Rainfall Thresholds of the 2014 Smutná Valley Debris Flow in Western Tatra Mountains, Carpathians, Slovakia

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ABSTRACT
An extensive debris flow occurred, in the Smutná valley, Western Tatra Mts. in Slovakia on 15 May 2014. The aim of this study is to describe the morphology of the observed debris flow and to evaluate the conditions that preceded its formation as well as the previous activity of debris flows on this path. The observed debris flow is among the most extensive ones in terms of morphometric characteristics in the Roháčská valley and its tributaries (e.g., the length of the erosion-accumulation zone of ~600 m, volume >1200 m^3). However, compared to previous studies from the Western Tatra Mts., it belongs to the average sized debris flows, or a minor event in terms of the general size classification based on the volume of debris flows. A similarly extensive debris flow was recorded on this track in the early 1970s after which only two additional minor events have been recorded there until 2014. The monthly precipitation totals in the 2013/2014 winter season were low compared to the long-term average. The main triggering factor for debris flow initiation was continuous rainfall that lasted 29 hours resulting in ~120–135 mm of precipitation. Most of the derived global empirical thresholds for debris flow initiation were exceeded as well as rainfall thresholds suggested by the published studies for the Western Tatra Mts.

KEYWORDS
debris flow; rainfall thresholds; morphometric analysis; Western Tatra Mts.; Carpathians; Slovakia

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1. Introduction

Debris flows are fast-moving masses of poorly sorted sediments saturated with water, which are among the most frequent slope processes in mountain areas (Iverson et al. 1997; Jakob and Hungr 2005). Steep slopes and the presence of an unconsolidated regolith accumulated in bedrock gullies or stream channels are essential for the occurrence of debris flows (Kotarba et al. 2013). These mass movements are triggered by an intense rainfall which reaches or exceeds certain thresholds (Wieczorek and Glade 2005; Guzzetti et al. 2008). These so-called rainfall thresholds can be defined by the intensity, duration, or amount of rainfall measured over a certain period of time. A rainfall-threshold model based on the intensity and duration of a specific rainfall event (intensity-duration, ID) is most commonly used to evaluate the conditions that preceded the debris flow event (e.g. Caine 1980; Jibson 1989). On the contrary, a model based on the amount of rainfall measured during a rainfall event (event-duration, ED) is used especially when the precipitation intensity is unknown (Caine 1980; Innes 1983; Zezere and Rodrigues 2002). Other types of rainfall thresholds are defined by the total event rainfall (e.g. Corominas and Moya 1996; Pasuto and Silvano 1998) or the intensity of rainfall during the precipitation event (event-intensity, EI; e.g. Jibson 1989; Aleotti 2004). Rainfall thresholds are commonly defined on global (Caine 1980; Innes 1983; Rebetez et al. 1997), regional (e.g. Sandersen et al. 1996; Kanji et al. 2003), or local scales (e.g. Wilson et al. 1992; Annunziati et al. 2000). Global rainfall thresholds represent a general minimum level below which debris flows do not occur irrespective of geology, land-use, or regional rainfall patterns (Guzzetti et al. 2007). By contrast, local rainfall thresholds are site-specific and thus are poorly known in many regions including the Tatra Mts., Western Carpathians.

The research on the precipitation that initiates debris flows in the Tatra Mts. is limited despite the fact that the extensive debris flows occur once in 15–20 years (Krzemień 1988) or even once per 2–3 years in the case of debris flows in the apex of the slope (Kotarba 1991). The research on this phenomenon started in the 1970s (e.g. Ingr and Šarík 1970; Krzemień 1988; Kotarba et al. 1987; Kotarba 1989, 1992, 1997, 1998) but only a few studies focused on the rainfall thresholds for debris flow initiation (e.g. Kotarba 1997) or rainfall conditions preceding the debris flows events (Kotarba 1998). Currently, debris-flow research mostly focuses on changes of debris-flow accumulation zones using aerial imagery (Kapusta et al. 2010; Kedzia 2010) or debris-flow dating by the dendrochronological analysis (e.g. Šilhán and Tichavský 2016, 2017).

