
Seasonal and spatial variability of the morphodynamics of slopes within snow avalanche starting zones in the Tatra Mountains

Zofia RĄCZKOWSKA^{1*}, Elżbieta ROJAN²

¹Department of Geo-environmental Research, Institute of Geography and Spatial Organization, Polish Academy of Sciences, Św. Jana 22, 31-018 Kraków, Poland

²Department of Geomorphology, Faculty of Geography and Regional Studies University of Warsaw, Krakowskie Przedmieście 30, 00-927 Warsaw, Poland

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*Correspondence to: Zofia RĄCZKOWSKA; e-mail: raczk@zg.pan.krakow.pl

ABSTRACT

The paper aims to examine the morphodynamics of slopes within snow avalanche starting zones in the Tatras. The analysis of morphodynamics is based on the results of a four-year programme of monitoring of slope surface changes at 8 study sites. It is focused on the comparison of slope activity in the winter and summer seasons. The results of the study were examined taking into consideration the meteorological conditions during the study period and the relief. It was found that relief in the Tatras favours the occurrence of snow avalanches. In the period without snow avalanches, secular morphogenetic processes modified slopes within the snow avalanche starting zones. As a result, the slope cover material was triggered and moved in a chaotic and random manner as well as accumulating. The sites of erosion and accumulation of material are varied in time and space within the snow avalanche starting zones. Generally, erosion is the main effect of secular morphogenetic processes.

KEYWORDS Snow avalanche starting zone; Slope morphodynamic; Seasonal differentiation; Spatial differentiation; Tatra Mountains

1. Introduction

Snow avalanches are a significant element of high-mountain denudational systems. Their starting zones are usually located in the uppermost parts of valley slopes. The morphological features of the

starting zones strongly influence the size and type of snow avalanches (McClung and Schaerer, 2006). However, the activity of snow avalanches manifests itself in mountain slope morphology (e.g. Rapp,

1960; Luckman, 1978; Becht, 1995; Kotarba, 2002; Hreško et al., 2005; Sas et al., 2010; Lempa et al., 2015). Erosional landforms in the starting zones of snow avalanches indicate that erosion predominates there, mostly on soil-mantled slopes, although erosion was also evidenced in an avalanche starting zone situated on bedrock (Moore et al., 2013).

It was also found that the activity of avalanches in the Tatra Mountains manifests itself in the slope morphology of the avalanche starting zone in forms of erosional landforms (Rączkowska et al., 2016a; Gądek et al., 2017). Kotarba (1976) and Hreško et al. (2005) indicated that, as a result of full-depth 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, deflation and erosion. The average values of surface lowering due to avalanche activity in the Tatras, range from several dozen to 350 mm during a single event (Stankoviansky and Midriak, 1998). One avalanche can transport several hundred kilograms, occasionally over a tonne of rock debris (Kłapa, 1980).

In the Tatra Mountains avalanches originate in the areas above the upper timberline (Rączkowska et al., 2016a), where processes related to the periglacial climate (Jahn, 1958, 1975) and slope alluviation (Kotarba, 1976, 1996; Midriak, 1996; Rączkowska, 1999) are prevalent. According to Kłapa (1980), based on many years of research, avalanche activity predominantly occurs in the nival season, one of the four morphogenetic seasons distinguished in the Tatras. The subsequent nivopluvial season, which is characterised by a rich set of geomorphological processes, is the most active in terms of the dynamics of the processes throughout the year. In turn, the pluvial season can be considered both as active and very active, depending on the type of summer, and especially on the occurrence of extreme rainfall.

Avalanches are among the rapid mass movements active in the winter half of the year, while in the summer half of the year slope morphodynamics are driven by rainfall induced processes. The modern development of slopes within avalanche starting zones is the result of full-depth avalanches and

other secular morphogenetic processes which determine change throughout the year. The share of these two types of process can vary over time.

The aim of the study is to examine the morphodynamics of slopes within the starting zones of avalanches in the Tatra Mountains, with particular attention to its differentiation between winter and summer seasons. It is based on the results of a four-year programme of monitoring of slope surface changes.

2. Study area

The Tatra Mountains form the highest range in the Carpathians, rising to 2655 m a.s.l. (Gerlachovský štít). The area is divided into the Western Tatras, the High Tatras and the Belianske Tatras. They are formed of a crystalline core built of granites and metamorphic rocks, rimmed with sedimentary rocks to the north (Nemčok et al., 1994; Piotrowska et al., 2015). The Tatra Mountains were glaciated in the Pleistocene which has resulted in an alpine character to their relief (Klimaszewski, 1988; Rączkowski et al., 2015).

The mean annual air temperature (MAAT) ranges from 2°C to about -4°C on the highest peaks (Hess, 1965; Konček ed., 1974; Žmudzka et al., 2015). The mean total precipitation ranges from about 1100 mm in the northern foothills to over 2000 mm on the highest parts, yet the highest precipitation occurs in the 1500–1900 m a.s.l. zone. The number of days with seasonal snow cover ranges from about 100 to over 220 (Ustrnul et al., 2015).

The study slopes are located within the snow avalanche starting zones, which in the Tatra Mountains are found at altitudes of 1142–2620 m a.s.l. in the alpine and subalpine zones. The size of the avalanche starting zones varies in size from 312 to 198,942 m². They are largest in the Western Tatras, where their area is 28,593 m² on average. Approximately 90% of the avalanche starting zones in the Tatra Mountains include 26–55° slopes (Rączkowska et al., 2016b).

The study of the slope morphodynamics within the avalanche starting zones was carried out on eight selected couloirs. Their location is shown in Figure 1. These couloirs were purposely selected to include the northern and southern slopes of the Ta-

tra Mountains and some slopes of eastern and western exposure. Table 1 contains the most important geological and morphometric features regarding the avalanche starting zones studied, and Figure 2 presents their altitudinal location. The starting zones studied differ in slope character and li-

thology. Layers of Quaternary sediments cover slopes on the Žleb Žandarmerii and the Osterva study sites, and rocky slopes lie on the Dwoisty Žleb and Malá Bašta. The slope inclination is mostly similar, varying between 30–47° in the Western Tatras and 40–67° in the High Tatras.

