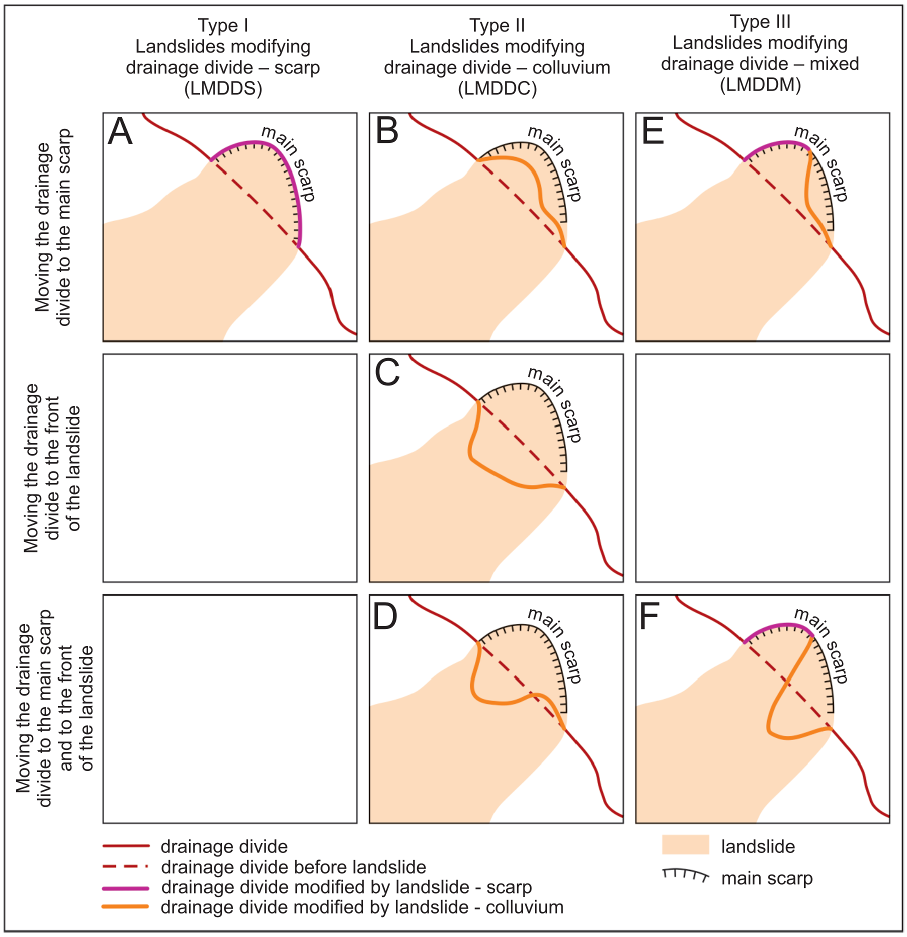


Fig. 6. Displacement of the drainage divide by a landslide

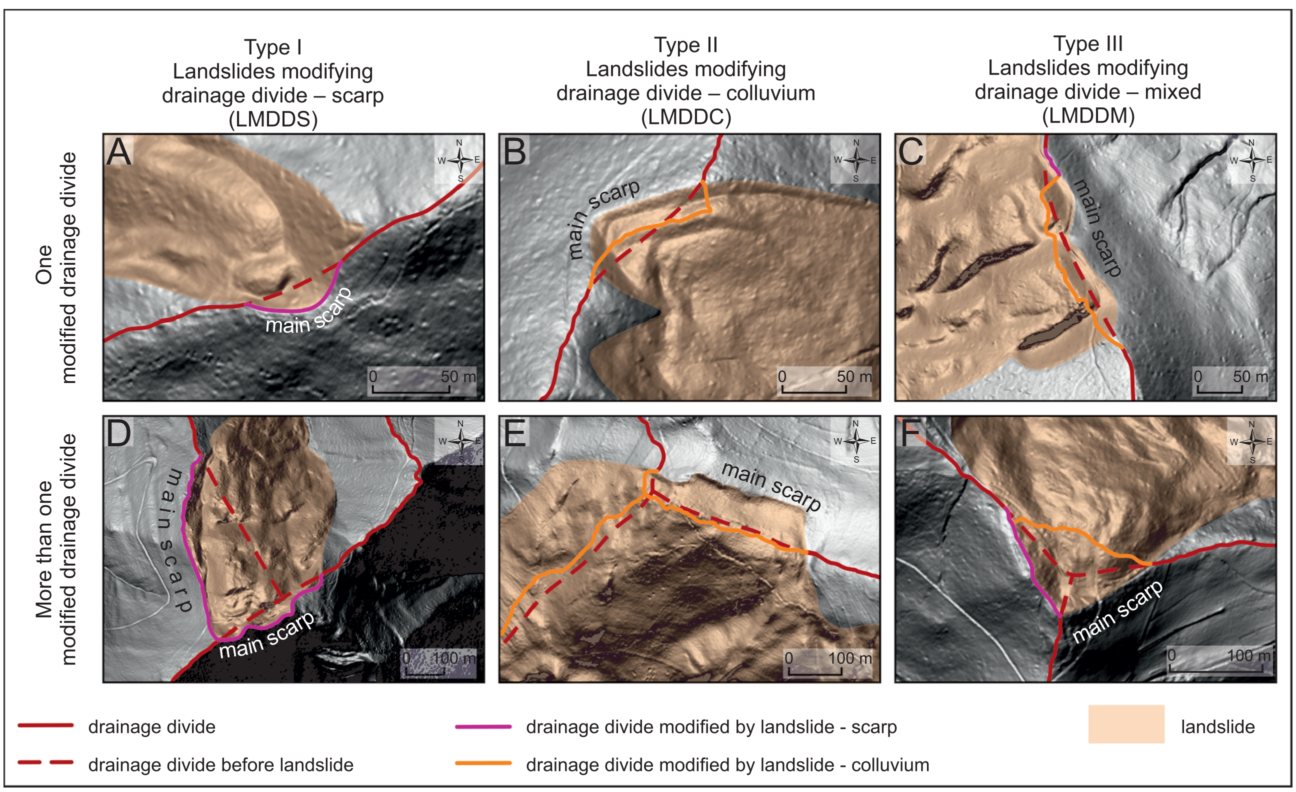


Fig. 7. Landslides modifying one or more than one drainage divides

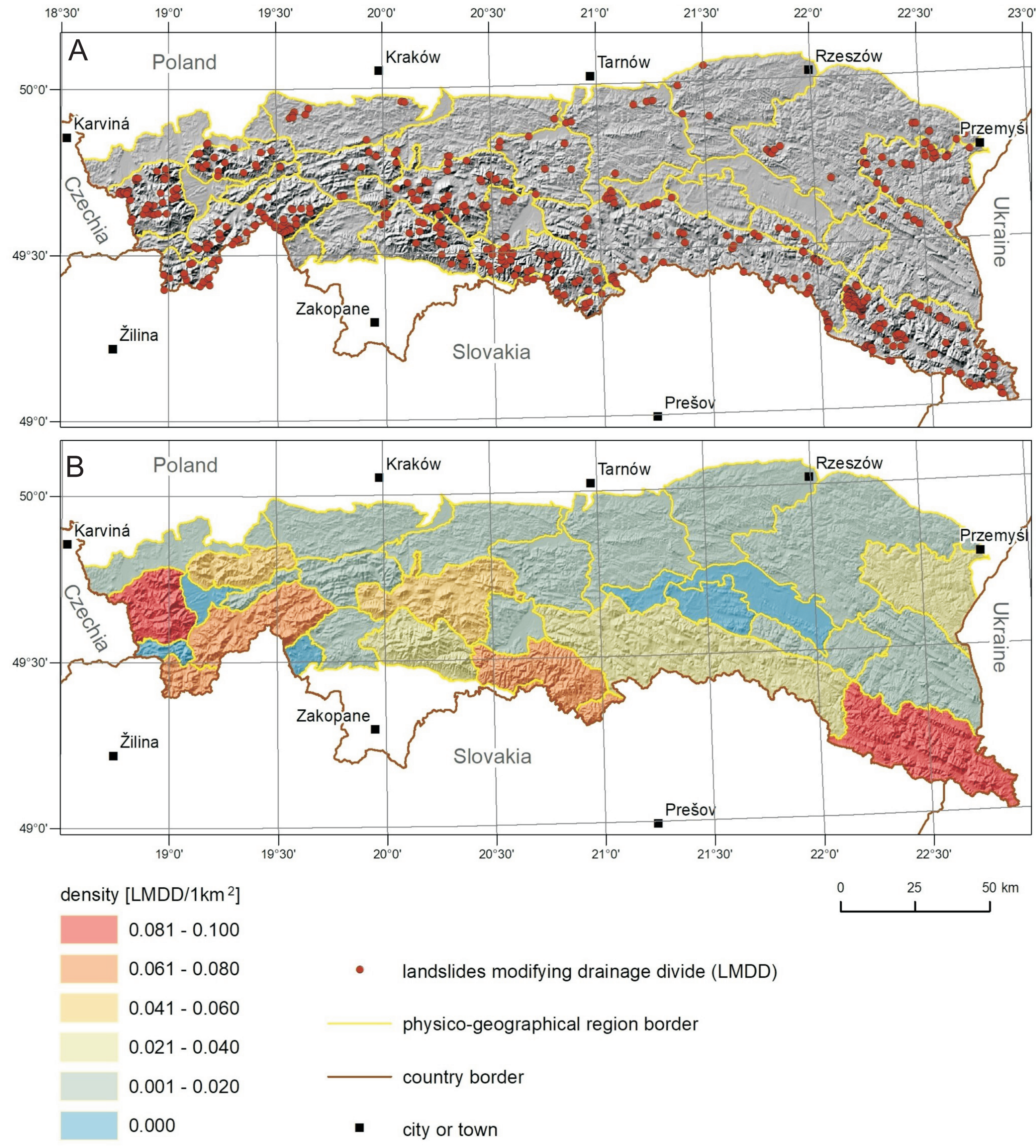


Fig. 8. Location of landslides modifying drainage divides in the Polish Outer Carpathians
A – location, B – density of LMDD in particular physico-geographical regions

the dominant relief type within each unit. The largest variability occurs in medium mountains (nos. 1–13 in Fig. 2 and Table 2). Here there occur 418 LMDDs, among which forms assigned to type I contribute to 63%, II – 24%, and III – 13%. All three landslide types occur within 9 of 13 mesoregions; in two mesoregions two out of three types occur – types I and III in the Góry Sanocko-Turczańskie (no. 1), and types I and II in the Beskid Makowski (no. 9). Type II was only observed in the Pasma Pawelsko-Krzeczowskie (no. 7), whereas LMDD have not been observed at all in the Międzygórze Jabłonkowsko-Koniakowskie (no. 4). In piedmonts and low mountains (nos. 14–26), type I landslides contribute to 86%, whereas types II and III contribute to 8 and 6%, respectively. All three landslide types occur in only 2 out of 13 mesoregions: in the Pogórze Przemyskie (no. 21) and Pogórze Popradzkie (no. 26). In three mesoregions there each occur two types of landslides. Types I and II occur in the Pogórze Strzyżowskie (no. 19) and the Pogórze Dynowskie (no. 20), while types I and III occur in the Pogórze Bukowskie

