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MORPHOLOGICAL AND MORPHOMETRICAL ANALYSES REVEAL THE AVALANCHE INFLUENCE OVER THE TALUS CONES IN THE RYBI POTOK VALLEY, TATRA MOUNTAINS

Abstract. Intense physical weathering engenders formation of scree cones at the foot of slopes dissected by couloirs. Combination of several geomorphic processes operating within the slope results in formation of cones of a polygenetic character (talus-alluvial cones, rockfall talus cones, or – in particular cases, talus-alluvial-avalanche cones). This study was aimed at determination of morphometric parameters characteristic for particular morphogenetic types of the cones in the Rybi Potok Valley in the High Tatra Mountains. For the purpose of the research, knowledge about the terrain and available cartographic materials (geological, geomorphological and topographical maps, LiDAR data) were employed. In the studied valley, 24 cones were selected and for each of them, morphogenetic types and morphometric parameters (surface, minimal and maximal height, roughness coefficient, Topographic Position Index) were determined. The correlations between different parameters enabled establishment and determination of the combination of morphometric parameters typical for the particular types of the cones. The impact of snow avalanches on one of the cones (at the mouth of Żleb Żandarmerii) was identified. This cone has morphometric parameters dissimilar to those of the other cones in the studied valley. It is the only cone in the valley which was classified as the avalanche cone.

Keywords: geomorphometry, geomorphology, Topographic Position Index, roughness, talus cones, Tatra Mountains

INTRODUCTION

Morphogenetic processes in the mountains occur in complexes distinctive for individual landforms within climate and vegetation zones (K o t a r b a et al. 1983). One of the major complexes of processes is intense physical weathering, followed by short-distance transport of its products, and deposition at the foot of rock walls and rocky slopes. What results from this is the development of talus heaps and talus cones at the foot of the rockwalls and rocky slopes, and the formation of cones at the mouth of couloirs dissecting them. Also important is the mechanism of debris transport on the surface of these forms, which may take various forms; from rolling individual clasts, to debris flows. Due to the concentration of runoff water and loose rock material in couloirs, the latter type of transport is common on cones (Kotarba 1997; Rączkowska 1999).

In the Alpine environment, talus cones are one of the most common features of relief; they are fan-shaped accumulations of rock fragments of various diameters (Klimaszewski 1981). Along with the delivery of the material, the cone grows sideways and upwards. Coarse-grained fractions are usually accumulated closer to the base of the cone (Klimaszewski 1981; Migoń 2006). In humid climates, debris flows are an important factor modifying the shape of the cone, since they dissect the cone in its upper part and overbuild its lower part (Migoń 2006). A high activity of debris flows on the talus slopes results in the development of alluvial cones (Kotarba 1992). Alluvial cones are basically accumulation forms of fluvial relief. Their morphometric parameters are dependent on the size of the catchment its geological structure, relief, and climatic conditions (Bull 1964; Klimaszewski 1981). The combination of several geomorphological processes responsible for the delivery of the material and its transport within the area of the cone leads to the formation of mixed forms; for instance, talus-alluvial cones, rockfall talus cones, etc.

Geomorphometry, focusing on a geometric analysis of land surface relief, is one of the principal quantitative methods used in geomorphology (Pike 1995, 2000; Rasemann et al. 2004). The main source of the data comprises field measurements and digital elevation models (Tobler 1976, 2000; Kasprzak, Traczyk 2010). The employment of a DEM (Digital Elevation Model) is conducive to further analysis and research, which combines expetise in the domains of Mathematics, Earth Sciences and Computer Science (Pike 2002). Based on DEMs, geomorphometry aims at determining parameters (viz. slope, exposure, topographic position index, etc.) characteristics of geomorphological objects (e.g. talus cones, moraines, alluvial valleys) and distinguishing these objects from the adjacent geomorphological objects by employing various mathematical and statistical techniques (Kasprzak, Traczyk 2010).

The purpose of this study was to determine morphometric parameters of different morphogenetic types of the cones in the Rybi Potok Valley, Tatra Mountains, Poland.

RESEARCH AREA

The study area is situated in the Polish part of the High Tatra Mountains (Fig. 1A), in the Rybi Potok Valley (Fig. 1B). The Tatras are the highest mountain range in the Carpathian Mountains and are located in the Central Western Carpathians (Kondracki 2000). The Rybi Potok Valley, being one of the three tributary valleys of the Białka Valley, has a total area of 11.5 km^2 and a length of approximately 4.2 km (Klimaszewski 1988). It is formed of granite and granodiorites of Carboniferous age (Jaczynowska 1980; Nemčok et al. 1994). The average annual precipitation in the Tatras ranges from 1100 mm in the foot-