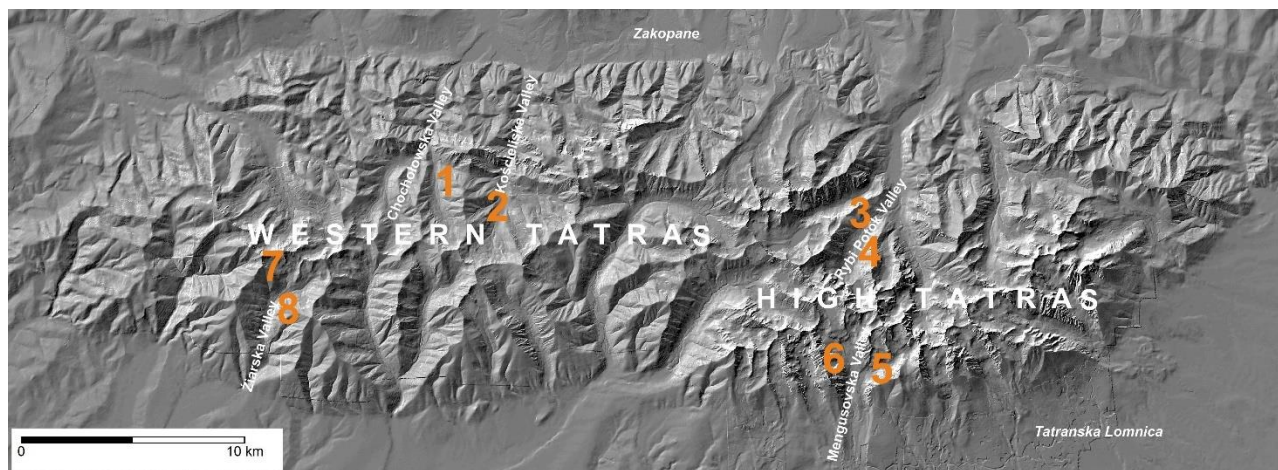


Figure 1 Location of the study sites marked by numbers. Their characteristics are in Table 1

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

	Location of the study site		Lithology (after Nemčok et al. 1994)	Slope type	Slope [°]	Aspect
1	Western Tatras, Chochołowska Valley	Pośredni Žleb	gneisses, migmatites	debris mantled slope	31–47	W
2	Western Tatras, Kościeliska Valley	Ornaczański Žleb	gneisses, migmatites	debris mantled slope	30–47	E
3	High Tatras, Rybi Potok Valley	Žleb Žandarmerii	biotite to two-mica granodiorites to granites, Quaternary sediments	debris mantled slope	45–67	E
4	High Tatras, Rybi Potok Valley	Dwoisty Žleb	biotite to two-mica granodiorites to granites	rocky slope	40–47	W
5	High Tatras, Mengusovská Valley	Ostrva	Quaternary sediments, biotite tonalites to granodiorites	debris mantled slope	45–67	W
6	High Tatras, Mengusovská Valley	Malá Bašta	biotite tonalites to granodiorites	rocky slope	45–67	E
7	Western Tatras, Žiarska Valley	Príslop	micaschists, gneisses, biotite to two-mica granodiorites to granites	debris mantled slope	40–47	SE
8	Western Tatras, Žiarska Valley	Baranec	micaschists, gneisses, migmatites	debris mantled slope	40–47	NW

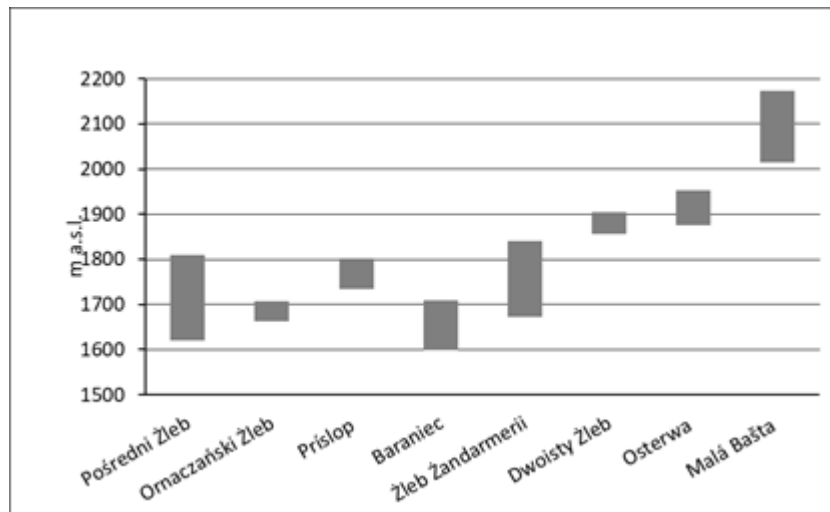


Figure 2 Altitudinal range of the study areas within the particular starting zone

3. Materials and methods

The size and direction of changes in the relief of the surfaces of the avalanche starting zones was determined using benchmarks. These benchmarks were steel pipes with a diameter of 1.27 cm and a length of 0.5 m (Fig. 3). They were installed within the erosional scars at each of the snow avalanche starting zones selected for study (Table 1, Fig. 4).



Figure 3 An example of benchmark and method of measurement

In total, 49 benchmarks were installed across the Tatras. The number of benchmarks in individual snow avalanche starting zones was from 3 to 10 (Table 2, Fig. 4).

The study sites were mainly placed in the central and lower parts of the avalanche starting zones, distributed along their cross section. Erosional scars and niches usually develop in those parts of the ava-

lanche starting zones, while they are less often found in their upper areas (Figs. 4 and 5).