In this study, we evaluate the topographic controls and rainfall conditions of the extensive debris-flow event that occurred on 15 May 2014 on the north-eastern slope of Plačlivé peak (2125 m a.s.l.) in the Smutná valley, Western Tatra Mts. as well as the previous activity of debris flows in this path. We compared the obtained threshold values with those established for the Western and High Tatra Mts. in order to obtain more robust threshold values for the region. Finally, we examine the validity of globally defined empirical thresholds for debris flow initiation in this region.

2. Study area

The Tatra Mts. are the highest part of the Carpathian range (Gerlachovský štít peak, 2654 m a.s.l.). The mountains consist of a Paleozoic crystalline basement composed of metamorphic (micaschist, gneiss, migmatite, amphibolite) and igneous rocks (granitic rocks) overlain by late Permian to Cretaceous sedimentary sequences and nappes (limestone, sandstone; Králiková et al. 2014). A tectonic uplift of the Tatra Mts. along the sub-Tatra fault system started in the Middle to early Late Miocene (~12–9 Ma) forming an asymmetrical horst structure surrounded by the Liptov, Poprad, and Podhale basins (Králiková et al. 2014).

Despite their limited extent, the Tatra Mts. represent a barrier for the north-south transport of air masses, which causes steep climate gradients (Niedźwiedź 1992). The mean annual air temperature (MAAT) in the northern foothills is 6 °C, while it is 8 °C in the southern ones. The highest elevations show MAAT of −2 °C (Niedźwiedź et al. 2014; Żmudzka et al. 2015). Similarly, the mean annual precipitation is influenced by prevailing north-west air flow that causes higher precipitation amounts on the northern slopes in comparison to the southern ones (Niedźwiedź 1992). The highest mean annual precipitation of 1600–1900 mm thus occurs on the northern slopes between 1400–2000 m a.s.l. Maximum monthly precipitation falls mainly in June and July when it reaches 240–260 mm and 220–250 mm, respectively (Niedźwiedź 1992). The duration of snow cover varies from 60–140 days in the foothills to about 220 days in the highest parts of the ridge (Ustrnul et al. 2015).

The Smutná valley is one of the side valleys of the more extensive Roháčská valley, Western Tatra Mts. It is located on the northern side of the main ridge of the Western Tatra Mts. (Figure 1) and it is surrounded by the Tri Kopy (2136 m a.s.l.), Ostrý Roháč (2088 m a.s.l.), Volovec (2063 m a.s.l.) and Rákoň (1876 m a.s.l.) peaks. The ridge is built of biotite to two-mica diorites and granites, whereas the valley is filled with Quaternary sediments of taluses, moraines, or rock glaciers (Nemčok 1994; Piotrowska et al. 2015). The investigated debris flow extends from the north-eastern foot of Plačlivé peak (2125 m a.s.l.) to the valley bottom (1503 m a.s.l.).