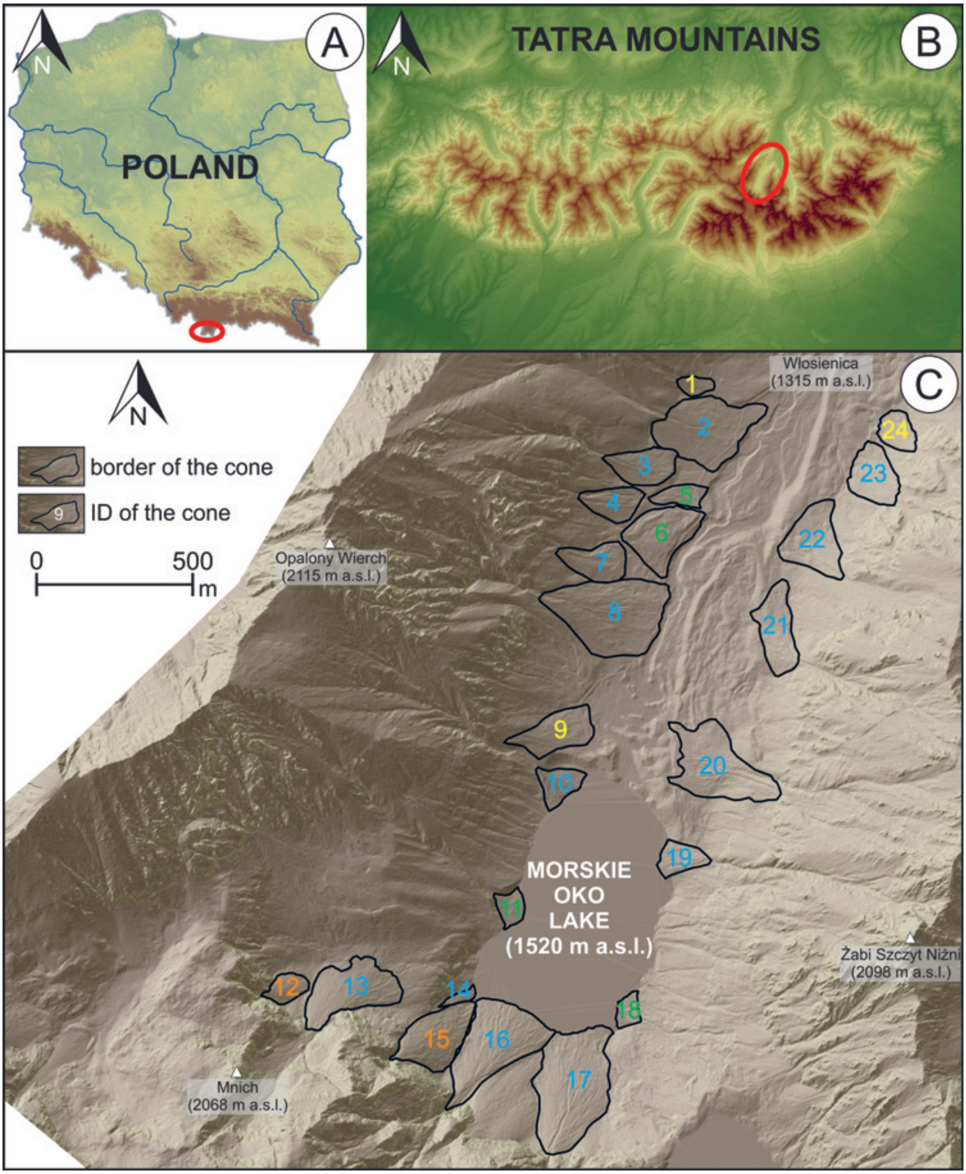


Fig. 1. Location of the study area (A, B) and location of the studied cones in the Rybi Potok Valley (C) on a shaded relief map generated from LiDAR data. The colour of numbers mark type of the cone: yellow – talus cones, orange – rockfall talus cones; green – alluvial cones; blue – talus-alluvial cones)

hills to 2000 mm in the higher parts (Niedźwiedź 1992; Ustrnul et al. 2015). Intense rainfall, conducive to the formation of debris flows, is concentrated in the summer period (Żmudzka 2010). The number of days with snow precipitation in the Rybi Potok Valley is 160–200 (Ustrnul et al. 2015). Above the altitude of 2000 m a.s.l., snow cover lingers for up to 230 days each year. In the Tatra

Mountains, the 0°C isotherm runs at the altitude of 1800 m a.s.l. (Hess 1965). Conditions favourable for physical weathering prevail between the altitudes of 1700–2050 m a.s.l. (Klimaszewski 1971). Physical weathering is facilitated by high fluctuations of the amplitude of the daily temperature of the ground surface, which reaches up to 40°C (Rączkowska 1993). Conditions conducive to frost weathering in the Tatras occur in 138 days of the year (Kłapa 1980).

The relief of the Rybi Potok Valley is the result of glacial and periglacial processes occurring in the Pleistocene, as well as periglacial and fluvial processes and mass movements in the Holocene (Klimaszewski 1988; Rączkowska 2006, 2007). As the result of several glaciations in the Pleistocene, the alluvial valley of Rybi Potok was transformed into a classic glacial trough (Klimaszewski 1988; Lindner et al. 1993), limited by distinct erosional edges (Klimaszewski 1988; Makos, Nowacki 2009), and by hanging glacial cirques on the south. Its bottom is filled with tills with numerous terminal and lateral moraine ridges and fluvioglacial and fluvial cover (Jaczynowska 1980; Klimaszewski 1988).

The relief of the valley is diverse. Its southern portion is formed by the arêtes of Mięguszowieckie Szczyty, Rysy, Cubryna and Gruby Wierch. The slopes of the valleys are characterised by rockwalls and rock slopes or debris-mantled slopes, the majority of which is covered by vegetation.

As the result of intense frost weathering under a periglacial climate, numerous couloirs dissecting the slopes of the valley were formed. Their location is tectonically predisposed. At the couloir outlets, cones of different origins developed along the entire perimeter of the bottom of the valley since late Pleistocene (Kotarba et al. 1987; Klimaszewski 1988). The largest are talus cones, built with angular and coarse debris supply by rockfall (Klimaszewski 1988). The alluvial cones resulted from the action of proglacial and pronival waters as well as rainwater (Kotarba 2004). During the Pleistocene, the most important role in the formation of the alluvial cones was performed by proglacial waters, whereas during Holocene it was predominantly by pronival waters and rain. The Pleistocene-aged glacial relief is currently slightly transformed by nonglacial geomorphological processes (Rączkowska 2008). The Little Ice Age was the last period of very intense activity of geomorphological processes (Kotarba 1992, 2004; Dzierżek, Nitychoruk 1986; Rączkowska et al. 2012). During the Little Ice Age, the geomorphological processes shaping the slopes and bottom of the valley predominantly consisted of debris flows, massive rockfalls, rockfall and snow avalanches, and mainly dirty avalanches (Kotarba 2004).

MATERIALS AND METHODS

The research was focused on the relief of the upper part of the Rybi Potok Valley, south of the Włosienica forest glade (Fig. 1C), but without regard hanging glacial cirques in the uppermost part of valley. The lower part of the valley was not included in the study due to the excessive anthropogenic impact on the terrain relief. The research was conducted employing geomorphological methods and GIS techniques. In order to determine the bounderies of the individual talus cones correctly, the following sources of information were utilized: i) field inspection, ii) topographic maps at a scale of 1:10 000, iii) geomorphological maps (Klimaszewski 1981, 1985; Kotarba 1992; Raczkowski et al. 2015), iv) geological maps (Jaczynowska 1980; Piotrowska et al. 2013, Wójcik et al. 2013) and v) LiDAR data, where the pixel size was 1 m × 1 m (www.codgik.gov.pl). On this basis, in the upper part of the Rybi Potok Valley, 24 cones were selected (Fig. 1C). The size of the landform was an additional selection criterion. The cones whose surface was too small for a viable DEM analysis were excluded from the analysis.

Geomorphometric analyses were performed with Esri ArcGIS 10. For each of the cones, the surface, maximum and minimum height, roughness coefficient and Topographic Position Index (TPI) were determined. The roughness coefficient was calculated using a tool of the Geomorphometry and Gradient Metrics Toolbox (Evans et al. 2014). The roughness was calculated for each of the cones using the rectangle neighbourhood of dimensions 3 m x 3 m. The TPI was calculated with a tool of the Land Facet Corridor Designer (Jennens et al. 2013). The Topographic Position Index describes the diversity of relief based on the difference in altitude between the altitude a.s.l. of a particular pixel and the average altitude a.s.l. of the surrounding pixels (Jenness 2006). The TPI results are dependent on the assigned type of neighbourhood (Weiss 2001; Wieczorek, Żyszkowska 2011). The higher the values of the assigned neighbourhood, the greater generalisation of the obtained results (Fig. 2). Here, for the calculation of TPI, a circular neighbourhood with a radius of 5 m was employed. To eliminate the edge effect (Griffith 1980, 1983; Griffith, Amrhein 1983),