The study was conducted in the years 2012–2016, comprising four winter periods and three summer periods. During the study period, however, there were no full-depth avalanches at any of the sites. The height of the pipe above the ground was measured at each benchmark (Fig. 3). The measurements were carried out twice a year – after the winter (once the snow had melted, usually in June) and after the summer (before snowfall, usually in October). In total, 126 measurement results were obtained.

Table 2 Number of benchmarks at study sites

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

On the basis of the differences between the measurements of the two periods – summer and winter, the seasonal or annual variability of lowering or accretion of the slope surface at the observation

sites can be determined. It was assumed that results with a negative value indicate a loss of soil from the slope, i.e. the predominance of erosion. Results with positive values indicate the supply of material,

meaning the predominance of accumulation. The number of cases and their percentage were the basis for the assessment.

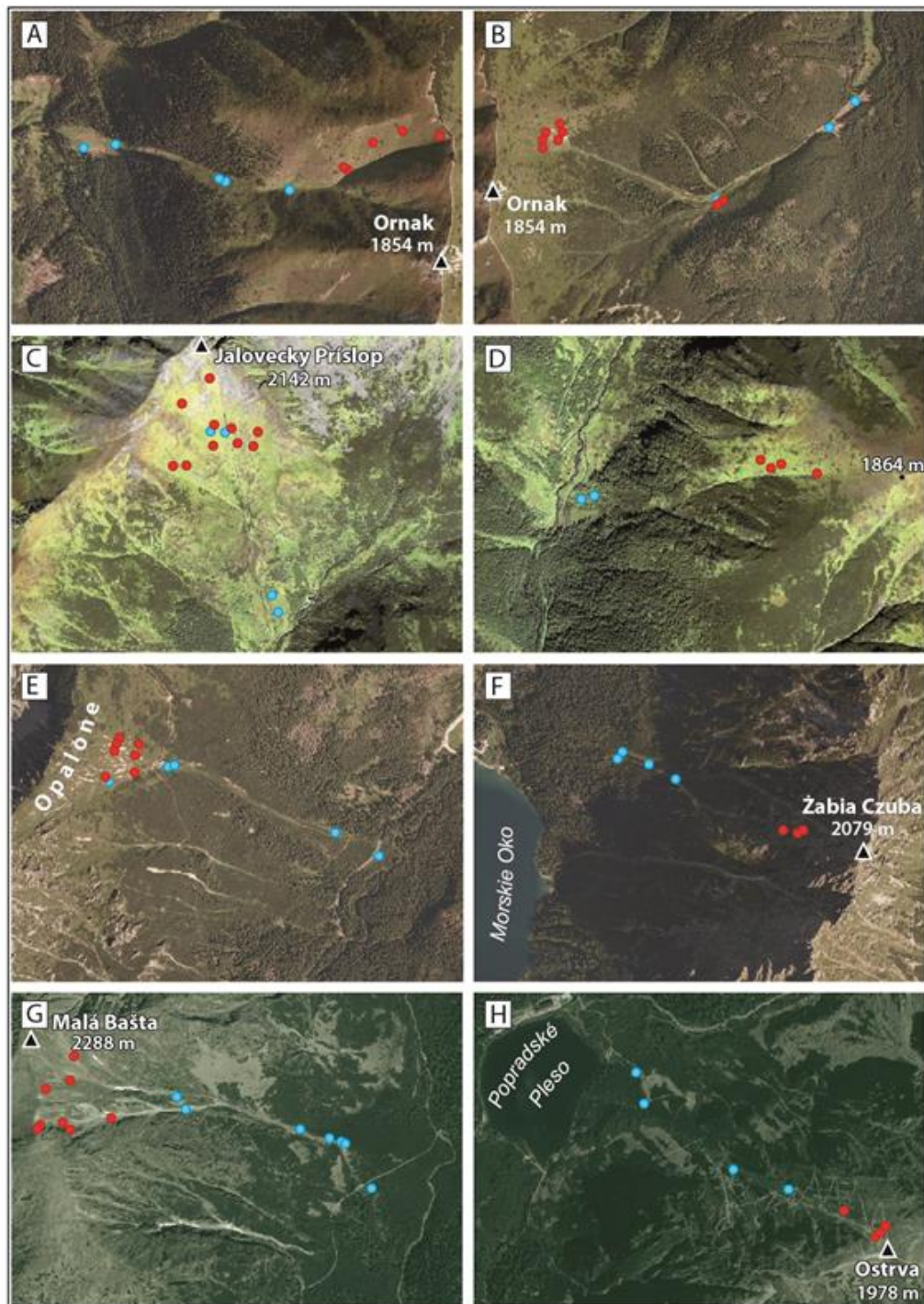


Figure 4 Location of the measurement points within the snow avalanche tracks. Red dots – steel pipes, blue dots – other benchmarks; A – Pośredni Żleb (1), B – Ornaczański Żleb (2), C – Przysłop (7), D – Baranec (8), E – Żleb Żandarmerii (3), F – Dwoisty Żleb (4), F – Malá Bašta (5), G – Ostrva (6), the number in bracket corresponds to the number of the study site in Figure 1

The meteorological conditions during the research period were determined using data from the Station of the Institute of Meteorology and Water Management at Hala Gąsienicowa, located at an altitude of 1520 m a.s.l. in the Polish section of the Tatras (<https://danepubliczne.imgw.pl/>). The data on daily precipitation and daily air temperature were used.