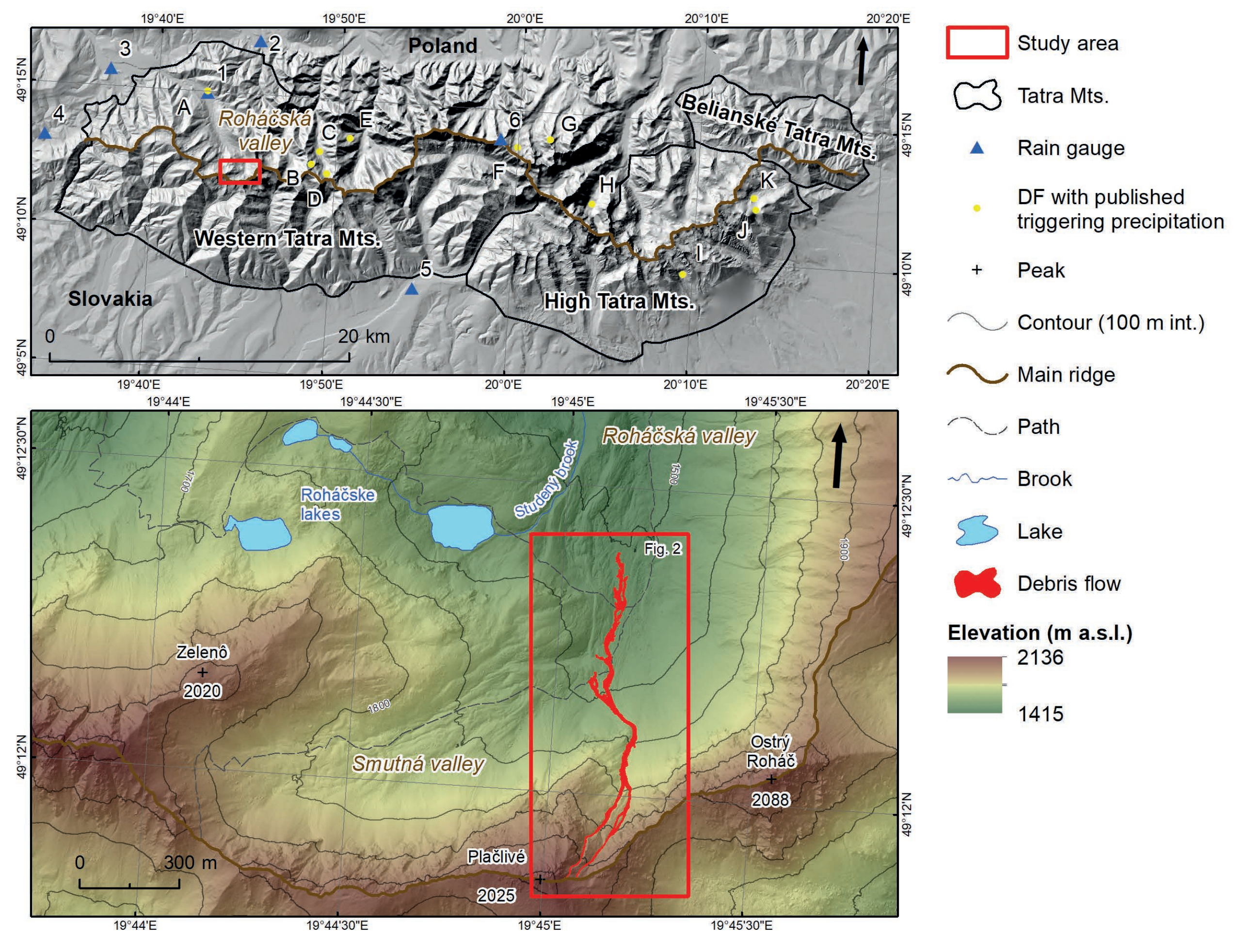

Fig. 1 Location of the study area, selected rain gauges and locations of debris flows with published triggering precipitation in the Tatra Mts. Note: (1) Zuberec-Zverovka (ZZ), (2) Vitanová-Oravice (VO), (3) Zuberec (ZU), (4) Huty (HU), (5) Podbanské (PB), (6) Kasprowy Wierch (KW), (A) Zverovka, (B) Dudowy cirque, (C) Starorobocianska valley, (D) Starorobocianski cirque, (E) *Żleb* Piszczałki, (F) Zielony Staw Gasieicowy, (G) *Żółta* Turnia, (H) Morskie Oko lake, (I) Velická valley, (J) Kežmarský *Štít* Peak, (K) Dolina Zeleného plesa, (DF) Debris flow.

3. Methods

3.1 Morphometric analyses of the debris flow

Geomorphological mapping of the debris flow was performed using orthophotomaps from 2015 (Eurosense), a detailed digital elevation model (DEM) with the horizontal resolution of 1 m (ÚGKK SR 2019) and verified by field mapping. The source zone of the debris flow was delineated based on the DEM using the Watershed tool in ArcMap 10.6 (Esri, Inc. 2018) and then manually adjusted, whereas the erosion-accumulation zone was delineated by manual vectorization at a scale of 1 : 500 based on the orthophotomaps. The area and length of the source and erosion-accumulation zones were determined based on the DEM using the 3D analyst - Add surface information tool in ArcMap 10.6 (Esri, Inc. 2018) to avoid inaccurate calculation due to the steep slopes. A minimal volume of debris transported by the debris flow was also derived from the difference between DEM and reconstructed surface before the event.

The spatial extent of the source and erosion-accumulation zones was verified in the field using GPS (Garmin GPSmap 60CSx) and a laser rangefinder (Stanley TLM 210) in July 2015. The field mapping also included measurements of the height of the lateral levees of the debris flow and the size of 5 largest clasts carried by the flow in three segments of erosion-accumulation zone. Temporal changes of the debris flow since 1973 were evaluated using manual vectorization of the erosion-accumulation zone of the debris flow based on the orthorectified aerial photographs from 1973, 1986, 2003 (TOPÚ 2016), and the orthophotos from 2015 (Eurosense). Based on this data the average recurrence interval of debris flow events in this track path was estimated.

