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THE MORPHODYNAMICS OF SLOPES WITHIN SNOW AVALANCHE STARTING ZONES IN THE TATRAS

Zofia Rączkowska[1] • Elżbieta Rojan[2] • Michał Długosz[1]

[1] Institute of Geography and Spatial Organization
Polish Academy of Sciences
Św. Jana 22, 31-018 Kraków: Poland
e-mails: raczk@zg.pan.krakow.pl • dlugoszm10@gmail.com

[2] Faculty of Geography and Regional Studies
University of Warsaw
Krakowskie Przedmieście 30, 00-927 Warsaw: Poland
e-mail: erojan@uw.edu.pl

Abstract

The upper sections of avalanche paths (avalanche starting zones) in the Tatras are being transformed by morphogenetic processes, both secular and rapid mass movements, which include avalanches. The erosion niches and scars occurring within the avalanche starting zones are most exposed to these processes. A three-year monitoring of the impacts of these processes leads to the conclusion that, in the absence of dirty avalanches, the efficiency of secular geomorphological processes is low (max. a few cm/year). Such avalanches can clearly transform the relief as is demonstrated by the results of analyses of erosion niches and scars on orthophotomaps. Furthermore, it was found that the direction of relief changes (accumulation or erosion) in the Tatras is spatially and temporally varied, as well as varying within individual avalanche starting zones, and sometimes within individual erosion niches or scars.

Key words

morphodynamic • slopes • avalanche • starting zones • Tatra Mountains

Introduction

The contemporary development of the alpine relief of the Tatras is the combined result of moderate long-term (secular) processes and extreme high-energy processes, which bring more spectacular effects (Kotarba et al. 1987; Kotarba 1999, 2002). The type, course and intensity of the processes vary depending on the altitudinal climate and vegetation zones as well as the substrate. The areas above the upper timberline are dominated by processes related to the periglacial climate (Jahn 1958, 1970) and slope alluviation (Kotarba 1976, 1996; Midriak 1996; Rączkowska 1999).

Snow avalanches are rapid mass movements recorded in periglacial areas. In the Tatras they are one of the less recognised extreme high-energy geomorphological processes. Their high morphogenetic efficiency has been mentioned, among others, by Kotarba (1976) and Hreško et al. (2005), who indicate that, as a result of dirty avalanches in the avalanche starting zone (the upper part of the avalanche path), soil destruction dominates and creates favourable conditions for consecutive processes, such as nivation, cryogenic processes and erosion. Erosion is predominant on soil-mantled slopes in the starting zone, although in the Alps evidence has been found for erosion on an avalanche starting zone situated on bedrock (Moore et al. 2013). The average values of surface lowering, due to the scraping of the surface by an avalanche in the Tatras, range from a few tenths of a millimetre to 350 mm during one event (Stankoviansky & Midriak 1998). One avalanche can transport several hundred kilograms, occasionally over a tonne, of rock debris (Kłapa 1980).

According to Kłapa (1980), avalanche activity dominates in the nival season, one of the four morphogenetic seasons distinguished in the Tatras based on many years of research. This is also when weathering takes place. The subsequent nivo-pluvial season, which is characterised by a distinctly rich set of geomorphological processes and varies in duration from year to year, is the most active in terms of the dynamics of the process throughout the year.

The modern development of slopes within avalanche starting zones is the result of dirty avalanches and other secular morphogenetic processes which change throughout the year. The share of these two types of process can vary over time. As a result of their activities, shallow niches and erosion scars of all sizes, usually without a clear edge, develop within the avalanche starting zones.

The aim of the study is to evaluate and assess the slope morphodynamics of the starting zones in avalanche areas in the Tatras. It is based on the results of the monitoring relief changes on avalanche trails, carried out in order to assess the contemporary impact of avalanches on the transformation of their terrain.

Study area

The Tatras are the highest range in the Carpathians, rising to 2655 m a.s.l. (Gerlachovský štít). Their total area is 785 km^2, of which approx. 22.3% lies in Poland and 77.7% in Slovakia (Radwańska-Paryska & Paryski 1995). The relief of the Tatras exhibits an alpine character formed during the Pleistocene glaciations (Klimaszewski 1988; Rączkowski et al. 2015).