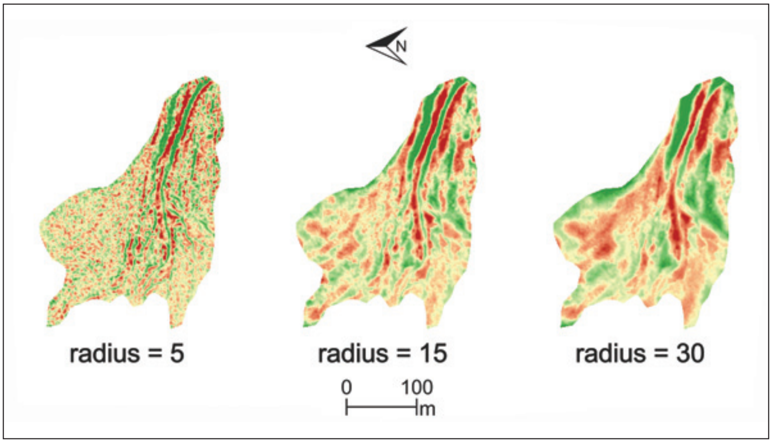


Fig. 2. The precision of the relief identification based on the calculation of the Topographic Position Index for the circular neighbourhood with the radii of 5 m, 15 m, 30 m, on example of cone no 20

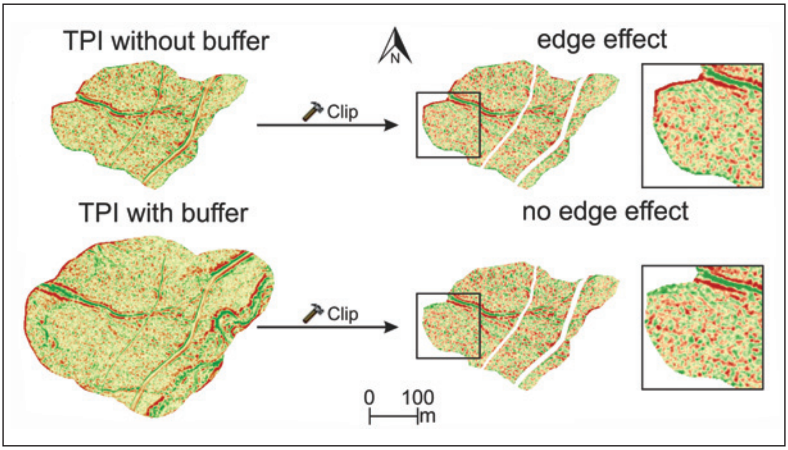


Fig. 3. Impact of the edge effect on the TPI results, on example of cone no 2. In order to obtain a precise representation of the cone surface relief, the TPI was calculated for the area increased by a buffer of 50 m, which was subsequently removed. Statistical analyses of the TPI were performed for the actual surface of the cone

while calculating the roughness and the TPI, we adopted 50 m buffer (Fig. 3). All anthropogenic linear objects that might have distorted the achieved result were excluded from measurements.

Subsequently to geomorphometric analysis, the genesis of the cones was determined using available geomorphological (Klimaszewski 1985; Kotarba 1992; Raczkowski et al. 2015) and geological maps (Guzik et al. 1959; Jaczynowska 1980; Nemčok et al. 1994; Piotrowska et al. 2013), expertise, knowledge about the terrain and the image of micro-relief of the cone surface obtained from LiDAR.

RESULTS AND DISCUSSION

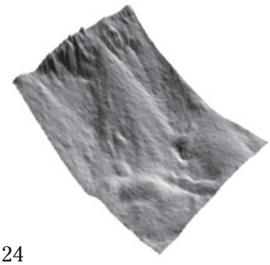
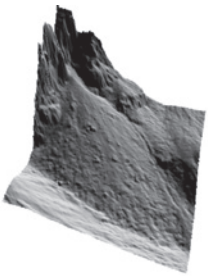
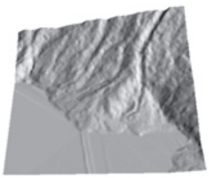
MORPHOGENETIC TYPES OF CONES

As a result of the geomorphological analyses, four morphogenetic types of cones were recognized: talus cones, rockfall talus cones, talus alluvial cones and alluvial cones. The major criterion for the determination of the different types of talus cones was evident sorting of the material and the lack of the debris flows gullies. Rockfall talus cones are characterized by lack of sorting, presence of large boulders and blocks on the surface, and the absence of debris flow gullies. Contrary the talus-alluvial cones are marked by the occurrence of the forms characteristic of debris flows, i.e. gullies and levèes. The alluvial cones are similar to the talus alluvial cones, however in addition to the gullies noticeable on their surface, they also exhibit a more conspicuous fan shape. They are formed by debris flows and fluvial transport and are composed of coarse-grained clasts with a significant proportion of finer fractions. They are also characterized by a less steep inclination of the surface than the talus-alluvial cones, and a low roughness coefficient. The characteristics of each cone type are listed in Table 1.

Among the studied cones, talus alluvial cones constitute the majority: there are 17 of them. The other types were identified in 2–4 forms (Fig. 1).

Table 1

Genetic types of the cones occurring in the analysed area. After B. Luckman (2004 a, b)

Genetic type of cone	Example of the cone; number according to Fig. 1	Morphological and morphogenetic features
Talus cone	 24	Talus cone is an accumulation of loose, coarse, usually angular rock debris at the outlet of a rocky chute dissecting steep rocky slopes or a rockwall. The dominant process involved in its development is rockfall. The basic characteristics are fall sorting (i.e. increase in the mean grain size downslope) and a convex slope. Gullies do not occur on the cone surface.
Rockfall talus cone	 15	Rockfall talus cone is an accumulation of loose, coarse, usually angular rock boulders and debris produced by the breakup of massive rockfalls. It generally lacks fall sorting and has a more complex longitudinal profile. Gullies do not occur on its surface.
Talus-alluvial cone	 17	Talus-alluvial cone has significant debris flows forms (gullies and levèes) extending across the talus slope. Fluvial activity and rockfall are the main processes involved in its development.
Alluvial cone	 18	Alluvial cone is an accumulation of loose material transported mainly by fluvial activity, supported by other geomorphic processes. Small gullies occur on its surface. It is more fan-shaped (flat) than cone-shaped (convex).

MORPHOMETRY OF THE CONES

On the basis of the analysis of DEM, Basic morphometric parameters of the cones are listed in Table 2.

Table 2

Basic morphometric parameters of the 24 analysed cones in the Rybi Potok Valley.

