S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
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USING TLS FOR MONITORING TALUS SLOPE MORPHODYNAMICS IN THE TATRA MTS.

Abstract. This paper presents changes of surface relief of talus slopes in the Tatra Mts. based on terrestrial laser scanning (TLS) surveys conducted over five years. The changes are results of rapid mass movements, mainly debris flows and rockfalls. The results of the TLS surveys were analyzed with regards to meteorological conditions. It was found that debris flow activity is strongly related both to rainfalls and loose debris availability. The usefulness of the TLS survey for evaluation of the volume of rock material transported by rapid mass movement as well as the way this transport takes place was proven.

Keywords: talus slopes, TLS surveys, mass movements, meteorological conditions, Tatra Mts**.**

INTRODUCTION

Debris flows and rockfalls are typical of steep mountain environments with rapid, high energy mass movements. Debris flows belong to the most spectacular and important geomorphic processes in the Tatra massif, which is evidenced by numerous, active (fresh or renewed) and inactive debris-flow tracks (Kotarba 2004; Rączkowska 2006; Hreško et al. 2008; Kapusta et al. 2010; Kotarba et al. 2013; Długosz 2015). The debris flow tracks transport huge masses of weathered material across the slope system, supplying and covering the bottom of glacial cirques and valleys. High magnitude rainfalls are considered a direct trigger of debris flows (Innes 1983; Iverson 1997; Kotarba 1992a; Frattini et al. 2009). Based on some 20 years of observations in the High Tatras, the debris flows which extend over the full length of the debris slope are triggered by rainfall of 35–40 mm h^{-1} intensity or at least 80–100 mm d^{-1} (Kotarba 1992a, 2002). Occurrence of debris flows depends also on the availability of debris material to be transported (Innes 1983; Jakob, Bovis 1996; Iverson 1997; Bovis, Jakob 1999; Glade 2005). However, talus slopes are not affected by debris flows even during heavy rainstorms, when they are covered and protected by snow cover (Kotarba et al. 2013). Rockfalls are presently much rarer in the Tatras then debris flows in comparison to the amount in the past (Kotarba 2004; Rączkowska 2006).

Morphological changes after extreme events can be quickly and flexibly documented by terrestrial laser scanning (TLS) with high precision and accuracy (Abellan et al. 2006; Milan et al. 2007; Lato et al. 2009; Wasklewicz, Hattanji 2009; Schürch et al. 2011). Digital elevation models (DEMs) built from repeated TLS surveys permit producing DEM of Difference (DoD) that enables assessment of elevation variations and estimation of volumetric changes over time (Cavali et al. 2008; Baldo et al. 2009). DoD maps make it possible to analyze morphological changes in slopes and channels from the quantitative (scour and fill changes in volume) and qualitative (spatial patterns of erosion and deposition) perspectives (Theule et al. 2012; Picco et al. 2013). The analysis can be performed from different perspectives, ranging from the accounting of volumetric (Theule et al. 2012) and channel geometry changes (Wasklewicz, Hattanji 2009) to the correlation of morphometric indexes and different components of the geo-hydrological processes (Cavalli, Marchi 2008; Glenn et al. 2006; Tarolli et al. 2008).

The aim of this paper is to analyze spatial changes of surface morphology on the talus slopes of the glacial cirque in the Tatra Mts. over a five year period. We performed multitemporal TLS surveys over two talus cones exposed to debris-flow dynamics and rockfall activity. The repeated TLS surveys permit following the transportation pattern of rockfall material. An advantage of the study is the possibility of exploring the linkage of debris flow and rockfall events with rainfall and air temperature measured at the base of the slope.

STUDY AREA

The study area is located in the upper Rybi Potok Valley in the Tatra Mountains (Poland), which are the highest part of the Carpathians (Fig. 1). The area is built of resistant Carboniferous granitoids (Fig. 2; Piotrowska et al. 2014, 2015) dissected by a system of faults of a SW-NE direction, which conditioned the development of the hanging glacier cirques (Piotrowska 1997). Thin veins of mylonite form zones of weakness inside granitoids and usually are followed by chutes (Piotrowska et al. 2014).

The area is characterized by an alpine relief (Fig. 3; Rączkowski et al. 2015b) formed during Pleistocene glaciations (Klimaszewski 1988; Baumgart-Kotarba, Kotarba 1997). The upper part of the Rybi Potok Valley cover system of glacial cirques hang over the Morskie Oko Lake in the bottom of a glacial trough, with almost 1000 m difference of altitude between ridges (peaks at 2438 m a.s.l.–2376 m a.s.l.) and the lake (1520 m a.s.l.). The slope consists of steep or vertical rock walls with a system of talus cones below (Fig. 3). The climate is variable between maritime and continental influences. The mean