The climate is transitional between maritime and continental influences. Mean annual air temperature (MAAT) ranges from over 3°C in the valley bottoms to about −4°C on the highest peaks (Hess 1965; Niedźwiedź 1992; Konček ed. 1974). Mean total precipitation ranges from about 1100 mm in the northern foothills to over 2000 mm in the highest parts. The highest precipitation of 1500-1900 m occurs on the northern slopes. The number of days with snow ranges from about 100 on the foothills to almost 300 on the highest peaks (Hess 1965, 1996; Konček ed. 1974).

Avalanche starting zones are found at altitudes of 2620-1142 m a.s.l. (Rączkowska et al. in print) in the alpine and subalpine zones. They are located highest in the High Tatras, where the average altitude of the avalanche starting zone is over 200 metres higher than in the Belianske and Western Tatras. This reflects altitudinal differences between these parts of the massif.

Avalanche starting zones vary greatly in size – from 312 to 198,942 m^2. Their average surface area is the largest in the Western Tatras – 28,593 m^2. The average surface area in the Belianske Tatras is nearly half this, and is up to four times smaller in the High Tatras. The size of the starting zones affects, among other things, the types of avalanches. The large starting zones in the Western and Belianske Tatras favour the occurrence of dirty or slab avalanches, while the much smaller zones in the High Tatras encourage the formation of powder snow avalanches (Žiak & Długosz 2015; Rączkowska et al. in print). Approximately 90% of the avalanche starting zones in the Tatras include 26-55° slopes. Regional differences can be seen in this respect: among the areas analysed in the Western Tatras there is a higher percentage of 26-36° slopes, and in the High Tatras a higher percentage of 37-55° slopes. The differences in slope inclination of the avalanche starting zones, as well as the differences in their surface area, may affect the types of avalanches prevailing in a given place (Rączkowska et al. in print). The differences between the characteristics of the slopes in the avalanche starting zones in the High and Western Tatras are presented in Figure 1. In the Western Tatras these are debris-mantled slopes, and in the High Tatras they are often mixed rocky and debris-mantled slopes.

The couloirs presented in Table 1 were selected for the systematic study of the impact of avalanches on slope morphodynamics. The table contains the most important geological and morphometric features regarding their avalanche starting zones. Their location is shown in Figure 2.

The areas for the detailed survey were purposely selected to include the northern and southern slopes of the Tatra Mountains and some slopes on the eastern and western exposure.

Methods

In order to determine the size and direction of changes in the relief of the surfaces of the avalanche starting zones, benchmarks were installed within erosion scars at each of the selected study sites (Tab. 1, Fig. 2).