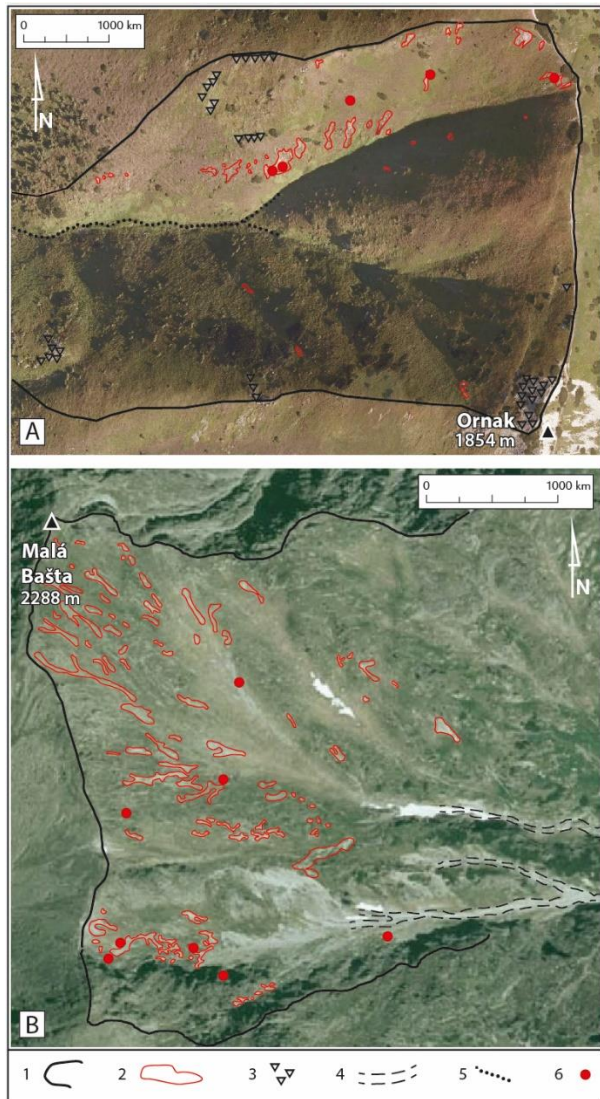


Figure 5 An examples of the snow avalanche starting zones. A – Pośredni Żleb study site in the Western Tatras, the slopes are mantled with compact covers of regolith and vegetation. B – Malá Bašta study site in the High Tatras, the rock slopes are bare or sparsely covered with regolith and vegetation; 1 – boundary of snow avalanche starting zone, 2 – erosional scars, 3 – blockfield, 4 – debris flow gully, 5 – initial channel, 6 – benchmark

Additionally, the fractional composition of the slope covers was determined at study sites in the Polish section of the Tatras. Soil samples were collected from each of the four study sites there. The number of samples varied from 3 to 5 at individual sites. The grain-size composition of the soil samples was determined using a combined sieving method and a Malvern laser particle-sizer (<2 mm).

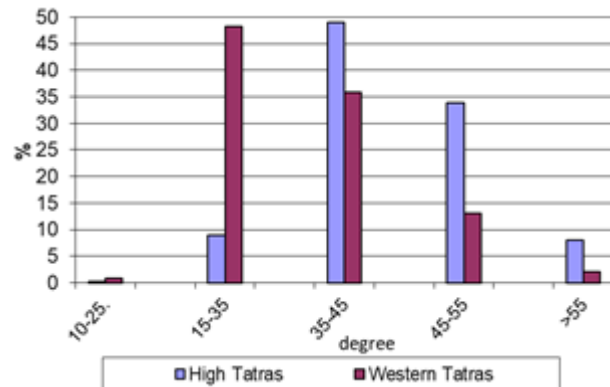


Figure 6 Inclination of slopes within the avalanches starting zones

4. Results

4.1 The morphological characteristics of snow avalanche starting zones

Starting zones are usually located on the source areas of rocky chutes and couloirs at an altitude 1697–1856 m a.s.l. in the Western Tatras and 2022–2101 m a.s.l. in the High Tatras (Table 3). They differ in size and morphology. These forms are much larger, but with lower slope inclination, in the Western Tatras (Fig. 6). According to McClung and Schaerer (2006) such an inclination (20–35°) favours the occurrence of slab and loose wet avalanches. These are mostly on debris mantled slopes covered by vegetation. In the High Tatras the slopes within the starting zones are often areas with bare and rocky surface and a very variable inclination that favours not only slab (30–45°) but also dry (30–60°) and cascade avalanches (60–90°).

The erosional scars in the avalanche starting zones are characteristic landforms developed due to avalanche erosion combined with sheep grazing in the Tatras (Rączkowska et al., 2016b; Gądek et al., 2017). They differ in number and size in individual starting zones.

Table 3 Characteristics of snow avalanche starting zones

Region	Upper limit (m a.s.l.)			Lower limit (m a.s.l.)			Area of starting zone (m ²)		
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Western Tatras	2228	1301	1856	2085	1157	1697	198942	755	28593
High Tatras	2620	1222	2101	2587	1142	2022	194365	312	6971

4.2 Grain-size composition of the study sites

The results of the analysis of soil samples show that they are mostly composed of a sand fraction, however finer material is also present (Fig. 7). There is no distinct difference found between the study sites in the High Tatras and the Western Tatras, and also there are very few differences found between individual study sites. Although the presence of fine material in the grain-size composition of soil indicates that there is material which can be easily triggered and moved.

4.3 Meteorological conditions

During the study period, meteorological conditions varied between individual winter and summer seasons respectively (Figs. 8 and 9).

Thermal and humidity conditions during the winters of the study period are characterised by relatively low precipitation and high variability of temperature (Fig. 8). Generally, precipitation was rather low. Heavy precipitation only occurred on two occasions, but of a different character. The temperature frequently fluctuated around freezing. This resulted in a fluctuation of the presence of snow cover and its short duration. This discontinuity in snow cover presence was especially noted in the winter of 2013/2014.

The 2014 summer season was more humid regarding both the persistence and totals of precipitation (Fig. 9). There were few daily totals higher than 30 mm, which are considered extreme events (Niedźwiedź et al., 2015) which could even have triggered debris flows (Kotarba, 1992).