Number of the cone	Area [m²]	Roughness (R)	H max [m a.s.l.]	H min [m a.s.l.]	TPI Standard deviation (SD_{TPI})
1	5470	0.54	1405	1360	0.14
2	49046	0.48	1419	1325	0.16
3	20384	0.55	1464	1371	0.23
4	15984	0.65	1494	1393	0.28
5	8335	0.45	1389	1352	0.22
6	30749	0.47	1415	1359	0.23
7	19792	0.62	1515	1405	0.22
8	68534	0.54	1523	1376	0.21
9	24068	0.57	1508	1393	0.19
10	12706	0.50	1437	1395	0.26
11	8063	0.44	1420	1395	0.20
12	9431	0.74	1698	1593	0.21
13	41197	0.61	1678	1521	0.18
14	3148	0.67	1465	1395	0.25
15	35352	0.76	1620	1400	0.32
16	58136	0.61	1574	1395	0.27
17	75252	0.58	1570	1395	0.24
18	6558	0.47	1416	1395	0.24
19	12168	0.60	1457	1395	0.28
20	52879	0.54	1558	1399	0.25
21	20972	0.57	1492	1389	0.23
22	31374	0.57	1478	1358	0.22
23	22953	0.72	1462	1342	0.24
24	11822	0.70	1422	1328	0.20

The average size of the cones in the studied valley is about 27 000 m^2, SD = 20 700. Szeroki Piarg is the largest cone (no. 17) with an area of over 75 000 m^2, located in the southern part of the valley, directly by the Morskie Oko lake, beneath Mięguszowieckie Szczyty Summits, at the outlet of the gully descending from Mięguszowiecki Kocioł glacial cirque (Fig. 1C). Cone number 14 is the smallest cone, with an area of only 3 100 m^2. It is also located in the southern part of the valley, in the proximity of the lake (Fig. 1C). The size of the cone, like the others whose base is part of the shoreline of the Morse Oko lake, is not precisely estimated. For the purpose of the analyses, only the part above water of the cones was taken into consideration. The cones' surface is largely dependent on the size and geological and geomorphological characteristics of the supply zone. Namely, cones located beneath wide and high rock walls and slopes are characterised by a large surface supply zone and highest denivelation, have the largest surface (no. 2, 8, 16, 17, 20). These are mainly talus cones (of average area 13,787 m^2), talus-alluvial cones (average area = 33,635 m^2) and rockfall talus cones (average area = 22,392 m^2). The surfaces of alluvial cones differ significantly, despite the large supply zones. Small are cones descending to the lake as part of material is transported directly to the lake. The average area of the alluvial cones in the study area is 13,426 m^2.

Cone 12 (see Fig. 1C), is the form whose apex and base are located the highest (1698 m a.s.l. and 1593 m a.s.l. respectively: Fig. 4). The lowest apex belongs to the cone 5 and is located virtually at the bottom of the valley. The greatest difference in height between the apex of the cone and its base (220 m) was observed in Kosowinowy Piarg (no. 15). The cones located in the western part of the valley, from Włosienica to Morskie Oko (no. 1–9) have an average relative height of 87 m, whereas those on the opposite slope (no. 20, 21, 22, 23, 24): 119 m. The cones located in the southern part of the valley (no. 12–17) are characterised by the highest average relative height: 151 m. This results from the size and characteristics of the areas from which they are supplied. The cones situated on the eastern and western shores of Morskie Oko (10, 11, 18, 19) have the lowest average relative height of 15 m. It is probable that only the upper parts of these cones are visible above the waterline, which is confirmed by the fact that their catchment areas are rather large. We also found that the greatest average relative height is characteristic for rockfall talus cones (163 m), whereas the smallest is characteristic for alluvial cones (35 m). The talus cones and tallus alluvial cones have intermediate values (85 m, and 115 m respectively). Moreover, in the case of the 24 cones, the relative height is correlated with the size of the cone. However, this correlation is not linear. The largest cones in the valley (no. 2, 8, 16, 17, 20) are characterised by a lower ratio between the size and height (415) than the other 19 cones (215).

The lowest values of inclination were observed for the rockfall talus cones and the talus cones (Fig. 4). The former are characterised by a linear and complex shape of the longitudinal profile; the latter by a concave shape (Fig. 4). The alluvial cones, however, have the least steep inclination and most complex shape of the longitudinal profiles. The talus alluvial cones are the most diverse as regards the inclination and longitudinal profile. This group comprises all the basic types of shapes, but the majority is constituted by the cones with a complex profile.

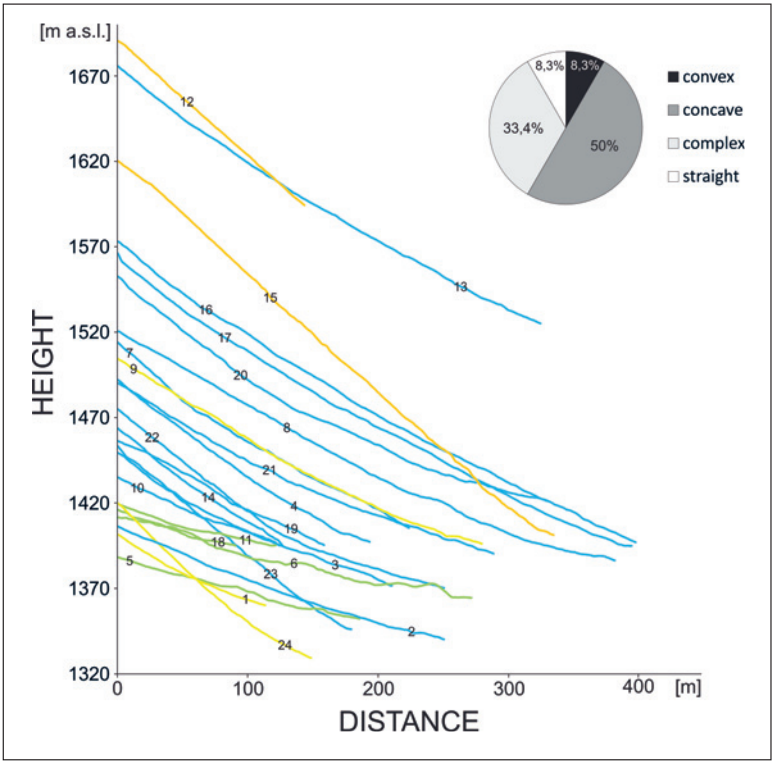


Fig. 4. Longitudinal profiles and percentage of cones of particular shape of longitudinal profile (yellow line – talus cones, orange line – rockfall talus cones; green line – alluvial cones; blue line – talus-alluvial cones). On lines are numbers of cones as on Figure 1

The highest roughness coefficient (R = 0.76) is characteristic of the rockfall talus cone 15 (Kosowinowy Piarg), while the lowest (R = 0.44), is of alluvial cone 11 (Mały Piarżek) (Fig. 5). The arithmetic mean of the roughness coefficient for all 24 cones is 0.58. The lowest roughness coefficient is typical of the alluvial cones (R_{mean} = 0.46), while the highest – of the rockfall talus cones (R_{mean} = 0.75). The mean roughness coefficient of the cones located in the southern part of the study area (no. 12, 13, 14, 15, 16, 17) is high R = 0.66, resulting from the supply of the material from the upper parts of the steep slopes, which continually undergo intense weathering. The alluvial cones (no. 5, 6, 11, 18) have a low roughness coefficient. The mean values of the roughness coefficient of the talus cones and the talus-alluvial cones are very similar (0.60 and 0.59 respectively). However, the value of this parameter depends on the location of the cones. The average value of the roughness coefficient of the talus and talus-alluvial cones of the on the east side of the valley is 0.70 and 0.60 and is higher than that of the talus cones and the talus-alluvial cones located on the western side that reaches 0.56. The contribution of alluvial processes to the formation of the cones on the western side was probably greater than that of gravitational processes. Large portions of the