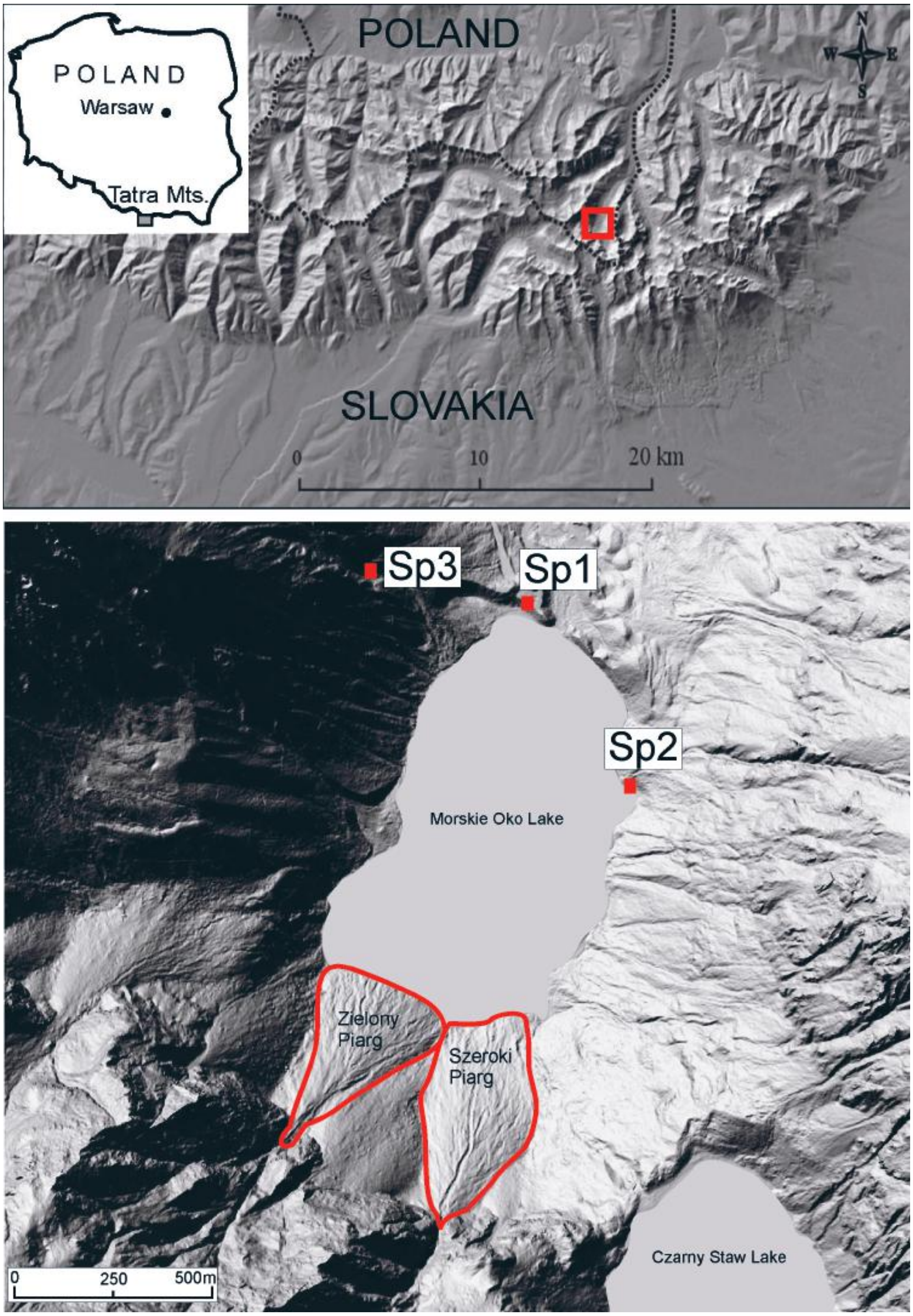


Fig. 1. Study area and sites of TLS survey (SP)

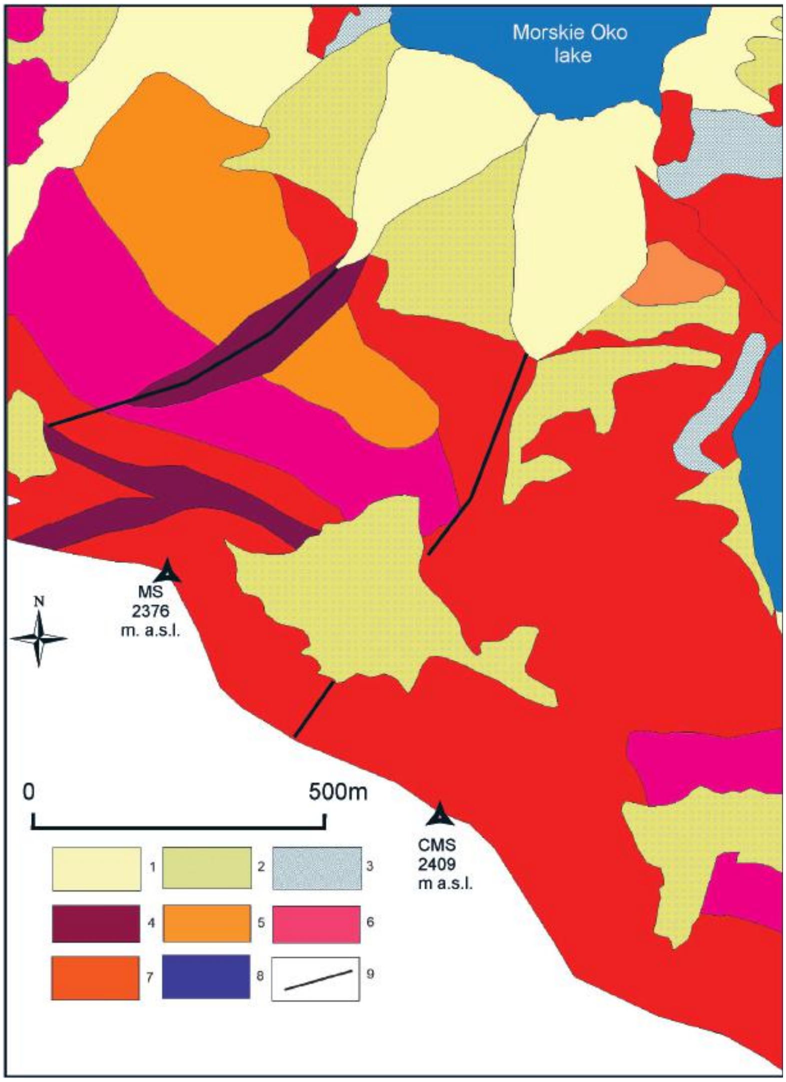


Fig. 2. Geological sketch of the study area. 1 – loamy-sandy-stony to boulder sediments of talus--alluvial cone, 2 – loamy-sandy-stony to boulder sediments of talus cone, 3 – moraine deposits, 4 – mylonites and cataclasites, 5 – granites with pegmatites and aplites, 6 –granites with K-feldspars, 7 – granodiorites and tonalites, 8 – lakes, 9 – faults

annual air temperature (MAAT) ranges from 6°C at the foothills to –4°C on the highest peaks (Konček ed. 1974; Niedźwiedź 1992; Żmudzka et al. 2015). The mean total precipitation ranges from approximately 1100 mm in the north foothills to more than 2000 mm in higher parts (Ustrnul et al. 2015). The highest precipitation of 1500–1900 m occurs on the northern slopes (Hess 1965; Cebulak 1983). The number of days with seasonal snow cover