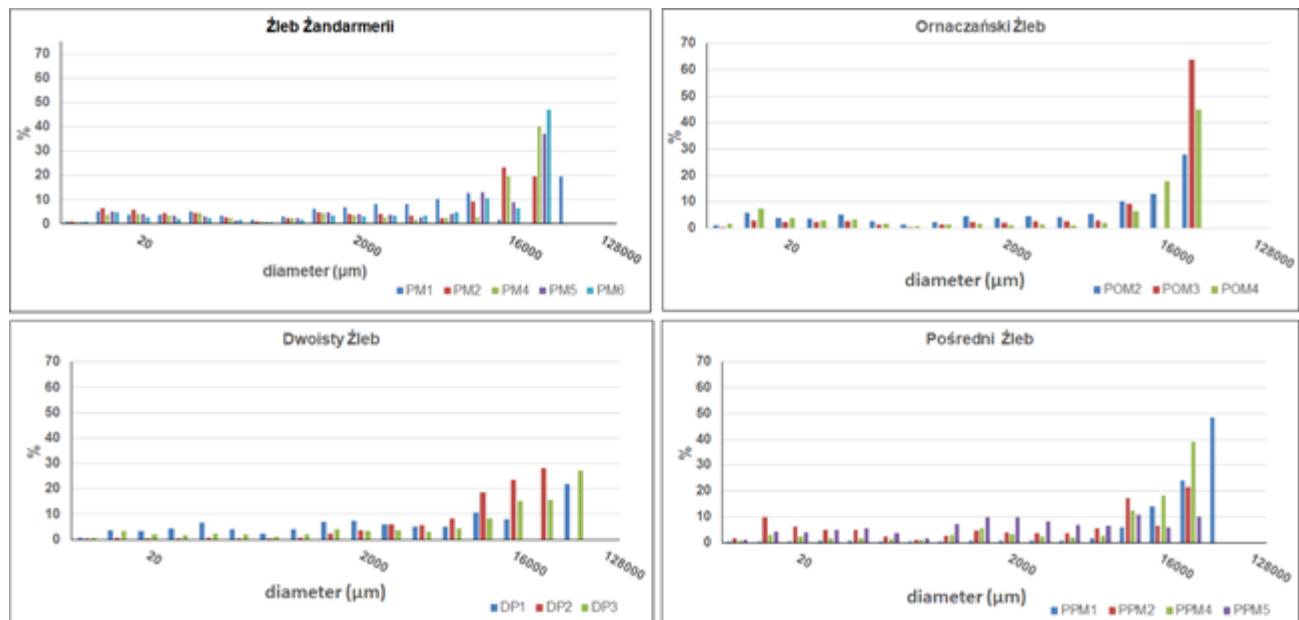


Figure 7 Differentiation of grain-size composition of soils on slopes within the snow avalanche starting zones in the Polish part of the Tatras. PM1–PM6, POM2–POM4, DP1–DP3, PPM1–PPM5 marks soil sample number