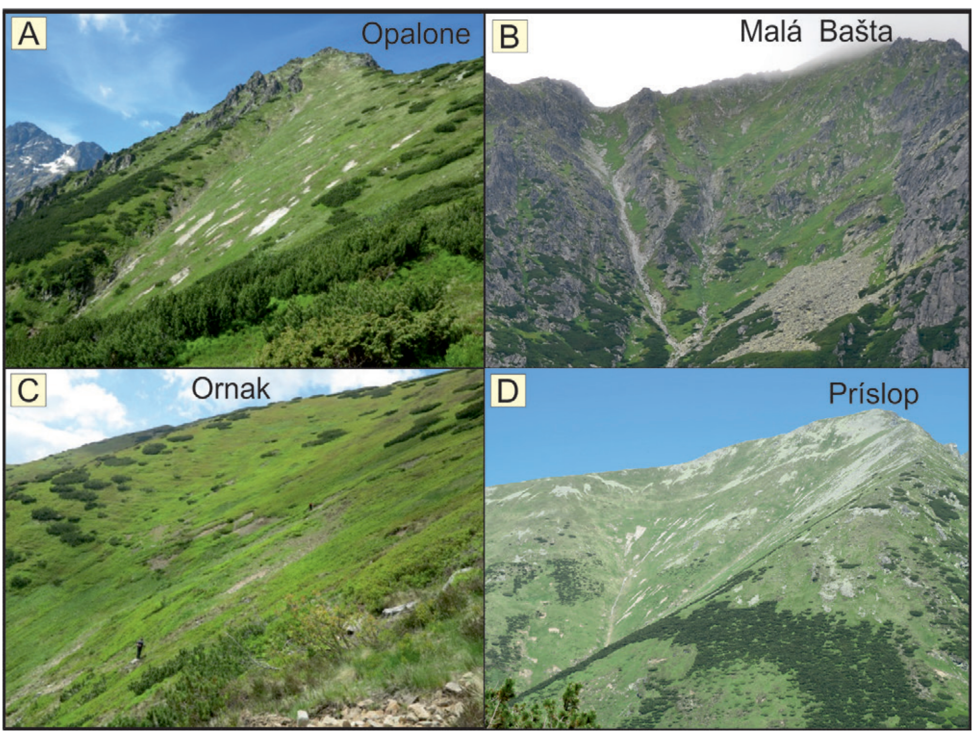

Figure 1. Avalanche starting zones in the High Tatras – Żleb Żandarmerii (A), Malá Bašta (B) and in the Western Tatras – Żleb Ornaczański (C) and Príslop (D)

Table 1. Characteristics of study sites (No. = number in Fig. 2)

No.	Location of the study site		Lithology (after Nemčok et al. 1994)	Slope type	Altitude [m a.s.l.]	Slope [°]	Aspect
1	Western Tatras, Chochołowska Valley	Pośredni Żleb	gneisses, migmatites	debris mantled slope	1,621-1,808	31-47	W
2	Western Tatrs, Kościeliska Valley	Ornaczański Żleb	gneisses, migmatites	debris mantled slope	1,664-1,706	30-47	E
3	High Tatras, Rybi Potok Valley	Żleb Żandarmerii	biotite to two-mica granodiorites to granites, Quaternary sediments	debris mantled slope	1,674-1,840	45-67	E
4	High Tatras, Rybi Potok Valley	Dwoisty Żleb	biotite to two-mica granodiorites to granites	rocky slope	1,581-1,881	40-47	W
5	High Tatras, Mengusovská Valley	Ostrva	Quaternary sediments, biotite tonalites to granodiorites	debris mantled slope	1,876-1,951	45-67	W
6	High Tatras, Mengusovská Valley	Malá Bašta	biotite tonalites to granodiorites	rocky slope	2,015-2,173	45-67	E
7	Western Tatras, Žiarska Valley	Príslop	micaschists, gneisses; biotite to two-mica granodiorites to granites	debris mantled slope	1,736-1,802	40-47	SE
8	Western Tatras, Žiarska Valley	Baranec	micaschists, gneisses; migmatites,	debris mantled slope	1,602-1,640	40-47	NW

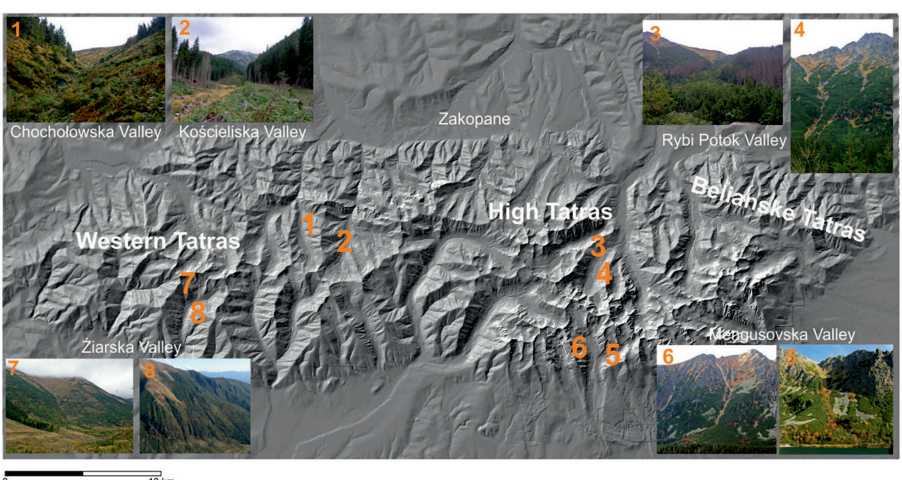

Figure 2. Locations of the study sites

These benchmarks were steel pipes with a diameter of ½ inch (1.27 cm) and a length of 0.5 m (Fig. 3). In total, 49 benchmarks were installed across the Tatras in each avalanche starting zone 3 to 10 (Tab. 2, Fig. 3).