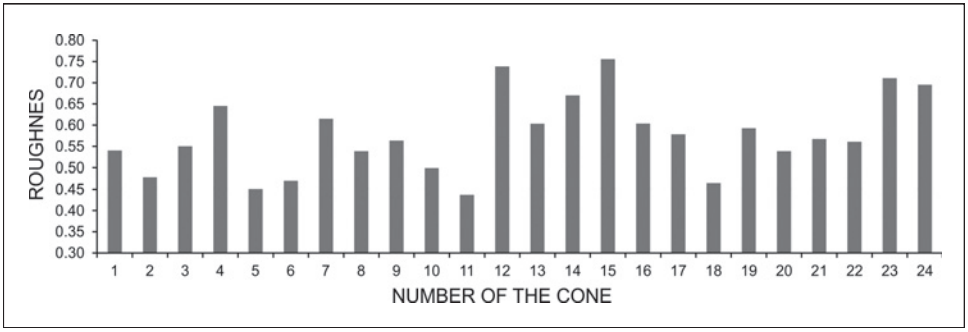


Fig. 5. Values of the roughness coefficient

western slopes of the valley are occupied by Quaternary cover (N e m č o k et al. 1994), easily available for transport by debris flows or avalanches.

The highest standard deviation of Topographic Position Index (SD_{TPI}), which is a measure of the relief diversity, was reached for cone 15 ($SD_{TPI} = 0.32$), while the lowest was for cone 1 ($SD_{TPI} = 0.14$). For the majority of the cones in the valley, the values of the standard deviation of TPI oscillate around an average value of 0.23. The highest value of the averaged SD_{TPI} is characteristic of the rockfall talus cones (0.27), whereas the lowest is of the talus cones (0.18). For the talus-alluvial cones and the alluvial cones, the averaged SD_{TPI} takes intermediate values (0.42 and 0.22 respectively). A low value of SD_{TPI} in the case of the talus cones indicates that they have the least diverse micro-relief of the surface, which is related to gravitational sorting of debris material and the lack of debris flow gullies. The alluvial cones and the talus-alluvial cones are dissected by debris flow gullies and alluvial troughs, which brings about the surface diversity. The rockfall talus cones are characterised by the greatest diversity of micro-relief, resulting from the presence of chaotically arranged large boulders and blocks. Just like in the case of roughness, the location of the cones is somehow correlated with the complexity of their relief. The lowest complexity is typical of the cones located on the western side of the valley (no. 1–9) and is reflected in the low standard deviation $SD_{TPI} = 0.21$, whereas the cones located on the opposite slope (no. 19–24) have the higher average $SD_{TPI} = 0.23$. The highest average value of this indicator was obtained for the cones located in the southern part of the analysed valley (no. 12–17): $SD_{TPI} = 0.25$. The other cones located at Morskie Oko Lake (no. 10, 11, 18, 19) are also characterised by the high average value $SD_{TPI} = 0.24$.

COUPLING DEBRIS CONE ORIGIN AND MORPHOMETRIC PARAMETERS

Comparison of genetic classification of the cones in the Rybi Potok Valley and their morphometric parameters enabled the identification of morphometric features that are typical for the particular genetic types. The talus cones have a relatively high roughness coefficient in the range from 0.54 to 0.7 (cones 1 and 24 respectively); however the standard deviation of TPI in their case is relatively low (i.e. 0.14 – 0.2). The alluvial cones have the lowest obtained roughness coefficient ranges between 0.44 and 0.47 (cones 11 and 6 respectively). The standard deviation of TPI for the alluvial cones (0.20 – 0.24) is close to the average for the entire analyzed population of the cones (0.23). The rockfall talus cones have the highest roughness coefficients: 0.74 and 0.76 (cones 12 and 15 respectively). The standard deviation of TPI for these cones is 0.21 – 0.32. The largest group of the cones in the studied area is constituted by the talus-alluvial cones, whose roughness coefficient ranges from 0.48 to 0.72 (cones 2 and 23 respectively); however the standard deviation of TPI is 0.18 – 0.28.

The particular genetic types of the cones are concentrated in not clearly distinguished groups (Fig. 6). Among the four genetic types of the cones, the talus-alluvial cones constitute the largest and most diverse group in terms of morphometric parameters. The parameters, apart from two exceptions (cones 2 and 13), take central values in the span of the roughness and TPI values. The talus cones are composed by only three elements by the group is also not coherent. The alluvial cones, and talus-alluvial cones form more homogeneous groups of similar parameters (Fig. 6).

The further, detailed analysis of morphological and morphometric features of the cones results in two modifications, which helped to better assess character of outliers.

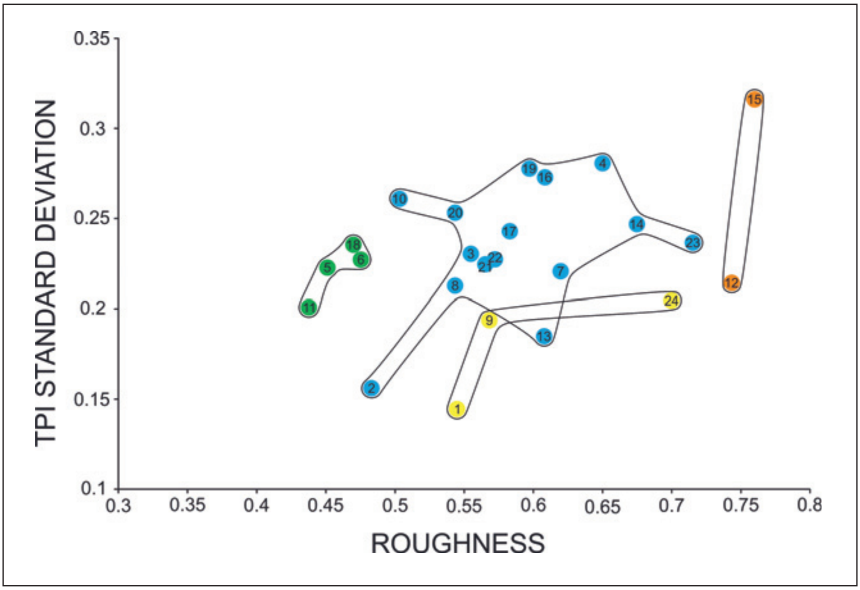


Fig. 6. Comparison of TPI and roughness coefficient for four genetic types of the cones in the Rybi Potok Valley: yellow – talus cone; green – alluvial cone; blue – talus-alluvial cone; orange – rockfall talus cone. Within dots are numbers of cones as on Figure 1

Cone 13 constitutes a form with clear boundaries; nevertheless it is the only one whose surface has heterogeneous relief. The western part is of a rough but homogenous nature that is similar to the character of the talus cone. This is confirmed by the morphometric characteristics (SD_{TPI} = 0.15, R = 0.62). The surface of the eastern part resembles the talus-alluvial cone, dissected by debris flow gullies (SD_{TPI} = 0.22, R = 0.59). This indicates the complexity of the processes forming the cone. Therefore, cone 13 has been divided into two zones (Fig. 7) whose morphometric characteristics correspond well to the determined morphogenetic types (Fig. 9).