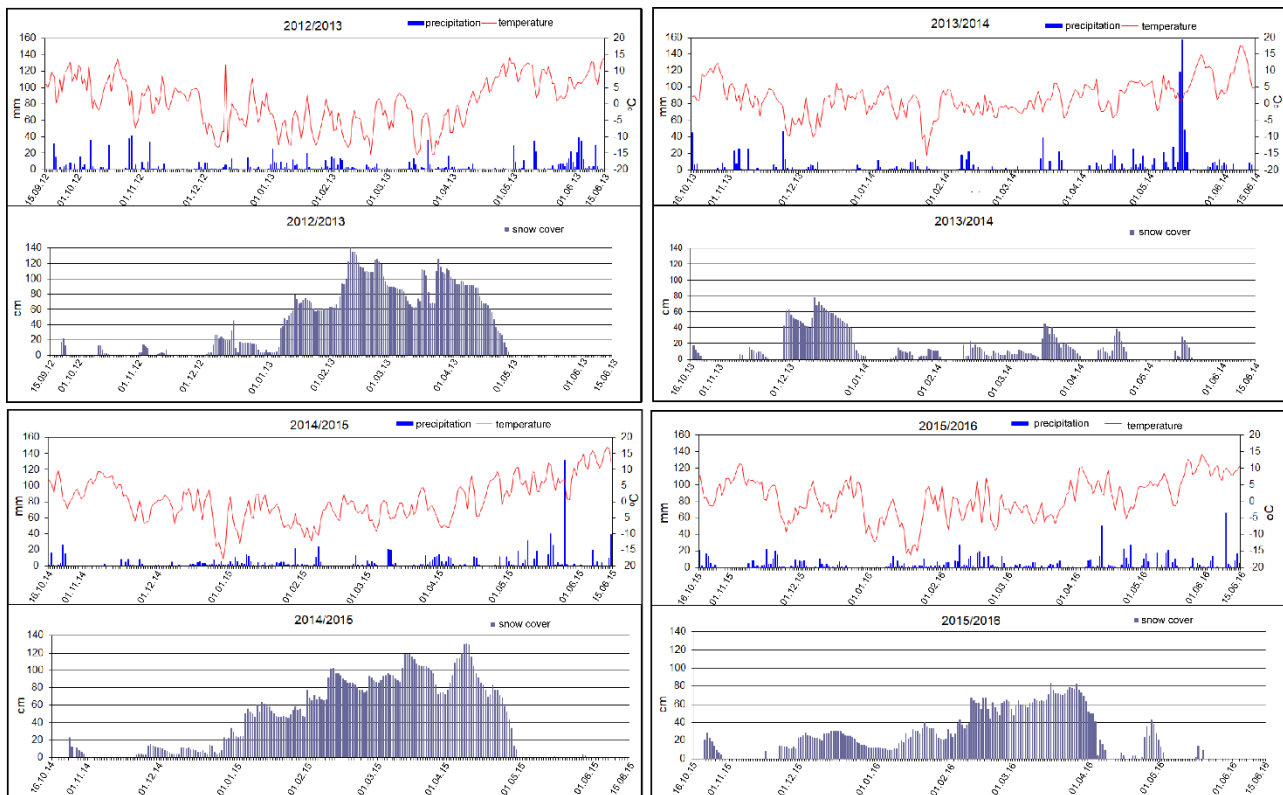


Figure 8 Meteorological conditions in the winter seasons during study period

Table 4 Changes of slope surface in studied starting zones in period 2012–2016

	Żleb Żandarmerii	Dwoisty Żleb	Ostrva	Malá Bašta	Pośredni Żleb	Ornaczański Żleb	Przysłop	Baranec
Erosion [%]*	50	66,7	100	50	80	80	78	100
Accumulation [%]*	50	33,3	0	25	0	20	22	0
No changes [%]*	0	0	0	25	20	0	0	0
Min** [cm]	-0,3	0,1	-1,4	0	0	-0,7	-0,2	-3,4
Max ** [cm]	4	-1,0	-4,5	-4,7	-7,0	6,6	-5,8	-6,2

* % of the total number of benchmarks in particular study site (couloir) ** difference in cm between the first and last measurement

4.4 Morphodynamic changes of the slope surface in snow avalanche starting zones

Significant variety appears between particular study sites when discussing slope activity during the four-year study period (Table 4). Lowering of the slope surface due to erosion occurred very frequently. It was found in 50 to 100% of measurements. Slope

accretion was found in far fewer measurements, and it was not even found at all at three study sites. There is also a large variation in the magnitude of the changes found in individual measurements. The changes range from 0 cm to 7 cm. In the winter season erosion prevails in six of the eight starting zones

studied, while accumulation prevails in only two of them (Fig. 10). The highest number of erosion events (>70% of measurements) was found in the Ostrva, Baranec and Prislop study sites located on southern slopes of the massif. These slopes are generally warmer and snow melted earlier there than on the northern slopes of the massif. The slope surface is affected by cryogenic processes and erosion by meltwater and rainwater.

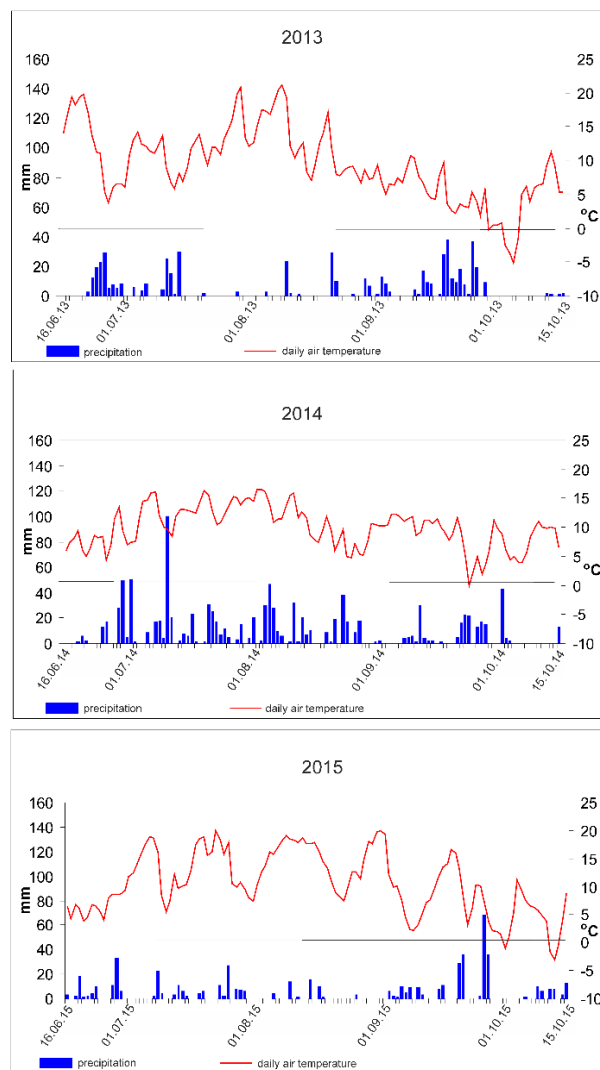


Figure 9 Precipitation and temperature conditions in summer seasons during study period

Two starting zones, where accumulation prevails, are located in the High Tatras at high altitude on the northern slopes of the massif, which favours the longer persistence of snow cover. Hence, the material accumulated in the traps formed in those places where the snow cover and the ground freeze

is preserved because it is exposed to erosion by rainwater for a shorter period.

Erosion prevails in the avalanche starting zones in the summer seasons, except for the Ostrva and the Prislop study sites where accumulation is equally or slightly more frequent (Fig. 10). Erosion was found in 20 to 90 % of measurements. Avalanche starting zones with a dominance of erosion are located on both the northern and southern slopes of the massif. Their exposure as well as the grain-size composition of soils are different. Such a pattern of slope morphodynamics in the summer season indicates that rainfall is the most important factor.