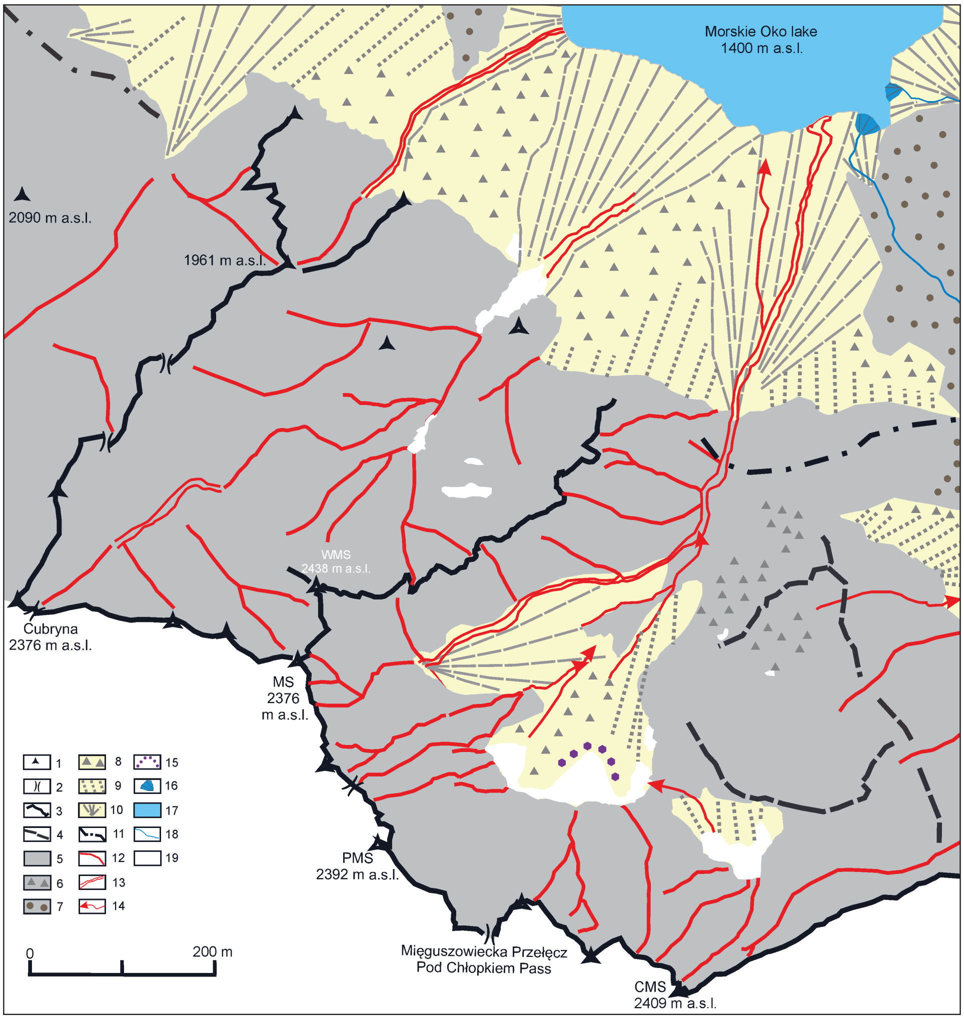


Fig. 3. Geomorphological sketch of the study area. 1 – sharp summit, 2 – pass, 3 – sharp rocky ridge, 4 – convex break in rocky slope, 5 – rockwall and rocky slope, 6 – rocky slope covered by rockfall debris, 7 – rocky slope covered by moraine, 8 – rockfall talus slope, 9– talus slope, 10 – talus-alluvial slope, 11 – step of hanging glacial cirque, 12 – rocky chute, 13- large debris flow gully (> 5m width), 14 – debris flow gully, 15 – protalus rampart, 16 – delta, 17– lake, 18 – stream, 19 – perennial snow patch. WMS – the Wielki Mięguszowiecki Szczyt peak, MS – the Mięguszowiecki Szczyt peak, PMS – the Pośredni Mięguszowiecki Szczyt peak, CMS – the Czarny Mięguszowiecki Szczyt peak

ranges from about 100 to over 220, respectively (Konček ed. 1974; Ustrnul et al. 2015).

The studied slopes are the talus cones named the Szeroki Piarg and the Zielony Piarg and the rocky slopes above them, located on the southern bank of the Morskie Oko Lake in seminal, alpine and subalpine belts. The talus cones chosen for the studies are frequently affected by debris flows (Figs. 4).

Fig. 4. Views of the Szeroki Piarg (left) and the Zielony Piarg (right) talus cones in the years of TLS surveys

METHODS AND DATA

FIELD OBSERVATIONS

The information about the occurrence of debris flows and rockfall on the studied slopes was collected during field visits in sequential years in the Rybi Potok Valleys. The photo-documentation of slopes was made by a Nikon camera. The exact dates of these hazardous events were obtained due to the kindness of M. Król, staff member of Tatra National Park.

TLS SURVEYS

After occurrence of each event, the terrestrial laser scanner surveys were undertaken. This was the first time TLS monitoring for geomorphological studies in the Tatras was performed. The TLS measurements were done on 24.10.2011, 24.07.2013 and 11.08.2017. A Riegl VZ-1000 terrestrial laser scanner was used for the first two surveys (Rączkowski et al. 2015a) and a long distance scanner, the Riegl VZ4000 was used in 2017. Having a solid survey and data processing strategy plays a decisive role in the quality of geomorphic change detection studies (Buckley et al. 2008). Therefore, each survey was taken from 3 positions (Fig. 1) located on opposite banks of the Morskie Oko Lake, in order to eliminate so called "measuring shadows" – areas covered by rocks, trees, buildings etc. The distance to the studied slopes was from 800 to 1200 meters. The precise position of the scanner was determined by connecting it with the GNSS (Global Navigation Satellite System) during the two first measurements with GPS RTK (real-time kinematic). The resulting point clouds have been pre-treated with Riscan Pro software as follows: 1. data from different positions were combined into one coherent point cloud, 2. the vegetation (grass, dwarf pine bushes) was removed, 3. data not related to area of the studied talus slopes and rock walls above was eliminated. Data prepared in this manner for a particular survey were exported to Las.1.2. format and next analyzed using ArcGiS 10.2.2.

The point clouds were transformed into high resolution terrain models (0.2 m grid), followed by a differential DoD analysis, which allowed to determine spatial changes in slope morphometry in the analyzed periods (2011–2013 and 2013–2017).

METEOROLOGICAL DATA

For evaluation of meteorological conditions, data from the meteorological station of the Institute of Meteorology and Water Management (IM&WM) located at northern bank of the Morskie Oko lake (1530 m a.s.l.) were used. Daily precipitation totals, daily mean air temperature as well as snow cover presence and thickness were analyzed. The data from the meteorological station of IM&WM at Hala Gąsienicowa (1520 m a.s.l., around 8 km directly west) were use as background material and to complete the analysis.

RESULTS

MORPHOLOGY OF THE SLOPE SYSTEM

The studied slope system consisting of a rock wall or a rocky slope and talus slopes, elongated vertically from 1520 m a.s.l at the base of the talus slopes to ridges at 2478 m a.s.l. Steep, almost vertical, the rock slopes are fragmented by couloirs and rockfall niches (Fig. 3), whereas talus slopes often present a more rich micro-relief appearance, reflecting the type of processes that model them.