Figure 3. Installing a benchmark

Table 2. Number of benchmarks at study sites

Area	Study site	Number of benchmarks
High Tatras	Žleb Žandarmerii	6
	Dwoisty Żleb	3
	Malá Bašta	8
	Ostrva	4
Western Tatras	Pośredni Żleb	5
	Ornaczański Żleb	9
	Príslop	10
	Baranec	4
Tatras	Total	49

The study sites were mainly positioned in the central and lower parts of the avalanche starting zones and distributed fairly evenly along their cross sections. Those parts of the avalanche starting zones usually present scars and erosion niches which are rarely found in their upper areas (Fig. 4).

The study was conducted in the years 2012-2015, including three winter periods, during which, however, there were no dirty avalanches at any of the sites. At each benchmark the height of the pipe above the ground was measured. The measurements were carried out twice a year – after winter (once the snow had melted, usually in June) and before winter (before snowfall, usually in October). In total, 137 measurement results were obtained.

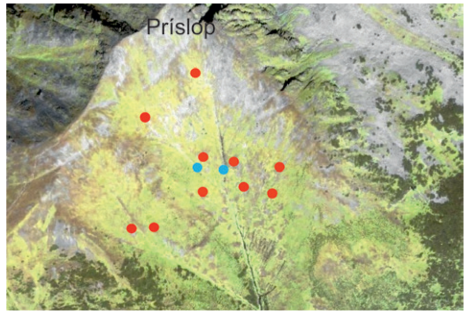

Figure 4. An example of the distribution of benchmarks at the Príslop study site. Red dots – benchmarks where steel pipes are installed, blue dots – other benchmarks

On the basis of the differences between the measurements in the two periods – before and after winter, the seasonal or annual variability of the lowering or accretion of the slope surface at the study sites can be specified. It was assumed that results with a negative value indicate a loss of mantle material (soil) from the slope, i.e. the predominance of erosion. Results with positive values indicate the supply of material, meaning the predominance of accumulation.

In order to assess the long-term erosion changes in the avalanche starting zones that may be associated with contemporary climate change in the Tatra Mountains (Żmudzka 2011a,b), measurements of the size of the erosion scars were taken from orthophotomaps dating from the years 1955, 1974 and 2009. The measurements were carried out in three of the selected research areas – Żleb Żandarmerii, Żleb Ornaczański and Żleb Pośredni in the Polish Tatras – due to the accessibility of orthophotomaps with a satisfactory image quality for the time periods analysed.

Results and discussion

Changes in the erosion niche and scar surfaces between 2012 and 2015

Taking into account the changes, i.e. the differences between the first and last measurements of the height of the benchmarks above ground level within the erosion scars over the three year period, including all the morphodynamic seasons, it can be concluded that the trends, as well as the size of these changes, vary from site to site. Erosion dominates in most study sites including at all benchmarks in the four starting zones examined, mostly located in the Western Tatras (Fig. 5). In these areas, avalanche starting zones are located on mantled slopes, which is also the case of the Ostrva site in the High Tatras (Tab. 1). On these slopes the material can easily be eroded as a result of cryogenic processes and slopewash, as well as by linear erosion connected with rainwater in summer or snowmelt in spring and autumn. The participation of meltwater indicates that the majority of the sites dominated by – or with a significant amount of – erosion are located on the southern slope of the Tatra Mountains and on the slopes of the western exposure. The erosion and removal of material may be facilitated by a greater amount of fine fractions in the particle size composition of the cover, which is indicated by the lithology of these areas (Tab. 1).