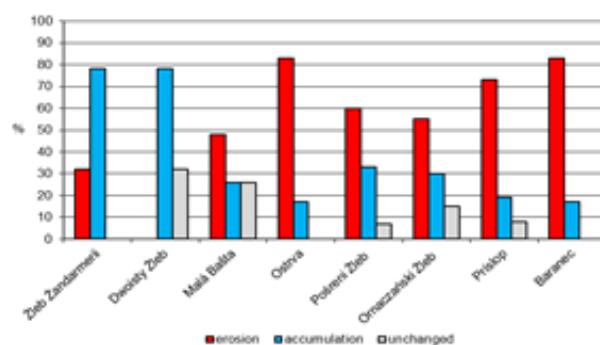


Figure 10 Morphodynamic changes at avalanches starting zones in the winter seasons in the years 2012–2016

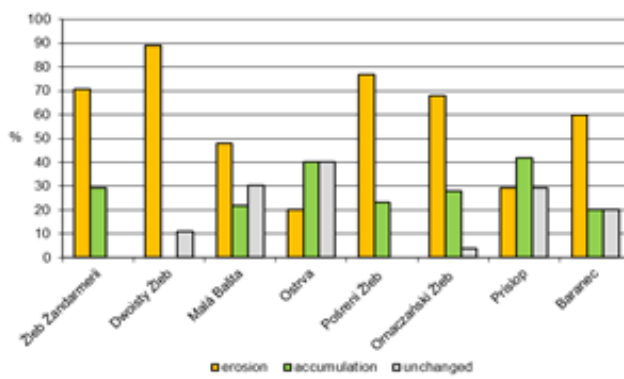


Figure 11 Morphodynamic changes at avalanches starting zones in the summer seasons in the years 2012–2015

4.5 Differentiation of slope morphodynamics in avalanche starting zones at a regional scale

The analysis of the results of measurements of slope morphodynamics in avalanche starting zones at the scale of the entire Tatra Mountains shows that erosion was found in 50% of all measurements, both in summer and winter seasons (Fig. 12). In addition, similar regularities are observed in accumulation, yet

accumulation was found in a smaller number of measurements (38% and 35%, respectively).

Differences occur when a separate analysis is made of the High Tatras and the Western Tatras (Fig. 13). In the summer season erosion dominates in both areas, occurring in more than 50% of the measurements. But in the winter season accumulation (55%) prevails in the High Tatras, while erosion (65%) prevails in the Western Tatras.

4.6 Differentiation of slope morphodynamics in subsequent years

Figure 14 presents the temporal variation of erosion and accumulation in the snow avalanche starting zones, in the form of yearly and seasonal changes. In general, the ratio between the different types of slope change (erosion, accumulation, unchanged) is more balanced in winter than in summer. Although a higher share of accumulation was found in winter, up to 40% of measurements, than in summer (only 25% of measurements), in the summer erosion occurs in up to 70% of measurements. In the winter its dominance was less pronounced, although the total share of erosion throughout the study period was higher than in summer.

5. Discussion

Research on the seasonal and spatial differentiation of snow avalanche starting zone morphodynamics is an attempt to answer the question of which processes are of greater importance in the development of erosional landforms – niches and scars within the starting zones. Are these cryogenic and nival processes, including avalanches and erosion, characteristic of the winter season or is erosion related to rainfall in the summer season? The results of the analysis of historical orthophotomaps indicate temporal and spatial variations in the development of erosional landforms within the avalanche starting zones in the Tatras associated with very different factors, but do not show regional or temporal regularities (Rączkowska et al., 2016b). At the same time, they clearly show a correlation between the enlarging of these forms and the

occurrence of large full-depth avalanches (Rączkowska et al., 2016b; Gądek et al. 2017).

The results of our research allow us to attempt an approximate assessment of the role of secular processes in the development of these erosional landforms in the Tatras. They indicate that slope changes are the effects of secular morphogenetic processes that are several times smaller than those previously observed as a result of snow avalanches (Stankoviansky and Midriak, 1998). However, they are similar to those obtained in previous studies of secular processes in the Tatras (Kotarba et al., 1987; Rączkowska, 2021). The average rates of lowering and accretion of slope surface, estimated from our measurements, are 8.4 mm/year and 4.2 mm/year respectively. These values are higher (by 1–2 mm/year) than those given by Midriak (1993) on the basis of research in the second half of the 20th century. It can be assumed that this is related to the influence of climate change on the course of secular morphogenetic processes. The results of our research, however, are an attempt to approximate the role of secular processes in the development of these erosional forms within the avalanche starting zones in the Tatras.

The pattern of slope changes in the avalanche starting zones caused by secular processes is complicated and ambiguous. It is difficult to define regularities in their spatial and temporal differentiation. Analysing them on a spatial scale, we found a dominance of erosion, both in the winter and summer seasons. It could therefore be assumed that the role of the activity of cryogenic processes and of meltwater erosion as well as of rainwater erosion in transforming the relief of the starting zones is similar. Moreover, a connection with the topography and features of slopes of the starting zones can be noted. The clear domination of erosion in the Western Tatras is favoured by the topography and elevation of avalanche starting zones. The slopes are not shaded there, as is often the case in the High Tatras, and the top layer of the soil thaws earlier. Moreover, slopes are mantled by weathering covers built with loose debris of different sizes including fine-grained mineral material.

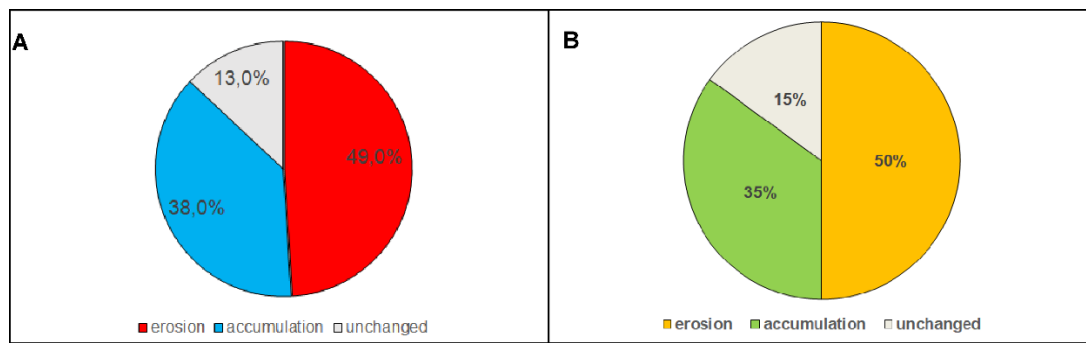


Figure 12 Diversity of morphodynamic changes in the avalanche starting zones between the winter (A) and the summer (B) seasons in the Tatras in 2012–2016