The studied Szeroki Piarg and Zielony Piarg, constitute the vast talus cones with exposure to the N, inserted into the glacial lake basin (Figs. 1 and 3). The Szeroki Piarg talus cone is situated below the 300-metres high rock threshold of the Kocioł Męguszowiecki glacial cirque, over which, in turn, rise the 400-meter high rock wall of the Pośredni Męguszowiecki Szczyt peak (2392 m a.s.l.) and the Wielki Męguszowiecki Szczyt peak (2438 m a.s.l.). The total length of the talus cone is approx. 600 m, and its average gradient is close to 22°. The Zielony Piarg talus cone, of 500 m total length and a lesser inclination is also situated below the high rock walls and rocky slopes of the Cubryna peak (2376 m a.s.l.). The whole slope (from the ridge to the bottom of the lake) has a stepped longitudinal profile. The thickness of the Szeroki Piarg talus cone in the above-water zone ranges from 15 m (in the upper part of the profile) to approx. 30 m (in the lower part) (Gądek et al. 2016). The gullies with side levees occurring on the surface of both talus cones imply that debris flows are the dominant processes which form the slope (Figs. 3 and 4).

RAPID MASS MOVEMENTS CALENDAR

Numerous debris flow gullies, of different ages, on both the Szeroki Piarg and the Zielony Piarg evidence that these processes are common there (Kotarba 1993–1994; Rączkowska 2011; Gądek et al. 2016). According A. Kotarba et al. (2013) new hillslope debris flows occur at least once per 10 years on the same slope in the Tatras. Debris flows are often triggered by local rain storms therefore their time and place are not predictable.

According to direct observation, a rainstorm which triggered debris flows both at the Szeroki Piarg and the Zielony Piarg talus cones occurred August 23rd, 2011 (Kotarba et al. 2013). These debris flows transformed existing debris flow gullies and formed new levees on the Szeroki Piarg as well as the delta below in the lake. On the Zielony Piarg talus cone a new gully formed on its right

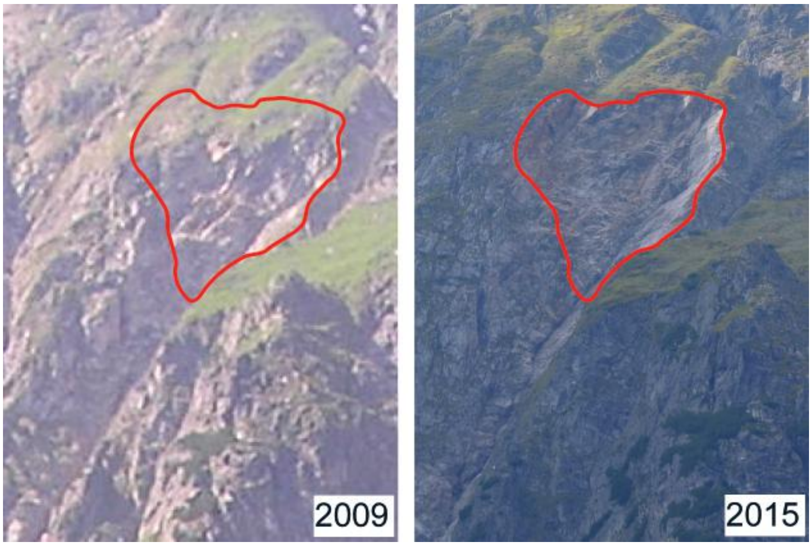


Fig. 5. Fragment of rocky slope of the Wielka Galeria Cubryńska before (left) and after (right) rockfall at September 24 2012

side and fresh debris was accumulated over the right side of the cone (Fig. 4 – 2011). Moreover, on September 23rd, 2012 a huge rockfall on the rock walls of the Cubryna peak (Wielka Galeria Cubryńska) occurred (Fig. 5) and caused a debris flow which was active till the 27th of September 2012 (Król 2012). The debris flow affected the central part of the cone (Fig. 4 – 2013). The debris flow transported fine and small rock clasts material trough the Mały Mięguszowiecki Kocioł glacial cirque and across the Zielony Piarg talus cones reaching the bank of the Morskie Oko Lake with a close to 5 meters wide tongue (Król 2012). Rockfalls are common in the area as was recorded historically in 1866, 1900, 1914, 1924, 1933, 1953, 1954 (Nyka 1956). The rockfalls' niche of a depth of up to 3.5 m was formed at an altitude of between 1841 and 1902 m a.s.l. (Rączkowski et al. 2015a).

According to the TLS surveys of the Polish Geological Institute, the talus slopes' surface did not display any changes related to gravitational processes between 2012 and 2014 (Rączkowski et al. 2015a).

The next hillslope debris flows occurred May 8th, 2015, when masses of snow-debris mixture flowed down to the central part of the Zielony Piarg talus cone which were covered by continuous snow cover. After one year another new debris flow event was recorded at the same place, on 24–25th of July 2016 (Fig. 4 – 2017). It affected a large part of the cone and formed fresh landforms such as gullies, tongues and levees. The tourist path was covered by fresh debris for a 70 m distance. No new landforms occurred on the Szeroki Piarg talus cone at that time, however some transformation of existing debris flow gullies were observed.