On the three remaining sites, both accretion of the slope surface by the accumulated material and its lowering due to erosion were recorded. This may be conditioned by the variation in the thickness of the soil cover on the rock-mantle slopes. Both trends were sometimes observed in different time sequences at the same benchmark point, which indicates the large extent of mosaicism of the slope modelling, even within a single study site. At the Żleb Żandarmerii site, accumulation was observed at all benchmarks, which may be due to the microtopography. The size of changes between successive measurements, meaning accretion or lowering of the slope surface, is 0.5 to 1.5 cm on average. The maximum size of these changes for the individual sites is between 2 and 6.5 cm (triangles in Fig. 5). A similar maximum rate of accretion was specified for talus slopes in the alpine and subnival zones of the Tatras (Kotarba 1976).

A slightly different pattern of slope modelling is indicated by the analyses of changes that only take place during the winter, i.e. from autumn to spring (Fig. 6). During this period, three categories of change are distinguished: erosion – increasing the height of the benchmark (greater exposure of the pipe) above the ground; accumulation – reducing the

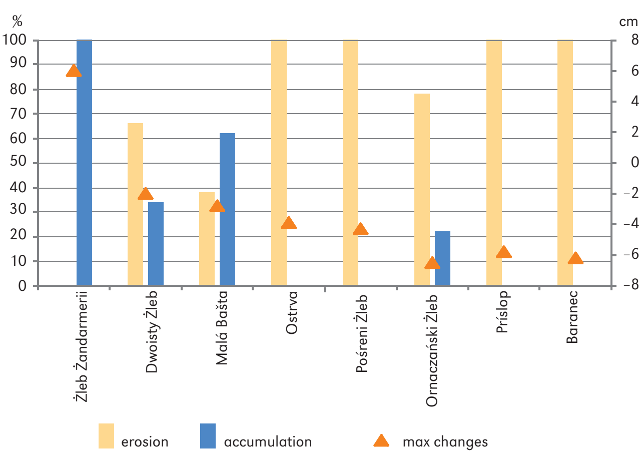

Figure 5. Morphodynamic changes of the erosion niches and scars in the starting zones: 2012-2015

height of the benchmark above the ground; and no pipe exposure change. At half of the sites, including Żleb Żandarmerii, all three categories of change occurred. At the other sites, four trends exist in various combinations, most frequently involving erosion. In over 50% of cases, erosion is predominant. The amount of accumulation reaches almost 80% at two of the sites, while at the others its share does not exceed 30%. Cases of no change are the least frequent. In the winter, as well as throughout the year, erosion prevails at the sites in the Western Tatras. In the High Tatras there is very great variation between the individual study sites – from erosion in 83% of cases within the erosion niches and scars in Ostrva to accumulation in 78% of cases in Żleb Dwoisty and Żleb Żandarmerii (Fig. 6).

The significant participation or predominance of erosion at most sites in winter indicates the considerable presence of cryogenic processes, as well as slopewash and linear erosion caused by meltwater, in the slope modelling of the avalanche starting zones in areas where there were no dirty avalanches. Meltwater comes from the melting of snow cover after winter as well as from the frequent appearance and disappearance of snow during the autumn. According to data from the meteorological station at Hala Gąsienicowa (1520 m a.s.l.), some periods of snow cover lasting for up to a dozen days or so occurred during the study in the autumn of 2013.

By contrast, the accumulation recorded at all study sites, although in a small percentage of cases, is due to the retention of material which was eroded from above. In places, snow cover frozen to the slope prevents its further transportation down the slope. In the summer this material may be eroded and discharged, leading to the slow development of erosion niches.

The regional diversity of morphodynamic changes

The analysis of the measurement of the size and direction of changes in the slope surface (elevation of the surface relative to benchmarks i.e. gain or loss of material) in the avalanche starting zone areas throughout the Tatras over the three-year period showed a reduction of the slope surface (erosion) in 67% of cases and slope build-up in only 33% of cases (Fig. 7A).