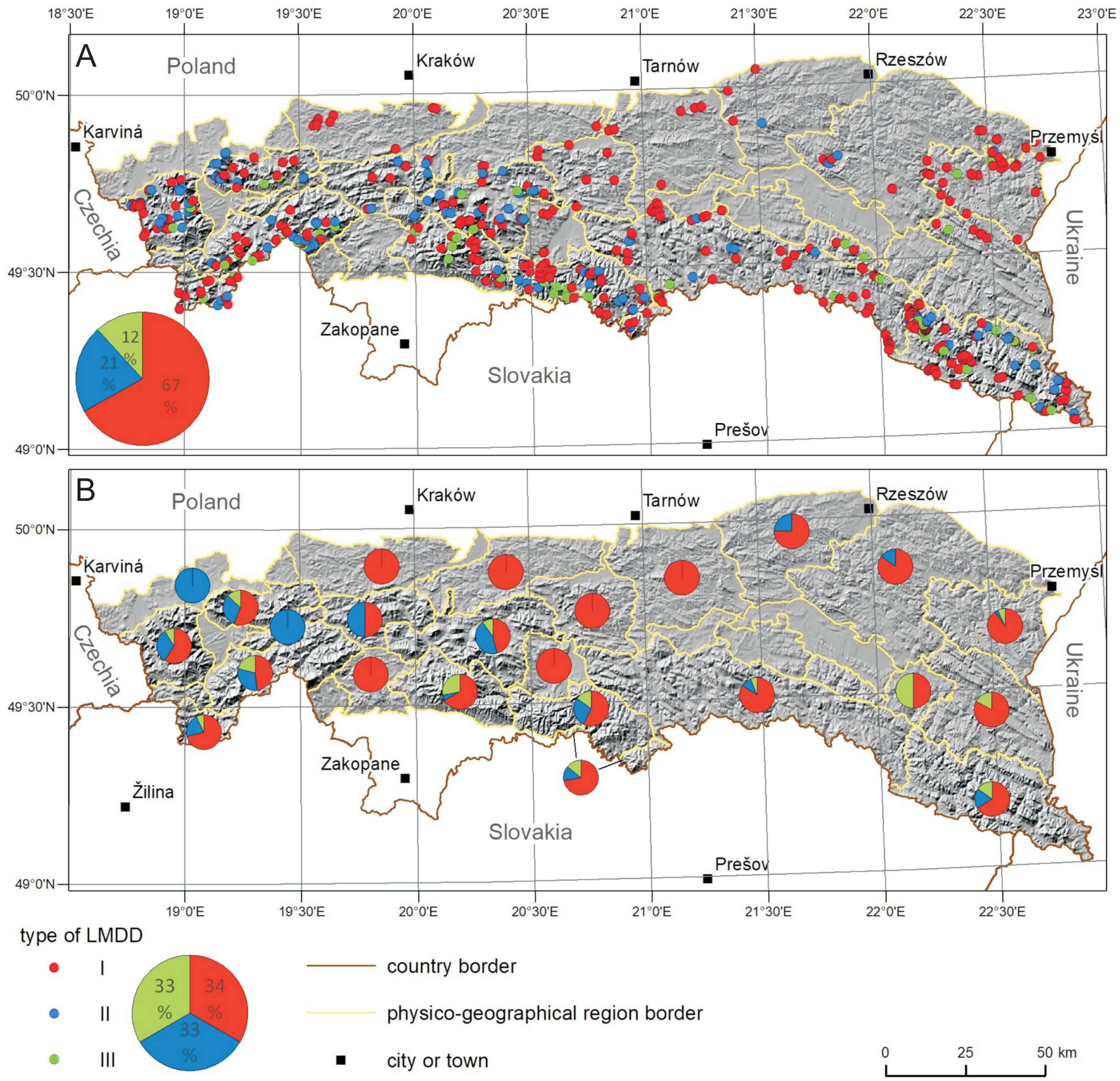


Fig. 9. Types of landslides modifying drainage divides in the Polish Outer Carpathians
A – location, B – percentage share in particular physico-geographical regions

(no. 22). In the Pogórze Śląskie (no. 14) only type II was observed and in 5 mesoregions only type I occurs. In the remaining two mesoregions, LMDD were not observed – i.e., the Pogórze Jasielskie (no. 23) and the Działy Orawskie (no. 24). The situation is different within basins (nos. 27–30), as LMDD occur only within the Kotlina Sądecka (no. 28) and all of those belong to type I (Fig. 9).