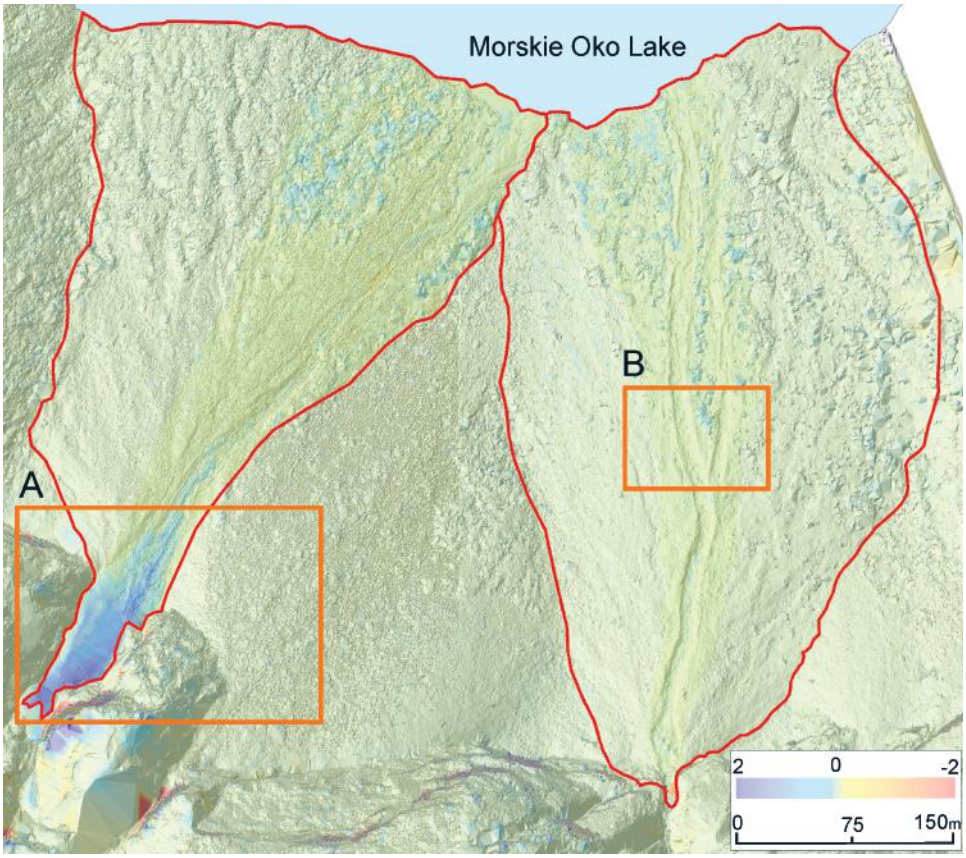


Fig. 6. DoD model of the studied talus cones surfaces for period 2011–2013. Rectangles A and B mark fragments of the talus cones shown in details on Figure 7.

CHANGES OF TALUS CONE SURFACES AFTER TLS

The results of TLS monitoring are the DoD models display accretion or erosion of talus cones. Figures 6 and 7 shows slope surfaces changes in particular analyzed time spans and figures 8 and 9 show fragments of slopes significantly changed and parts not changed at all. The size of these changes is between –2 by 2 meters in the vertical line.

The DoD model on Figure 6 shows changes of the Szeroki and the Zielony talus cones surfaces between 2011 and 2013 when cones were affected by debris flows. Both talus cones' surfaces almost entirely show near zero changes. The displayed changes (a few cm in size) should be designed to TLS instrument accuracy, distance of scanning and domination of coarse material on slope surface. According to (K o t a r b a et al. 1983) field experiment studies showed the rate of such slopes accretion is 0.03–0.06 cm/year maximum. The exception is the

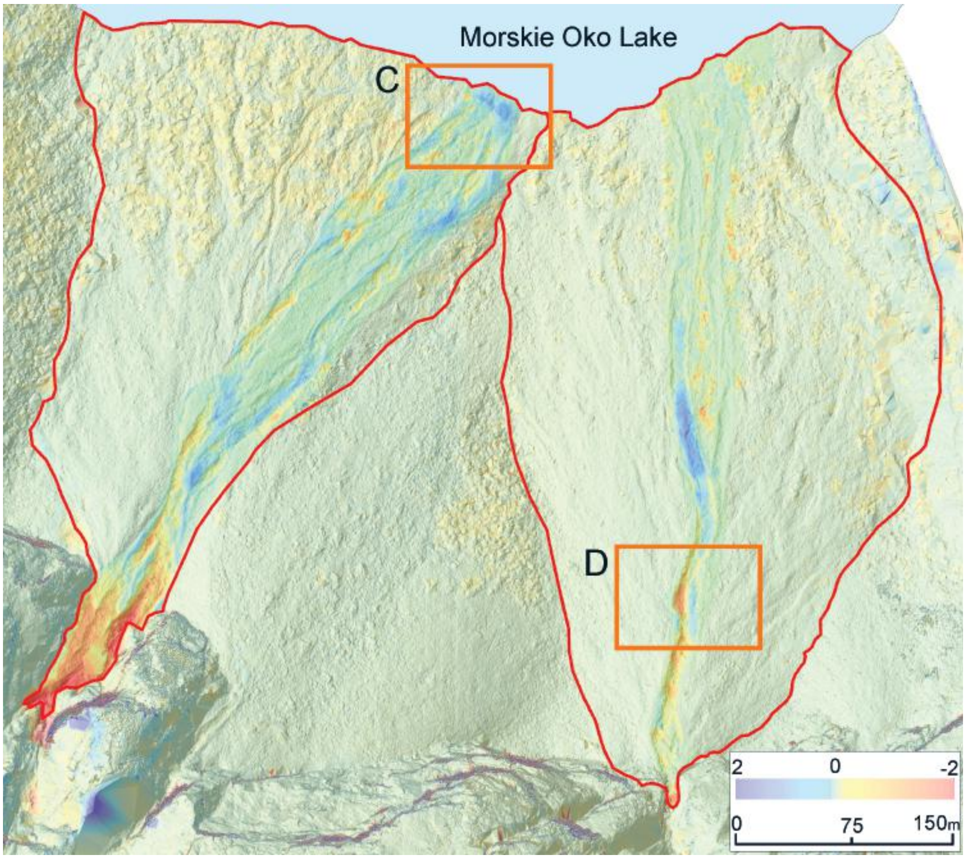


Fig. 7. DoD model of the studied talus cones surfaces for period 2013–2017. Rectangles C and D mark fragments of the talus cones shown in details on Figure 8.

uppermost part of the Zielony Piarg talus cone where significant changes were measured. The slope surface was built up to 6.5 m maximum in a zone up to 36 m wide and around 225 meters long as a result of delivery of debris by rockfall on September 23rd, 2012. The pre-existing debris flow gully was filled. Figure 8 shows detailed pictures of this slope fragments and for comparison, the completely unchanged fragments of the debris flow gully on the neighboring slope of the Szeroki Piarg talus cone.

The DoD model on Figure 7 present a different pattern of talus cone changes, which developed between 2013 and 2017. Accretion and erosion is found along the central part of the Szeroki Piarg talus cone in its upper part and along the right part of the Zielony Piarg talus cone from its top to the lake. The debris flow gully in the upper part of Szeroki Piarg was deepened and eroded material was deposited in the central part of the cone. The course of the debris flow gully being transformed resulted in more curves and new levees developed along the gully (Fig. 9).