In the Western Tatras, these differences are even greater, with erosion recorded in 92% of cases (Fig. 7C). However, in the High Tatras, the balance between accumulation and erosion are reversed compared to that described throughout the Tatras (Fig. 7B). These changes are the result of a broad spectrum of processes, from the cryogenic

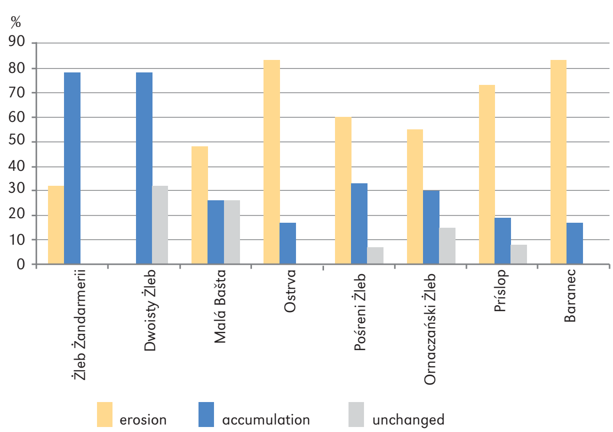

Figure 6. Morphodynamic changes at avalanche starting zones in the winter seasons in the years 2012-2015

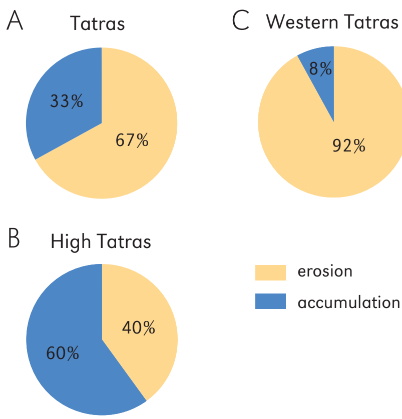

Figure 7. Diversity of morphodynamic changes in the avalanche starting zones in the Tatras: 2012-2015

processes between autumn and spring to the erosion processes associated with rainwater and snowmelt water running down the slope. The differences in erosion between the High and Western Tatras can be justified by the differences in lithology and slope types in the avalanche starting zones (Tab. 1), since the slope inclinations in the study areas are similar.

Within those erosion scars where surface lowering was recorded, the average loss of waste mantle material was 2.7 cm over three years, which is 0.9 cm/year. The average value of the accumulated material was lower, i.e. approx. 1.1 cm, which is less than 0.4 cm/year. The maximum erosion and accumulation values are similar, at 2.2 and 2.0 cm/year respectively. However, there are significant regional differences between the High and Western Tatras in the maximum values of erosion and accumulation (Tab. 3). But the average rates of slope lowering in the erosion scars in each of the areas (Tab. 3) are an order of magnitude greater than those specified by Midriak (2008). The rates are comparable with the denudation rate within erosional rills and small gullies which reached 1.7 cm/year (Midriak 2008).

The measurement results for the winter periods alone show a slightly different image of slope changes than that obtained from the results for all morphogenetic seasons, both throughout the Tatras and in the separate areas. This is the same regularity as was found when dealing with individual study sites (Fig. 8).

Table 3. Changes in the avalanche starting zones in the Tatra Mountains: 2012-2015

Area	Erosion		Accumulation	
	average [cm]	max [cm]	average [cm]	max [cm]
Tatras	2.7	6.5	1.1	6.0
High Tatras	1.9	3.9	1.2	6.0
Western Tatras	3.0	6.5	0.6	0.7

The results indicate the predominance of erosion (50% of cases) over accumulation (39% of cases) within the erosion niches and scars in the avalanche starting zone areas during the winter periods. In 11% of cases there is a balance between the two processes (Fig. 8A). In the Western Tatras, erosion predominates in winter (66% of cases) (Fig. 8C). In the High Tatras there is a dominance of accumulation during the same season (55% of cases) (Fig. 8B). The slopes in the avalanche starting zones of the Western Tatras are more active in winter – in only 9% of the

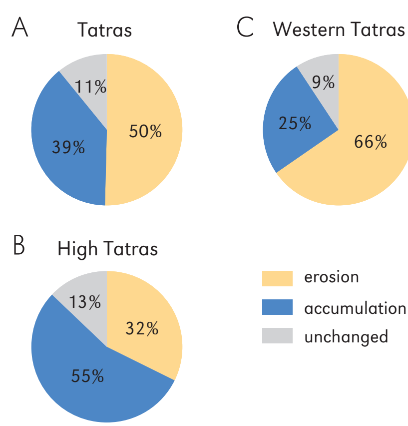

Figure 8. Diversity of morphodynamic changes in the avalanche starting zones throughout the Tatras and in their separate areas in winter: 2012-2015

observations was there no change recorded there.