DISCUSSION

IMPORTANCE OF THE RESEARCH

Drainage divide migration has been described inside the catchments of large Asian rivers, for instance in Taiwan, Nepal, China (Dahlquist et al., 2018), and Tibet (Chenn et al., 2021; Zhou et al., 2022). These studies linked DD migration with for instance landslide activity, which is enhanced by contemporary tectonic processes associated with earthquakes, geological setting, climatic conditions or extreme weather phenomena such as typhoons. Nowadays in the Carpathians, earthquakes are of minor significance as regards landslides (Gerlach et al., 1958; Pagaczewski, 1972; Wójcik, 1997; Rączkowski, 2007) and DD migration. Regardless of its location, a landslide that modifies the drainage divide changes the parameters of neighbouring catchments, such as their shape, range, and surface on which precipitation takes place. In this way, a landslide influences the hydrological parameters of the catchment, including the magnitude of retention and intensity of slope flow, while increasing slope erosion.

Table 2

Types of landslides modifying drainage divides in the Polish Outer Carpathians

Nº		Name of the mesoregion	Mesoregion area [km^2]	Number of LMDD	Density [LMDD/km^2]	Mean of density [LMDD/km^2]	Percentage share [%] Type I	Type II	Type III	I, II, III	
1	Medium mountains	Góry Sanocko-Turczańskie	1066.24	6	0.006	0.049	83	0	17	 type I - 63% type II - 24% type III - 13%	Medium mountains
2		Bieszczady Zachodnie	1146.56	108	0.094		66	19	15		
3		Beskid Śląski	479.99	44	0.092		59	32	9		
4		Międzygórze Jabłonkowsko-Koniakowskie	105.52	0	0.000		0	0	0		
5		Beskid Żywiecko-Kysucki	176.61	14	0.079		72	21	7		
6		Beskid Mały	377.30	16	0.042		56	31	13		
7		Pasma Pawelsko-Krzeczowskie	123.33	2	0.016		0	100	0		
8		Beskid Żywiecko-Orawski	687.22	48	0.070		48	31	21		
9		Beskid Makowski	434.43	8	0.018		50	50	0		
10		Beskid Wyspowy	833.16	41	0.049		46	44	10		
11		Gorce	548.14	21	0.038		67	5	28		
12		Beskid Sądecki	618.26	47	0.076		57	28	15		
13		Beskid Niski	1881.09	63	0.033		84	10	6		
			sum	418							
14	Piedmonts and low mountains	Pogórze Śląskie	580.35	2	0.003	0.009	0	100	0	 type I - 86% type II - 8% type III - 6%	Piedmonts and low mountains
15		Pogórze Wielickie	794.13	9	0.011		100	0	0		
16		Pogórze Wiśnickie	800.37	4	0.005		100	0	0		
17		Pogórze Rożnowskie	631.05	7	0.011		100	0	0		
18		Pogórze Ciężkowickie	1091.66	6	0.005		100	0	0		
19		Pogórze Strzyżowskie	1112.21	4	0.004		75	25	0		
20		Pogórze Dynowskie	1928.94	13	0.007		85	15	0		
21		Pogórze Przemyskie	804.93	29	0.036		90	3	7		
22		Pogórze Bukowskie	451.17	4	0.009		50	0	50		
23		Pogórze Jasielskie	342.08	0	0.000		0	0	0		
24		Działy Orawskie	114.40	0	0.000		0	0	0		
25		Pogórze Orawsko-Jordanowskie	355.80	1	0.003		100	0	0		
26		Pogórze Popradzkie	90.84	7	0.077		72	14	14		
			sum	86							
27	Basins	Kotlina Żywiecka	148.08	0	0.000	0.005	0	0	0	 type I - 100%	Basins
28		Kotlina Sądecka	323.54	6	0.019		100	0	0		
29		Obniżenie Gorlickie	165.54	0	0.000		0	0	0		
30		Kotlina Jasielsko-Krośnieńska	524.39	0	0.000		0	0	0		
			sum	6							