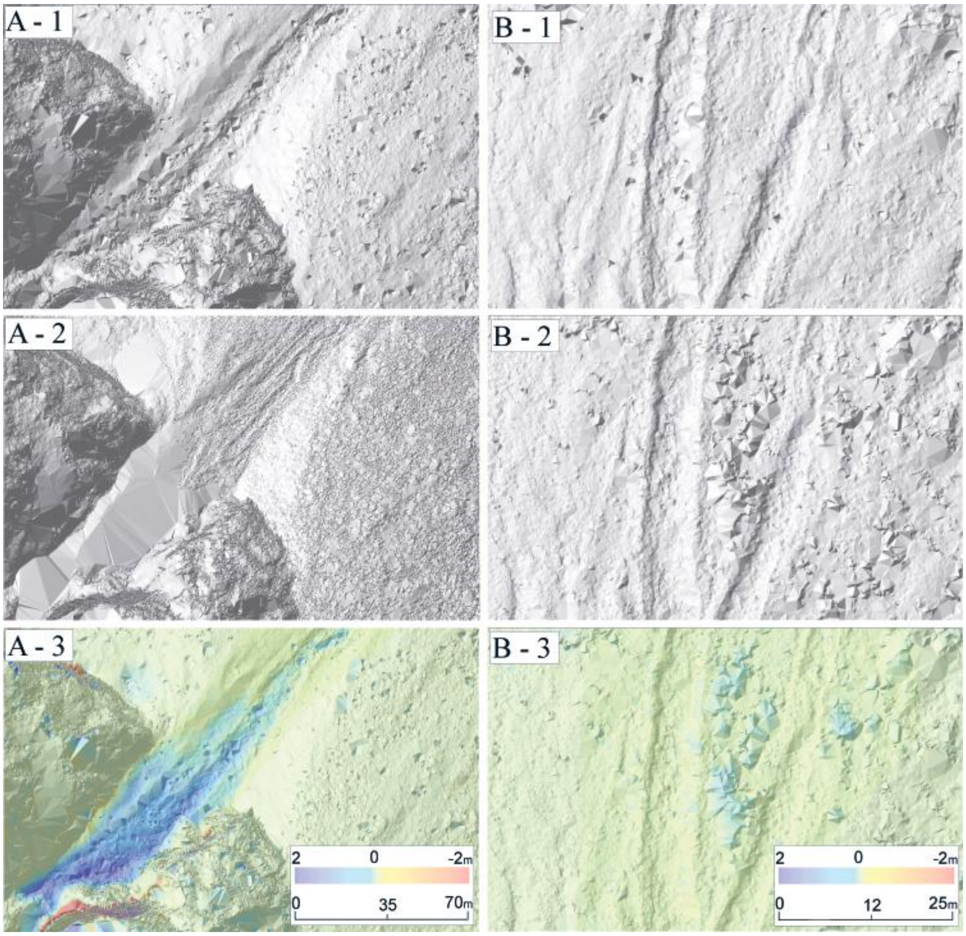


Fig. 8. Detailed digital terrain models and DoD model of the talus cones fragments marked at Figure 5. The Szeroki Piarg: A-1 – 2011, A-2 – 2013, A-3 – DoD; the Zielony Piarg: B-1 – 2011, B-2 – 2013, A-3 – DoD.

On the Zielony Piarg talus cone the most significant erosion covered those slope fragments where rock fall material had accumulated in 2012 (Fig. 7 and 9). Accretion and erosion is observed on the right side of the cone in the form of elongated structures characteristic for debris flows activities (Fig. 7). However, a mass of material eroded in the uppermost part of the cone was transported across the entire cone and accumulated at its base, where a large delta, nine meters wide developed in the lake (Fig. 9).

METEOROLOGICAL CONDITIONS

Analysis of meteorological data showed that precipitation totals the days when debris flows occurred was high enough to trigger debris flows. On August

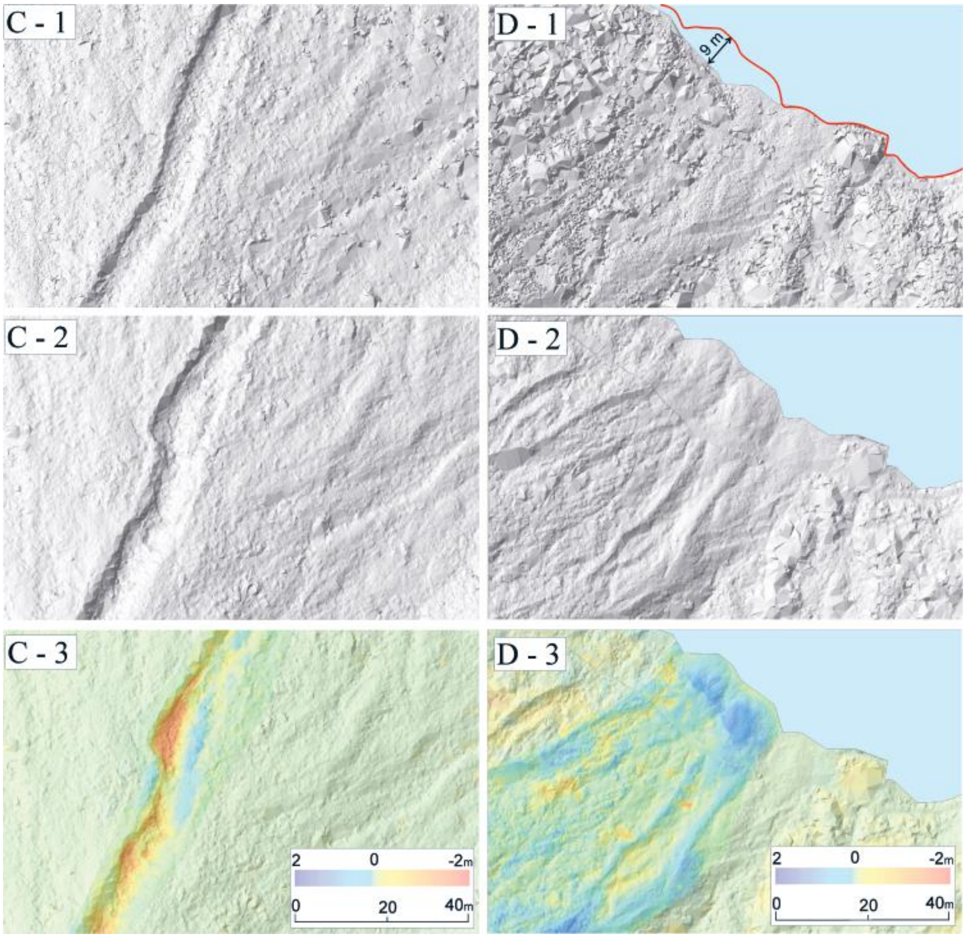


Fig. 9. Detailed digital terrain models and DoD model of the talus cones fragments marked at Figure 6. The Szeroki Piarg: C-1 – 2013, C-2 – 2017, C-3 – DoD; the Zielony Piarg: D-1 – 2013, D-2 – 2017, D-3 – DoD.