Comparing the results obtained from the analysis of the full three-year observations with the results of the winter-only observation periods, cases of the lowering of slopes (erosion) were recorded in a higher percentage of cases, both throughout the Tatras and in the separate areas. This shows that a significant role is played by rainwater during the summer in the modelling of slopes in the avalanche starting zones. In particular, high total and high intensity rainfalls initiate the transport of weathered material on the slopes, which can lead to debris flows (Kotarba 1992, 2004). There were several rainfall events during the study period with a total of 100-275 mm in 2-3 days, and on 11 July 2014 the daily rainfall reached 100.2 mm according to data from the meteorological station at Hala Gąsienicowa. The role of rainfall may be less significant at times when there are dirty avalanches.

Analysis of erosion niches and scars on historical orthophotomaps

On the basis of the measurement of erosion niches and scars in the avalanche starting zones of three selected avalanche paths, carried out using orthophotomaps, it was found that their surface was reduced by as much as two thirds in all study areas during the period 1955-1974 (Tab. 4). This indicates a clear reduction in erosion during this period. The main reason for this was the reduction of sheep grazing due to the creation of the Tatra National Park in 1953, preceding the complete cessation of this activity in the 1960s (Mirek 1996). These trends were not reversed as a result of the activity of avalanches, which was reconstructed on the basis of dendrochronological studies in the Rybi Potok Valley (Lempa et al. 2014), the increased frequency of precipitation extremes (Niedźwiedź 2003), or the associated alluviation recorded on the talus slopes of the Tatras (Gądek et al. in print).

Table 4. Changes in surface area of erosion forms found in the avalanche starting zones in the years 1955-2009

Year	Study sites		
	Żleb Żandarmerii [ha]	Żleb Ornaczański [ha]	Żleb Pośredni [ha]
1955	0.65	0.39	0.51
1974	0.20	0.13	0.24
2009	0.63	0.54	0.21

By contrast, orthophotomaps from 2009 indicate an increase in the surface area of the forms investigated at Żleb Żandarmerii and Żleb Ornaczański (Tab. 4), which is likely to be associated with avalanches in the period 1974-2009. According to historical data, a large dirty avalanche occurred at Żleb Żandarmerii on 16 March 2005 (Fig. 9).

Figure 9. A dirty avalanche at Żleb Żandarmerii, 16 March 2005

Source: P. Budzyna 1999-2013 (http://tinyurl.com/qb4qlwh)

There was no increase, however, in the area occupied by erosion niches and scars at Żleb Pośredni, although, according to Krzemień et al. (1995), avalanches occurred there with a frequency of 7-9 per year in the period 1985-1990.

The development of erosion niches and scars could also have been initiated by extreme precipitation – several days with large amounts of rainfall combined with convective rainfall of high intensity, such as occurred in July 1997. This precipitation could have triggered erosion on slopes with dense vegetation cover, as was observed on the slopes of Mt Beskid which is formed of similar rocks and covered with similar waste mantles. The differences in size changes between the erosion niches and scars of Żleb Pośredni and Żleb Ornaczański, located on opposite sides of the Ornak ridge, can be explained by local tectonics and geological structure (Piotrowska et al. 2011).

Slope transformation and the occurrence of dirty avalanches

In the couloirs selected for detailed field studies there were no dirty avalanches recorded in the years 2012-2015. This is probably why the change in the relief of avalanche starting zones that occurred is small. The modelling of these parts of the slopes and couloirs is in general predominantly the result of erosion, which may indicate the leading destructive role played by rainwater and/or wind during the non-winter periods compared to the cryogenic processes operating in the winter periods, from autumn to spring. The positive results obtained after winter (determined, in accordance with the accepted assumption, as accumulation) may be due, among other things, to the activity of frost processes, including needle ice. This is favoured by the presence of waste mantle on the slopes, e.g. at Żleb Żandarmerii.