3.2 Precipitation analysis

Data from five closest rain gauges and one more distant station operated by the Slovak Hydrometeorological Institute (SHMI 2014) and the Institute of

Tab. 1 Basic characteristics of selected rain gauges.

Weather station	Latitude (N)	Longitude (E)	Elevation (m a. s. l.)	Distance from debris flow (km)
Zuberec-Zverovka (ZZ)	49°14′59″	19°42′42″	1,030	5.8
Vitanová-Oravice (VO)	49°16′57″	19°45′26″	853	8.7
Zuberec (ZU)	49°15′38″	19°37′18″	763	11.3
Huty (HU)	49°13′80″	19°33′54″	808	13.6
Podbanské (PB)	49°08′24″	19°54′38″	972	13.6
Kasprowy Wierch (KW)	49°13′59“	19°58′58“	1,987	17.2

Meteorology and Water Management (NOAA 2016) were used to analyse the rainfall totals that preceded the formation of the debris flow (Table 1). The nearest station Zuberec-Zverovka (ZZ) located only ~6 km from the source zone of the debris flow was considered the most representative as it is also in the north-facing valley of the Western Tatra Mts. and at elevation of 1030 m a.s.l. The Podbanské station (PB) is the only one representing the southern flanks of the mountains. It was chosen because of its relatively small distance from the debris flow (~14 km) and its position at an elevation of almost 1000 m a.s.l. Because some of the closest meteorological stations do not provide continuous precipitation records without measurement failures, additional calculations were done using continuous time series of one more distant station Kasprowy Wierch (KW) located 17 km from the debris flow (NOAA 2016). Daily precipitation data were available for all selected weather stations operated by SHMI, providing accumulated rainfall totals recorded at 7 a.m. In contrast, 6-hour rainfall data are available from Kasprowy Wierch.

Precipitation conditions from the beginning of a climatological winter to the formation of the debris flow (December 2013 to May 2014) were assessed for an overall evaluation of soil saturation, which may have played a role in the initiation of the debris flow. 10-day precipitation sums recorded at all the six stations were analysed and monthly precipitation totals were also calculated for the same period and compared to long-term monthly precipitation averages recorded in the period of 1985–2014 (SHMI 2014; NOAA 2016). For a more detailed analysis of precipitation totals immediately prior to the formation of the debris flow, data recorded at all the weather stations were used. Daily precipitation sums for the period of 1 May to 15 May were analysed, as well as precipitation totals for 24 hours before the debris flow formation (considering the 5 hours from 15 May when the debris flow occurred in the morning hours and 19 hours from 14 May) were calculated.

Global threshold values for debris flow initiation based on the duration of precipitation during the whole rainfall event were derived (ED; Caine 1980, $E = 14.82 \times D^{0.61}$; Innes 1983, $E = 4.93 \times D^{0.504}$). The variable E [mm] in the ED threshold models indicates the amount of precipitation during a given event and the D [h] denotes the duration of the event. These equations indicate rainfall amounts above which debris flows are likely to occur. On the contrary, 4σ method provides a statistically defined threshold for the formation of debris flows that defines relatively extreme values based on long-term precipitation records (Rebetez et al. 1997). In this case cumulative precipitation over three consecutive days in the period of May, June and July 1989–2014 based on KW long-term data series was chosen (Rebetez et al. 1997; Engel et al. 2011). The threshold value for spring/summer period with potential debris flows occurrence was derived. Subsequently, it was compared with the observed 3-day precipitation sums before the Smutná valley debris flow measured at KW station.

4. Results

4.1 Debris flow morphology

The source zone of the debris flow is located at 1657–2013 m a.s.l. on the north-eastern slope of Plačlivé peak and covers the area of 147 570 m^2 (Table 2). It consists of chutes that are from a few decimetres up to a few meters deep, and two small detachment zones with a recently exposed bedrock that are a few decimetres deep and the material of which was probably removed during the debris-flow event (Figure 2 and Figure 3).