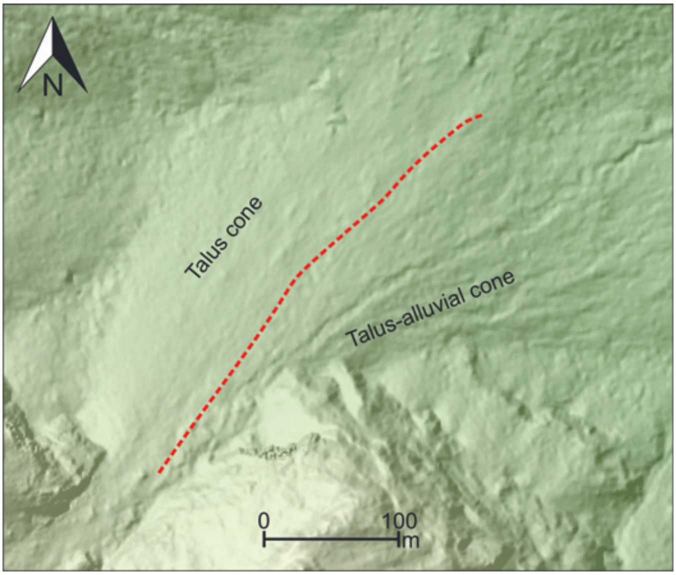


Fig. 7. Division of cone 13 into two parts – the western part exhibiting the properties of the talus cone, and the eastern part of the character of the talus-alluvial cone

Cone 2, located at the outlet of Żleb Żandarmerii couloir, has morphometric characteristics that differ from the characteristics of the other talus-alluvial cones. Both the SD_{TPI} (0.15) and roughness (R = 0.48) take the lowest values for this morphogenetic type. In addition, the longitudinal profile of the cone has been classified as linear. These features do not deny the talus-alluvial genesis of the cone, which is confirmed, inter alia, by the presence of a debris flow gully (Fig. 8); but they imply the operation of an additional factor causing smoothing and levelling of the cone surface. Żleb Żandarmerii is the place where one of the largest snow avalanches in the High Tatras descended. The couloir is 1 km long and merely 100 m wide at the mouth, which, together with the large catchment area (0.092 km^2), results in descending avalanches having high power. This is manifest in a pronounced (560 m) lowering of the treeline (Kaczka et al. 2015; Lempa et al. 2016). Despite the less frequent incidence of major avalanches in

Fig. 8. The relief of cone 2 exhibiting the rather smooth surface typical for cone modified by avalanches

the last 50 years (K a c z k a et al. 2015), numerous historical reports and analyses point out avalanche activity in the area (Z a r u s k i 1923; K ł a p a 1959; L a s k a, K a c z k a 2010; L e m p a et al. 2014; L e m p a et al. 2016). Therefore it can be assumed that the avalanches descending with great power must have descended throughout all Holocene, which contributed to a gradual smoothing of the cone located at the mouth of Żleb Żandarmerii couloir. This necessitates morphogenetic reclassification of cone 2 as talus-alluvial-avalanche. The results of the morphometric analysis confirm the hypothesis by M. K l i m a s z e w s k i (1988) who describes Żleb Żandarmerii as a V-shaped valley, at the mouth of which there is a huge cone whose process of creation and formation has been influenced by frequent avalanches. According to the definition of talus slopes modified by avalanches (L u c k m a n 2004b) and avalanche boulder tonques (i.e. road-bank and fan-like types) (R a p p 1959; L u c k m a n 2004a; O w e n s 2004), one of the major features of these forms is a smoothed, beveled surface. B. L u c k m a n (2004) reports that „avalanche modified screes have strong basal concavities", which in the foothills of cone 2 are disturbed by the road and fluvial relief.

In the case of distinguishing five types of genetic cones (viz. talus, alluvial, talus-alluvial, rockfall talus, talus-alluvial-avalanche) and dividing cone 13 into two zones, a new, more definite representation of the morphometric characteristics of the cones of various origins is obtained (Fig. 9).

The only cone in the analysed area that qualified as the talus-alluvial-avalanche is cone 2. This cone may be numbered among the group of avalanche cones, in accordance with the definition of the cones located on the paths of massive and

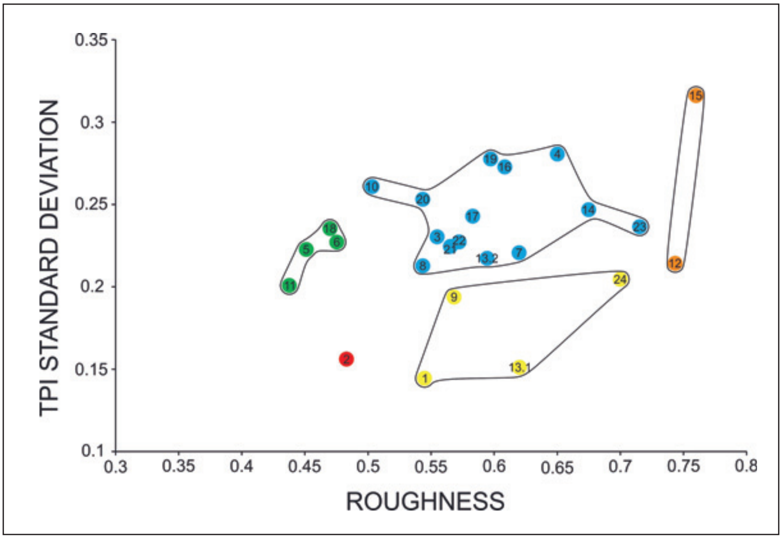


Fig. 9. Comparison of the TPI and roughness coefficient for the five genetic types of cones in the Rybi Potok Valley including the division of cone no. 13 into two subzones (13.1: western part and 13.2: eastern part). Explanations see Figure 6.

frequently occurring snow avalanches in the Alps (Jomelli, Francou 2000) and the Rocky Mountains (Luckman 1978). Although the Rybi Potok Valley is considered the most active snow avalanche valley in Poland (Nyka 1956) and snow avalanches may occur there from November to June (Kłapa 1959), only cone 2 reveals distinct characteristics of the avalanche cone. Żleb Żandarmerii cone is the first site in the Tatra Mountains and in the entire Carpathian Mountains where the existence of this type of cone has been identified and confirmed.

Based on dendrogeomorphological analyses, it has been pointed out that the largest avalanches occurring in Żleb Żandarmerii lose their energy only on contact with the terrain barriers located below the talus cone (i.e. the bottom of the riverbed, moraine ridge: Lempa et al. 2016). This is confirmed by the morphogenetic potential of snow avalanches in the area. In the case of the other cones in the Rybi Potok Valley, the course of the avalanche may be affected by the direction of cone inclination and the presence of debris flow gullies on its surface. An example of such a cone is cone 23, whose direction of inclination (south-west) determines the course of avalanches descending down the local gully (Lempa et al. 2016).