Changes in the relief of the Tatra avalanche paths, including avalanche starting zones, which result from the occurrence of wet or dirty avalanches, may be significant in the development of relief even though such avalanches are less common. An example might be the Żarska Valley in the Slovak Western Tatras, one of the areas selected for detailed study, where there are two study sites. On 25 March 2009, there was an extreme event which was called the avalanche of the century (Chrustek et al. 2010). Seven avalanches occurred in a short space of time, including one which covered the study site Príslop (Fig. 10).

In addition to the displacement of huge masses of snow, the avalanches destroyed a forest with hundred-years-old spruce trees and shifted a mixture of soil, waste mantle and rock material causing the re-modelling of the middle and lower parts of the slopes and couloirs (Fig. 8b). The snow-mineral-organic material accumulated by the avalanches, the volume of which was nearly 1 million m^3, covered 28 hectares and its

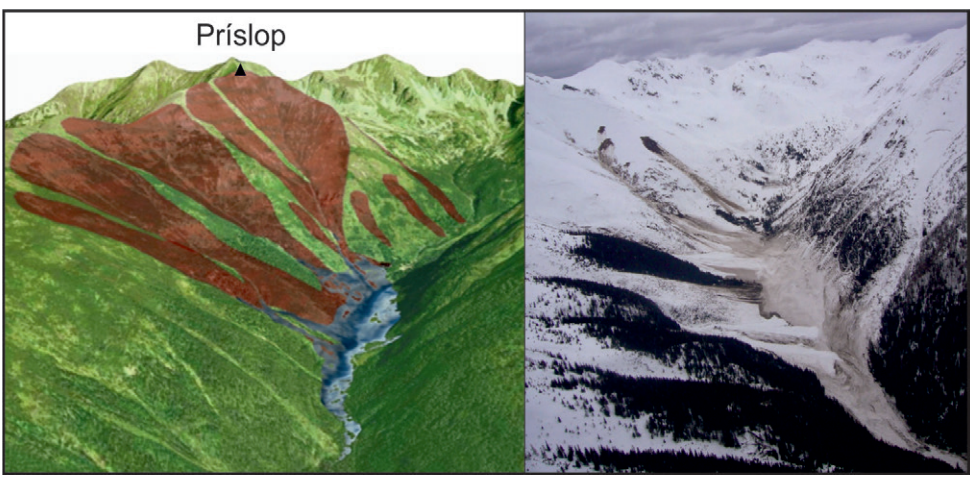

Figure 10. Areas covered by the changes resulting from the formation of avalanches in the Žiarska Valley on 25 March 2009

Source: changes based on Horská Záchranná Služba 2015; http://tinyurl.com/nuf7pod maximum depth reached 19.9 m (http://tinyurl.com/nuf7pod). During these events, a depth of up to 35 cm of the surface layer of the slopes may have been removed (Stankoviansky & Midriak 1998).

Summary

Due to their altitude, slopes in the avalanche starting zones in the Tatras are characterised by conditions fostering intensive modelling by morphogenetic processes – both rapid mass movements, as well as secular processes. Today, they are conditioned by natural factors, while until the 1960s they were also influenced by human activities. The results of the three years of monitoring research indicate that, in the absence of dirty avalanches, the efficiency of the secular geomorphological processes is small, even within erosion niches where the surface of the slope is unprotected by compact vegetation cover. The observed scales of accumulation and erosion are as much as several centimetres, on average approx. one centimetre. It should also be stressed that the direction of these changes, i.e. either accumulation or erosion, is highly variable spatially and temporally within one avalanche starting zone or even within the limits of a single niche or erosion scar. The diverse morphodynamics of the avalanche starting zones is favoured by their microtopography.

In the avalanche starting zones, the spatial variation in the morphodynamics of slopes for the entire year differs from that for the winter season. The differences in the morphodynamics of such slopes in the High Tatras and Western Tatras can be associated with lithological conditions. At the same time, taking into account the whole of the Tatras, the predominance of erosion has been indicated. This is a factor contributing to the morphogenetic processes active during the summer in particular.

Secular processes contribute to the development of erosion niches and scars in the starting zones. Significant re-modelling of the starting zones is caused by large dirty avalanches, which occur rarely. This is indirectly evidenced by changes in the size of erosion forms over time and observation of the effects of such events. However, documenting the morphogenetic role of dirty avalanches in modelling slope relief in relation to secular processes requires further study.

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Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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