LiDAR data is becoming better in terms of quality and availability, so performing similar DD-migration analysis is now possible for most parts of the world. The LMDD classification developed here based on studies of the Carpathians Flysch may be universally applied to different mountainous areas. The modified drainage divide position inside the landslide is basis of the methodology's applicability in landslide classification beyond the current study area. The actual dimension of most changes to the Polish Carpathians catchment surface have yet to be fully constrained and require further detailed studies.

LIMITATIONS

Analysis of drainage divide modifications caused by landslide processes is faced with a number of problems and limitations. These are dependent upon:
- LiDAR data availability;
- DEM resolution and precision;
- strong terrain transformation caused by landslides;
- changes in terrain morphology caused by human activity;
- a subjective approach to the reconstruction of a drainage divide before the landslide took place.

The resolution of DEM used in the analysis should be matched to the terrain type and morphology of the study area. This is because both overly low and high resolution may unfavourably influence the analysis. A too-low resolution scenario presents problems as regards the correct recognition of landslide boundaries and changes caused by subsequent downslope movements. And, an extremely high resolution may bring with it excessive data, from which selection of data crucial for the analysis becomes problematic. Additionally, DEM precision has an impact on the magnitude of changes that can be detected in the model. In the case of data from the Polish Carpathians, the average error is 0.15 m (Wężyk, 2015). Changes below this value cannot be detected or at least are highly uncertain. Strong, usually multi-stage transformation of terrain morphology by landsliding in the landslide zone can hamper and even prevent the detection of the boundaries and ranges of a particular form. Such limitations may also prevent a pre-landslide reconstruction of the drainage divide, or at least will result in one subject to large error. Additionally, the presence of anthropogenic objects in the area may also influence the formation of present-day drainage divides.

CONCLUSIONS

Our analysis of the Polish Outer Carpathians landslides supports the following conclusions:

In the Carpathians, drainage divides are modified as a result of landslides, and this phenomenon is much more frequent than was expected before the analysis. Such landslides occur not only within the highest mountain ranges, but also throughout the northern foothills.

A surprising result of the analysis is the movement of the drainage divides into colluvium. As a result of landslide activity, entire rock layers may be displaced in such a way that inside the colluvium there are points with the locally highest elevations, on which the drainage divides are located, and the water flow is not always towards the landslide front.

LMDD can be divided into 3 types depending on the location of the modified drainage divide: type I – landslides modifying drainage divides – scarp (LMDDS); type II – landslides modifying drainage divides – colluvium (LMDDC); and type III – landslides modifying drainage divides – mixed (LMDDM).

Currently, in the Carpathians, modification of drainage divides by landslides does not occur extensively, unlike in other landslide areas, e.g. New Zealand, Taiwan.

The proposed methodology is applicable to mountain areas for which LiDAR data is available. These data enable the identification of the land surface under the vegetation cover, which is important for the detection of landslides in the Carpathians.

If landslides in the area analysed are older than the LiDAR data, it may be difficult or impossible to recreate the drainage divides from before the landslide; such a situation occurs in the Carpathians. Therefore, the methodology developed and classification of landslides that modify drainage divides require application to landslide areas in the other parts of the world, with different geological structures and geomorphological conditions.

A certain limitation of the analysis was the limited availability of data from before the landslides occurred, but if new landslides appear in the study area, this method can be used provided there are drainage divides before and after the landslide occurred. This is possible by multiple LiDAR measurements.

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