The erosion-accumulation zone extends at 1503–1657 m a.s.l. and has the total length of 593 m. The volume of the debris material transported and accumulated during the event is estimated at >1200 m^3. The debris flow runs in the northerly direction along the Mt. Plačlivé ridge, then it sharply changes direction to the northwest and enters the open slope of the debris flow fan. Here, the track is 2–2.4 m deep (Figure 2), ~10 m wide, and reaches an average slope of 25°. Significant lateral levees along the debris flow are 0.2–0.5 m high and generally tend to become higher down the slope. The maximum size of the blocks transported by the debris flow reaches 1.5–3.5 m. The side track of the debris flow diverges in the fan area, which is probably the original straight track of the debris flow formed during the initial phase of the event. The side track was subsequently

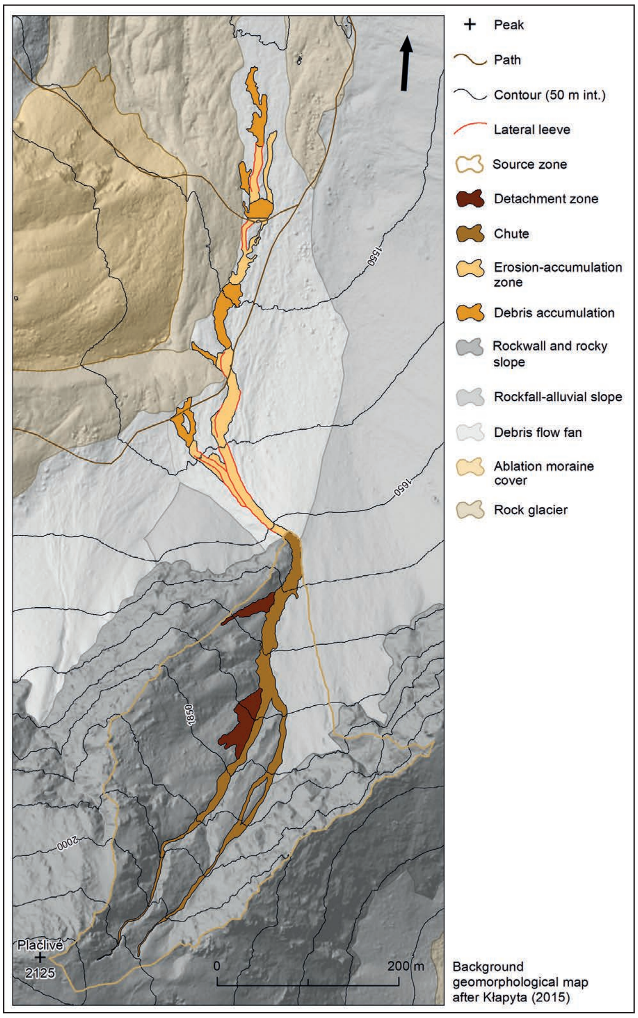

Fig. 2 Geomorphological map of the debris flow in the Smutná valley.

blocked by a stronger surge of the debris flow that deepened the track towards the north.

In the next segment the debris flow undulates slightly in front of a rock-glacier terminus. In this section, the track is ~13 m wide and only 1–1.5 m deep. There is an accumulation of debris inside the track, so it takes on a convex shape, with an average slope of 18°. There is a significant accumulation of debris at an elevation of 1560–1549 m a.s.l. The debris flow here takes on a predominantly convex shape, with the width of about 12 m and the average slope of 12°. This part of the debris flow is already entirely located on the surface of a rock glacier. In the following segment, the debris flow passes through several previously eroded troughs 4–9 m wide that were grassed before the formation of the debris flow. There are lateral levees approximately 0.2 m high. The maximum size of the transported debris is mostly 15 cm and the slope of this part of the track reaches 11°. In the last section of the track, there is only a flat accumulation of the fine-grained debris ~7 cm in size mixed with a sandy matrix. The average width of this final part of the debris flow is 10 m and the average slope is ~8°.

Tab. 2 Morphometric characteristics of the investigated debris flow in the Smutná valley.