CONCLUSIONS

- Morphometric parameters delineating the character of the cones surface vary substantially in accordance with the origin of the cones. Rockfall talus cone exhibit the most diversified relief. This may be illustrated by the example of Kosowinowy Piarg (cone 15), which is a form characterised by the highest values of the morphometric parameters (SD_{TPI} = 0.32, R = 0.76). The micro-relief of the alluvial conesis the least diversified. Mały Piarżek may serve as an example (cone 11: SD_{TPI} = 0.2, R = 0.44).

- Morphometric parameters of the genetically different cones may be classified as follows: i) rockfall talus cones have the greatest roughness and SD_{TPI}, the values of which are equal to or greater than the averages, ii) alluvial cones are characterised by the lowest roughness values and low SD_{TPI} values, iii) talus cones exhibit low values of SD_{TPI} and roughness values within a wide range located between the values typical of alluvial cones and rockfall talus cones, ii) talus-alluvial cones are characterised by average or high SD_{TPI} values and roughness values occupying a wide range similar to that of the talus cones.
- The cone located at the mouth of Żleb Żandarmerii couloir, descending from the north-eastern slopes of the Opalony Wierch summit, exhibits morphogenetic (talus-alluvial genesis) and morphometric (linear longitudinal profile, little diversity of micro-relief due to the low roughness and SD_{TPI} values) properties indicating its polygenetic character, which additionally results from the activity of snow avalanches. This is the first “avalanche cone” (talus-alluvial-avalanche cone) identified in the Tatras and the Carpathians.
- Morphometric analyses of the 24 cones in the upper part of the Rybi Potok Valley attest to the efficiency and applicability of this type of geomorphological tool. The results, however, are of the nature of a case study; thus the development of a reliable classification of landforms, such as cones or other elements of Alpine relief, requires further studies comprising other valleys in the Tatras and the Carpathians.

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REFERENCES

Bull W. B., 1964, *Alluvial fans and near-surface subsidence in western Fresno County*. USGS Professional Paper 437-A, A1–A71.

Dzierżek J., Nitychoruk J., 1986. *Types of fossil rock glaciers in the Polish High Tatra Mts.*. Bulletin of the Polish Academy of Sciences, Earth sciences 34, 4, 409–418.

Evans J. S., Oakleaf J., Cushman S. A., Theobald D., 2014. *An ArcGIS Toolbox for Surface Gradient and Geomorphometric Modeling, version 2.0-0*. Available: http://evansmurphy.wix.com/evansspatial. Accessed: 2014 Dec 2nd.

Griffith D., 1980. *Towards a theory of spatial statistics*. Geographical Analysis 12, 325–339.

Griffith D., 1983. *The boundary value problem in spatial statistics*. Journal of Regional Science 23, 377–387.

Griffith D. A., Amrhein C. G., 1983. *An evaluation of correction techniques for boundary effects in spatial statistical analysis: traditional methods*. Geographical Analysis 15, 352–360.

Guzik K., Michalik A., Watycha L., 1959. *Mapa geologiczna Tatr Polskich 1 : 10 000, arkusz Miedziane*. Wyd. Geologiczne, Warszawa.

Hess M., 1965, *Piętra klimatyczne w polskich Karpatach Zachodnich*. Zeszyty Naukowe Uniwersytetu Zeszyty Naukowe UJ, Prace Geograficzne 11, 1–267.

Jaczynowska W., 1980. *Mapa geologiczna Tatr Polskich 1 : 10 000, arkusz Mięguszowiecki*. Wyd. Geologiczne, Warszawa.

Jenness J., 2006. *Topographic Position Index (TPI) v. 1.2, Flagstaff, AZ*. Jenness Enterprises, http://www.jennessent.com/arcview/tpi.htm.

Jenness J., Brost B., Beler P., 2013. *Land Facet Corridor Designer: Extension for ArcGIS*. Jenness Enterprises, Available at: http://www.jennessent.com/arcgis/land_facets.htm

Jomelli V., Francou B., 2000. *Comparing the characteristics of rockfall talus and snow avalanche landforms in an Alpine environment using a new methodological approach: Massif des Ecrins, French Alps*. Geomorphology 35, 3, 181–192.

Kaczka R. J., Lempa M., Czajka B., Janecka K., Rączkowska Z., Hreško J., Bugar G., 2015. *The recent timberline changes in the Tatra Mountains: A case study of the Mengusovská Valley (Slovakia) and the Rybi Potok Valley (Poland)*. Geographia Polonica 88, 71–83.

Kasprzak M., Traczyk A., 2010. *Geomorfometria granitowej części Karkonoszy*. Landform Analysis 13, 33–46.

Klimaszewski M., 1971. *A contribution to the theory of rockface development*. Studia Geomorphologica Carpatho-Balcanica 5, 139–151.

Klimaszewski M., 1981. *Geomorfologia*. PWN, Warszawa, 1063 pp.

Klimaszewski M.,1985. *Geomorfologia, 1 : 30 000*. [in:] *Atlas Tatrzańskiego Parku Narodowego*. K. Trafas (ed.), Wyd. TPN i PTPNoZ, Zakopane–Kraków.

Klimaszewski M., 1988. *Rzeźba Tatr Polskich*. PWN, Warszawa, 668 pp.

Kłapa M., 1959. *Lawiny.* Wierchy 28, 127–163.

Kłapa M., 1980. *Procesy morfogenetyczne i ich związek z sezonowymi zmianami pogody w otoczeniu Hali Gąsienicowej w Tatrach*. Dokum. Geogr. IGiPZ PAN 4, 55 pp.

Kondracki J., 2000. *Geografia regionalna Polski*. Wydawnictwo. Naukowe PWN, Warszawa, 440 pp.

Kotarba A., 1992. *Natural Environment and Landform Dynamics of the Tatra Mountains*. Mountain Research and Development 12, 2, 105–129.

Kotarba A., 1997, *Formation of high-mountain talus slopes related to debris-flow activity in the High Tatra Mountains*. Permafrost and Periglacial Processes 8, 2, 191–204.

Kotarba A., 2004. *Zdarzenia geomorfologiczne w Tatrach Wysokich podczas małej epoki lodowej*. [in:] *Rola Małej Epoki Lodowej w przekształcaniu środowiska przyrodniczego Tatr*. A. Kotarba (ed.), Prace Geograficzne IGiPZ PAN 197, 9–55.

Kotarba A., Kaszowski L., Krzemień K., 1987. *High-mountain denudational system of the Polish Tatra Mountains*. Geographical Studies, Special Issue 3, 106 pp.

Kotarba A., Kłapa M., Rączkowska Z., 1983. *Procesy morfogenetyczne kształtujące stoki Tatr Wysokich*. Dokumentacja Geograficzna 1, 82 pp.

Laska M., Kaczka R. J., 2010. *Dendrochronologiczna rekonstrukcja lawin w Tatrach Wysokich.* [in:] *Nauka, a zarządzanie obszarem Tatr i ich otoczeniem*. Vol. 1. Zakopane, 89–94.