23rd, 2011 a daily precipitation of 41.4 mm occurred within less then two hours (Kotarba et al. 2013). It was a local rainstorm near the Morskie Oko as only 5 mm was recorded at the nearby meteorological station at Hala Gąsienicowa (Fig. 10). On July 25th, 2016, the total daily precipitation recorded at the Morskie Oko meteorological station was very similar and amounted to 44 mm (Fig. 11). However, there is no available information about its intensity as only totals were recorded at that time. This rainfall was preceded by a few rainy days with daily totals of from 40 to 85 mm, which occurred about a week earlier.

From May 3rd, 2015, the temperature began to rise rapidly and caused a rapid decrease in snow cover. Rainfall totals on May 6th and 8th, although low (15 mm and 5 mm respectively) were supplemented by melting snows and as a result, a debris flow – a wet dirty snow avalanche was triggered (Fig. 12).

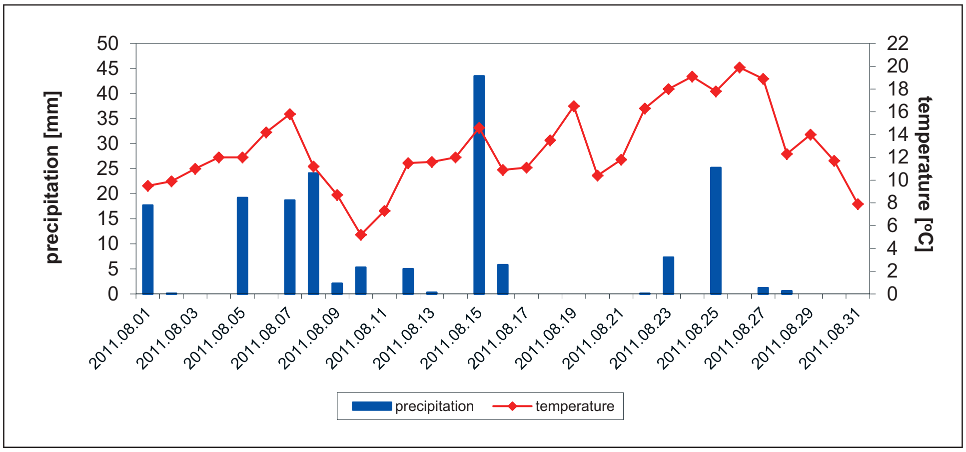


Fig. 10. Daily precipitation and daily mean air temperature in August 2011 at the Hala Gąsienicowa meteorological station

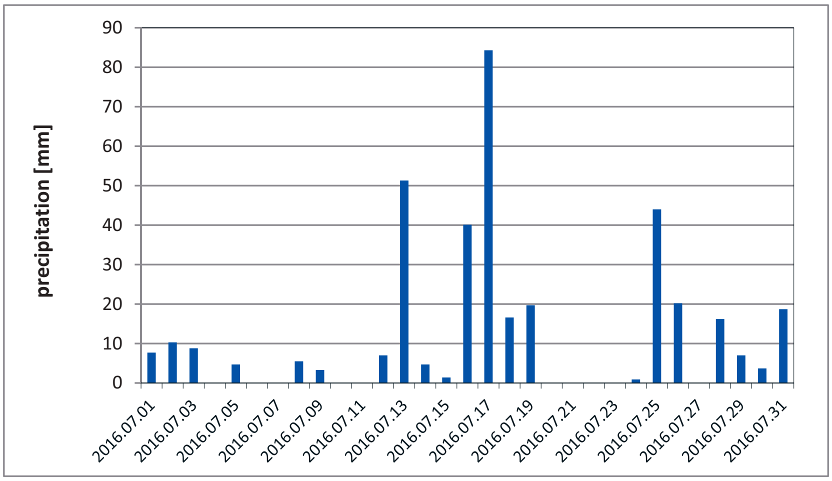
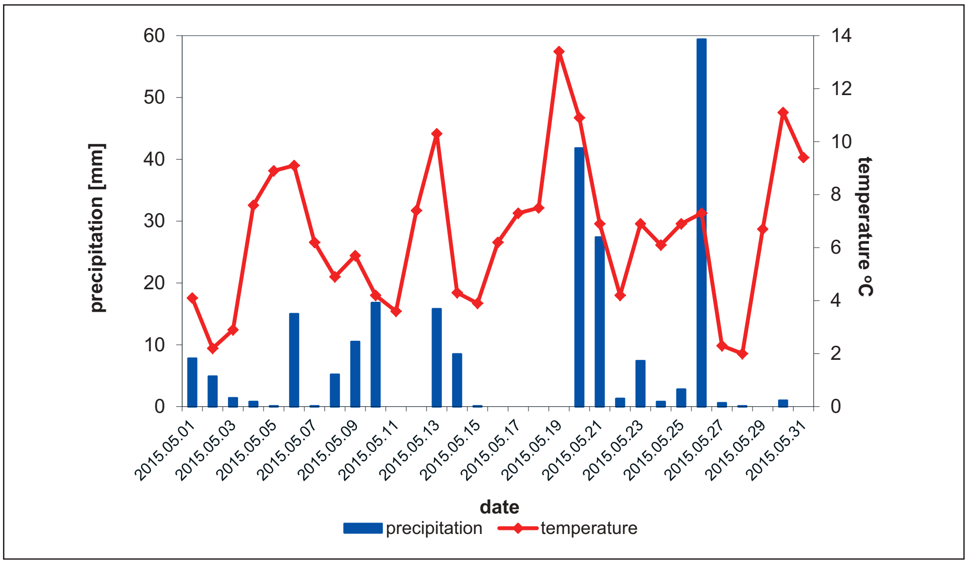


Fig. 11. Daily precipitation in July 2016 at the Morskie Oko meteorological station

However, in the shaded slopes continuous snow cover existed and protected the slope against debris flows which could have been triggered by high amount rainfalls on May 21st and 27th, 2015.

A few days period before the 25th of September 2012 was characterized by rapid changes of daily mean air temperature. It could be assumed that on the 20th and 21st of September air temperature at an altitude around 400 meters higher then Morskie Oko meteorological station was below 0°C followed by a rapid growth (Fig. 13). The temperature changes were accompanied by rainfalls, finished by snowfalls and followed by rapid melting. Therefore, hydrometeorological conditions favored the rockfalls.