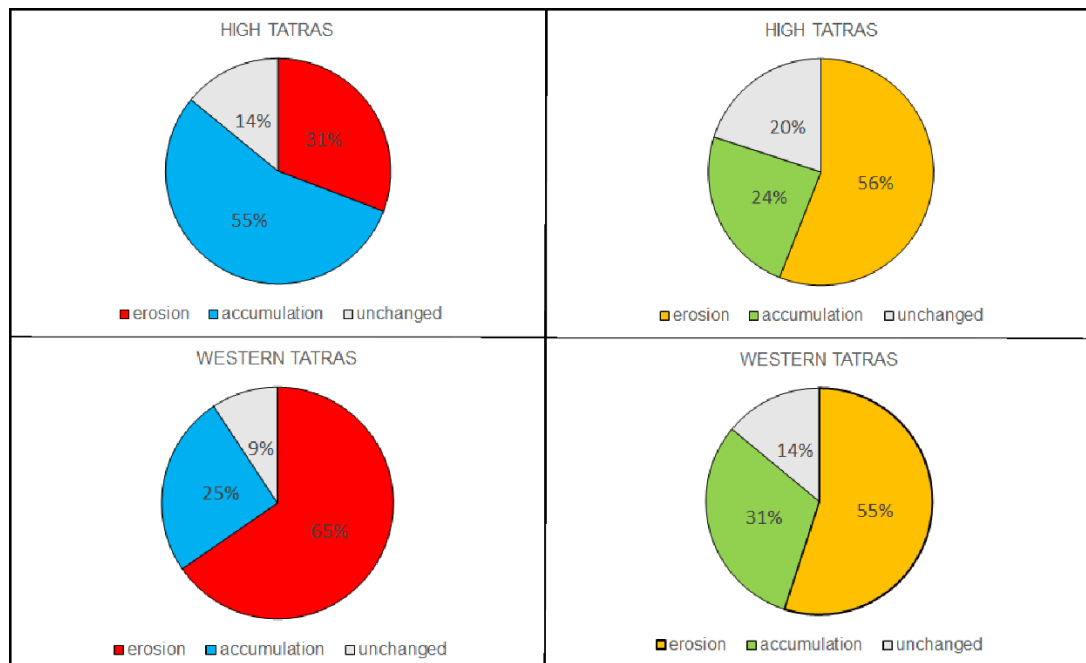


Figure 13 Regional diversity of morphodynamic changes in the avalanche starting zones between the winter (A, C) and summer (B, D) seasons in the Tatras in 2012–2016

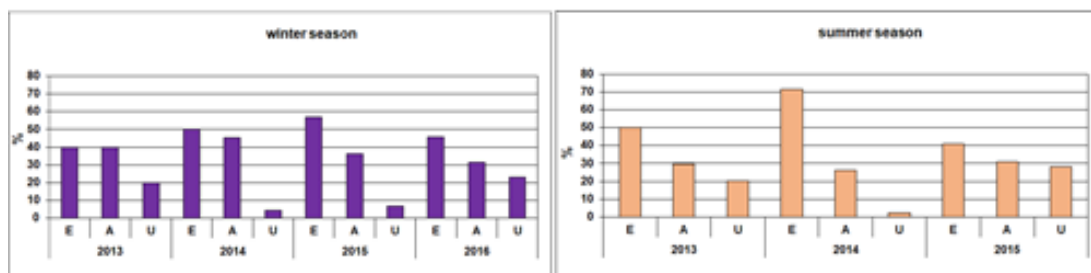


Figure 14 Temporal diversity of morphodynamics at the avalanche starting zones between particular winter and summer seasons. A – accumulation, E – erosion, U – no changes

When analysing the seasonal changes of slopes in the avalanche starting zones the relation to meteorological conditions can be noted. During summer the amount of erosion depends mainly on

rainfall. In the humid and cool summer of 2014, active erosion was occurring and there were few points where no change was found. In the 2013 and 2015 summer seasons with similar meteorological

conditions, the structure of morphodynamic change was also similar. Differences in the morphodynamics of the slopes during the winter are more difficult to relate to meteorological conditions. The duration and thickness of snow cover in 2013 and 2014 were similar and the ratio of erosion and accumulation differed. Rather, the occurrence of heavy precipitation in the period without snow cover is of importance. For example, the rainfall in May 2015 is likely to have resulted in a clear predominance of erosion over accumulation in the winter of 2014/2015 (Figs. 8 and 14). The nature of the precipitation is also important, e.g. in May 2014 there was heavy snowfall which was not reflected in the ratio of the amount of accumulation and erosion in the winter of 2013/2014.

6. Conclusions

The relief in the Tatra Mountains is conducive to the formation of avalanches. The analysis of slope inclination in the avalanche starting zones shows that in the High Tatras there are conditions for the formation of small powder snow avalanches of probable higher frequency, while in the Western Tatras, full-depth avalanches occur less frequently, but can be larger.

The morphogenetic role of avalanches depends on the occurrence of full-depth avalanches. In the period of the year when avalanches do not occur, slopes in their starting zones develop as a result of different morphogenetic secular processes related to rain or meltwater or cryogenic processes. Meltwater and rain water play a major role in slope modification. As a result, the material of the slope covers is triggered and moved in a chaotic and random manner, as well as being accumulated. The sites of erosion and accumulation of material are varied in time and space within the avalanche starting zones.

In general, erosion is the main effect of secular morphogenetic processes. This applies to both the winter and summer seasons. In the summer seasons, the intensity of modification of the slopes in the avalanche starting zones is related to the meteorological conditions, which is not the case in the winter seasons. The activity of secular morphogenetic processes maintains or develops the erosive scars or niches existing in avalanche starting zones. In this

way, it facilitates erosion caused by full-depth avalanches.

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