Lempa M., Kaczka R. J., Rączkowska Z., 2014. *Rekonstrukcja aktywności lawin śnieżnych w Białym Żlebie (Tatry Wysokie) na podstawie przyrostów rocznych świerka pospolitego (Picea abies L. Karst.)*. Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej 16, 105–112.

Lempa M., Kaczka R. J., Rączkowska Z., Janecka K., 2016. *Combining tree-ring dating and geomorphological analyses in the reconstruction of spatial patterns of the runout zone of snow avalanches, the Rybi Potok Valley, the Tatra Mountains.* Geographia Polonica 89, 1, 31-45.

Lindner L., Nitychoruk J., Butrym J., 1993. *Problem of number and age of glaciations in the Tatra Mts. against thermoluminescence dating of glaciofluvial sediments in the Biały Dunajec drainage basin*. Przegląd Geologiczny 41, 1, 10–21.

Luckman B. H., 1978, *Geomorphic work of snow avalanches in the Canadian Rocky Mountains*. Arctic and Alpine Research 10, 261–276.

Luckman B. H., 2004 a. *Avalanche boulder tonque*. [in:] *Encyclopedia of geomorphology*. *Vol. 2*. A. Goudie (ed.), Routledge, London, s. 41.

Luckman B. H., 2004 b. *Scree*. [in:] *Encyclopedia of geomorphology*. *Vol. 2*. A. Goudie (ed.), Routledge, London, 915–917.

Makos M., Nowacki Ł., 2009. *Rekonstrukcja geometrii powierzchni lodowców z maksimum ostatniego zlodowacenia (LGM) w polskich Tatrach Wysokich (zlewnie Roztoki i Rybiego Potoku)*. Przegląd Geologiczny 57, 72–79.

Migoń P., 2006. *Geomorfologia*. Wydawnictwo Naukowe PWN, Warszawa, 461 pp.

Nemčok J. (ed.), Bezák V., Biely A., Gorek A., Gross P., Halouzka J., Janák M., Kahan S., Kotański Z., Lefeld J., Mello J., Reichwalder P., Rączkowski W., Roniewicz P., Ryka W., Wieczorek J., Zelman J., 1994. *Geologická mapa Tatier 1 : 50 000*. GÚDŠ, Bratislava.

Niedźwiedź T., 1992, *Climate of the Tatra Mountains*. Mountain Research and Development 12, 2, 131–146.

Nyka J., 1956. *Dolina Rybiego Potoku (Morskiego Oka): monografia krajoznawcza*. Sport i Turystyka 46, 133 pp.

Owens I., 2004. *Avalanche, Snow*. [in:] *Encyclopedia of geomorphology*. *Vol. 2*. A. Goudie (ed.), Routledge, London, 41–44.

Pike R.J., 1995. *Geomorphometry-process, practice, and prospect*. Zeitschrift fur Geomorphologie, Supplement band 101, 221–238.

Pike R. J., 2000. *Geomorphometry – diversity in quantitative surface analysis*. Progress in Physical Geography 24, 1, 1–20.

Pike R. J., 2002. *A bibliography of terrain modeling (geomorphometry), the quantitative representation of topography*. USGS Open file report, 02–465.

Piotrowska K., Michalik M., Rączkowski W., Iwanow A., *Szczegółowa Mapa Geologiczna Tatr w skali 1 : 10 000*. Narodowe Archiwum Geologiczne, PIG-PIB. Warszwa, in print.

Rapp A., 1959. *Avalanche boulder tonques in Lappland*. Geografiska Annaler 41, 34–48.

Rasemann S., Schmidt J., Schrott L., Dikau R., 2004. *Geomorphometry in mountain terrain*. GIS & Mountain Geomorphology, Springer, Berlin, 101–145.

Rączkowska Z., 1993. *Ilościowe wskaźniki niwacji w Tatrach Wysokich*. Dokum. Geogr. IGiPZ PAN 4–5, 63–81.

Rączkowska Z., 1999. S*lope dynamics in the periglacial zone of the Tatra Mts.*. Biuletyn Peryglacjalny 38, 127–133.

Rączkowska Z., 2006. *Recent geomorphic hazards in the Tatra Mountains*. Studia Geomorphologica Carpatho-Balcanica, 40, 45–60.

Rączkowska Z., 2007. *Współczesna rzeźba peryglacjalna wysokich gór Europy*. Prace Geograficzne IG i PZ PAN 212, 252 pp.

Rączkowska Z., 2008. *Współczesna ewolucja rzeźby Tatr*. [in:] *Współczesne przemiany rzeźby Polski*. L. Starkel, A. Kostrzewski, A. Kotarba, K. Krzemień (eds.), Instytut Geografii i Gospodarki Przestrzennej UJ, Kraków, 35–56.

Rączkowska Z., Łajczak A., Margielewski W., Święchowicz J., 2012. *Recent landform evolution in the Polish Carpathians*. [in:] *Recent landform evolution, the Carpatho-Balkan-Dinaric Region*. D. Loczy, M. Stankoviansky, A. Kotarba (eds.) Springer, Dordrecht, 47–101.

Rączkowski W., Boltižiar M., Rączkowska Z., 2015. *Relief*. [in:] *Atlas of the Tatra Mountains. Abiotic Nature*. sheet V.1, map 1 (1 : 100 000), Tatrzański Park Narodowy, Zakopane.

Tobler W. R., 1976, *Analytical cartography*. The American Cartographer 3, 1, 21–31.

Tobler W. R., 2000, *The development of analytical cartography: A personal note*. Cartography and Geographic Information Science 27, 3, 189–194.

Ustrnul Z., Walawender E., Czekierda D., Šťastný P., Lapin M., Mikulová K., 2015. *Precipitation and snow cover*. [in:] *Atlas of the Tatra Mountains, Abiotic Nature*. sheet II.3, maps 1 and 5 (1: 250 000), Tatrzański Park Narodowy, Zakopane.

Weiss A., 2001. *Topographic Position and Landforms Analysis*. [in:] *Poster presentation, ESRI User Conference, San Diego, CA.*, Available by permission from the author at http://www.jennessent.com/arcview/TPI_Weiss_poster.htm.

Wieczorek M., Żyszkowska W., 2011. *Geomorfometria – parametry morfometryczne w charakterystyce rzeźby terenu, Polski*. Przegląd Kartograficzny 43, 130–144.

Wójcik A., Derkacz M., Wasiluk R., 2013. *Arkusz Tatry Wysokie (1061). Szczegółowa Mapa Geologiczna Polski w skali 1 : 50 000*. Narodowe Archiwum Geologiczne, PIG-PIB. Warszwa.

Zaruski M., 1923. *Na bezdrożach tatrzańskich. Wycieczki, wrażenia, opisy*. Warszawa, 279 pp.

Żmudzka E., 2010. *Współczesne zmiany wielkości i charakteru opadów w Tatrach*. [in:] *IV Konferencja Przyroda Tatrzańskiego Parku Narodowego a* Człowiek. Streszczenia prac. Tatrzański Park Narodowy-Polskie Towarzystwo Przyjaciół Nauk o Ziemi, Zakopane, 105.