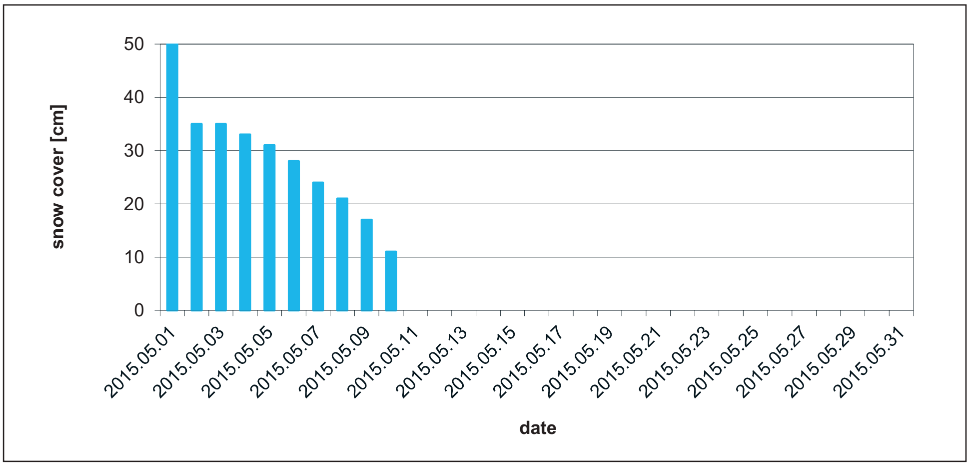


Fig. 12. Daily precipitation and daily mean air temperature and snowcover in May 2015 at the Morskie Oko meteorological station

DISCUSSION

Slope morphodynamics is an effect of secular and rapid high energy geomorphological processes. The activity of debris flows in the study area during the Holocene was confirmed by the sediment pattern in the Morskie Oko lake (K o t a r b a 1992b, 1993–1994). The presence of drop stones in lake sediment suggests that material was transported across the slope system by rapid, high-energy mass movements.

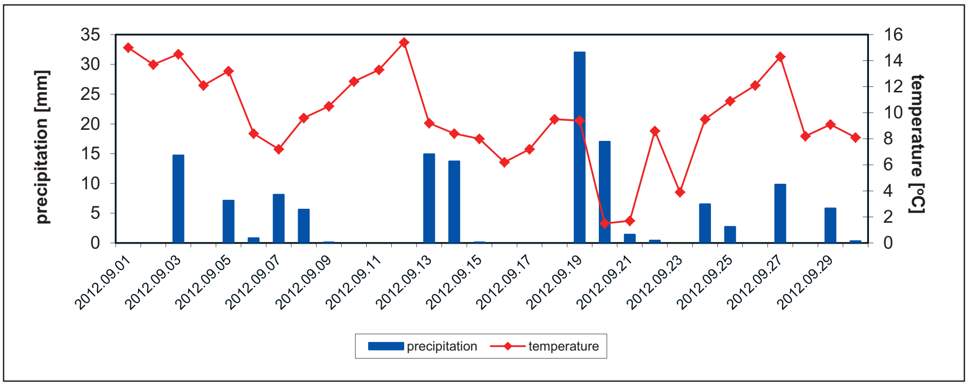


Fig. 12. Daily precipitation and daily mean air temperature and snowcover in May 2015 at the Morskie Oko meteorological station

High resolution, TLS-derived DEMs have the potential to enhance the mapping and the measurement of morphological changes connected to water and sediment dynamics (Baldo et al. 2009; Blasone et al. 2014). Analysis of results of the TLS monitoring of slope morphodynamics confirm the significant role of rapid mass movement, especially debris flows, in modifying the talus slope in the Tatras. In the analyzed time intervals, changes of surface relief of talus slopes appear as a result of rapid mass movements, among which prevails those related to debris flows. No changes of slope surfaces related to other gravitational processes were found, both in our DoD analysis (Figs. 5 and 6) and in the analysis of DoD from time intervals without debris flow events (Rączkowski et al. 2015a).

The steepness of the talus slope and rock slopes above them in the studied area favor debris flow activity. It is widely acknowledged that slope gradients in excess of 20° are normally a prerequisite for debris flow occurrence (Hungr 2005).

Debris flows are commonly triggered by intense surface-water flow caused by heavy precipitation or rapid snow melt, leading to the erosion and mobilization of loose soil or rock on steep slopes (Innes 1983; Iverson 1997). The debris flows in 2011 and 2016 were triggered by rainfalls which fit thresholds established by A. Kotarba (2002), when their totals are considered. The rainstorm in 2011 was of high intensity (Kotarba at al. 2013), which could only be assumed for rain in 2016, as rain intensity was not recorded at that time by IM&WM. In both cases, a period with wet weather occurred around one week before. According to M. G. Winter et al. (2005) optimal conditions for debris flows occur when high magnitude rainfall follows a period of wet weather, which was also suggested by A. Kotarba (2002) regarding the Tatras.

The results of the TLS monitoring showed not only the importance of precipitation in triggering debris flows but also the role of availability of debris material to be moved by a debris flow, in their occurrence and morphological effectiveness. Debris supply and loose sediment availability were considered as key factors in debris flow formation in earlier studies (J a k o b, B o v i s 1996; B o v i s, J a k o b 1999; G l a d e 2005). A rainfall event during July 2016 triggered a huge debris flow on the Zielony Piarg talus cone, while only a very small one occurred on the nearby talus cone of Szeroki Piarg. The reason is the presence of a great amount of loose debris accumulated in the uppermost part of the Zielony Piarg as an effect of rockfall in 2012, which developed within the mylonite zone. Liquefaction of loose meta-stable debris by water concentrated in the chute above trigger debris flow. The part of this rockfall debris, accumulated in the chute above (R ą c z k o w s k i et al. 2015a), was removed by a wet snow avalanche in May 2015, which did not cause changes to the talus cone surface as it was protected by snow cover.

CONCLUSIONS

The complexity of modification of talus slopes by rapid mass movements was displayed by the application of TLS surveys. This permits following spatial-temporal variability of debris material's erosion and accumulation. Additionally, morphometric parameters of new landforms, size of existing landform transformations and volume of displaced material are easily and precisely measured.

Rainfalls and availability of loose debris were confirmed as main contributors of debris flows occurrence.

The TLS survey is an effective tool for monitoring effects of rapid mass movements, such as debris flows and rockfalls. However, when slow mass movements are considered (mainly gravitational processes), the changes of slope surface are too minimal to be measured, even over a few years.

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