Characterictic	Source zone	Erosion-accumulation zone
Area (m^2)	147,570	9,687
Length (m)	785	593
Widht (m)	300	13
Maximum elevation (m a.s.l.)	2,123	1,657
Minimum elevation (m a.s.l.)	1,657	1,503
Mean elevation (m a.s.l.)	1,892	1,564
Elevation range (m)	466	156
Maximum slope (°)	88	37
Mean slope (°)	47	19

4.2 Long-term precipitation conditions prior to the debris flow

The most significant snowfall of the 2013/2014 winter season was recorded in the first decade of December 2013 (Figure 4). At that time heavy snowfall occurred mainly in the northern windward areas of the Tatra Mts., bringing up to a few decimetres of snow. By contrast, there was little precipitation for the rest of the month (Figure 4). Overall, monthly precipitation totals lower by 26% (PB) to 59% (ZZ) were recorded in December 2013 compared to the long-term average for 1985–2014 (SHMI 2014). In January 2014, even lower (up to 70% at ZZ station) precipitation totals were recorded compared to the long-term average as no significant snowfall occurred until the second decade of January. During February 2014, precipitation totals were also lower compared to the long-term monthly average with the maximum decrease of 36% at the PB station. The lowest precipitation were recorded mainly in the last decade of the month. On the contrary, precipitation totals in March 2014 were above the long-term average at all the stations by an average of 20%. Increased precipitation was also recorded in April 2014, especially in its second decade when it was up to 30% above the long-term average. Precipitation in May 2014 was also well above the average for 1985–2014 (up to 167% at ZZ station). The highest 10-day precipitation was recorded in the second decade of May when the debris flow occurred (Figure 4).

4.3 Precipitation totals immediately prior to the debris flow

Low daily precipitation totals mostly below 7 mm (ZZ of 2. 5. 2014) were recorded at the weather stations in early May 2014. The exception was PB where the total of 31 mm d^{-1} occurred on 3 May. Precipitation decreased between 8 May to 10 May, with daily totals below 3 mm. After a subsequent short-term increase to ~25 mm d^{-1}, precipitation reached immeasurable amounts. On 14 May, precipitation increased sharply to

Fig. 3 A view of the individual parts of the debris flow.
Note: (1) recently exposed bedrock in the detachment zone, (2) erosion-accumulation zone of the debris flow, (3) debris flow track in the debris flow fan area, (4) debris flow accumulation.

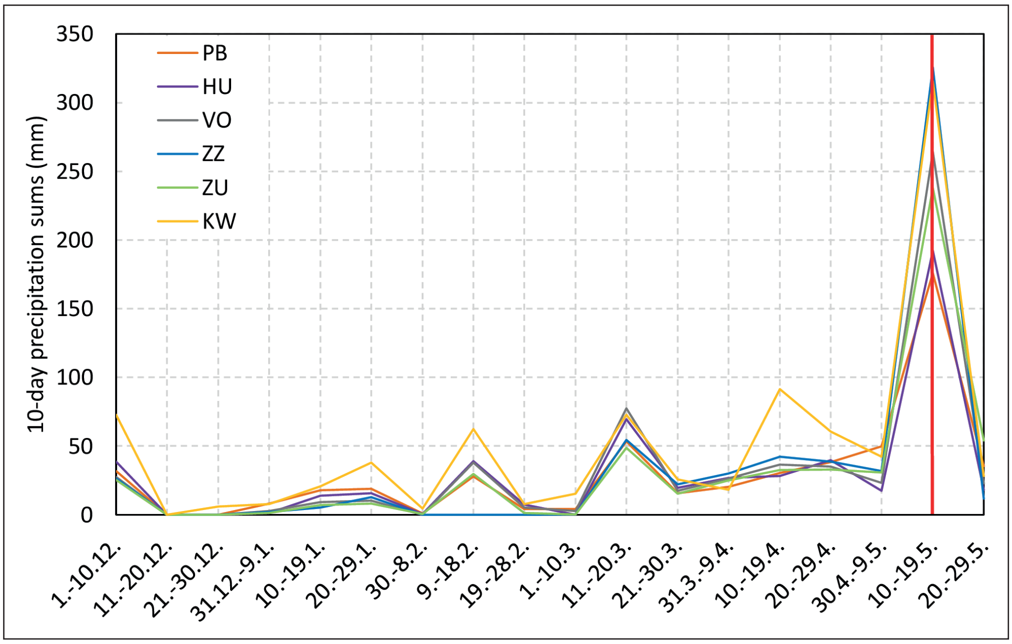

Fig. 4 10-day precipitation sums measured from 1 December 2013 to 29 May 2014.
Note: Red line indicates the occurrence of the debris flow.

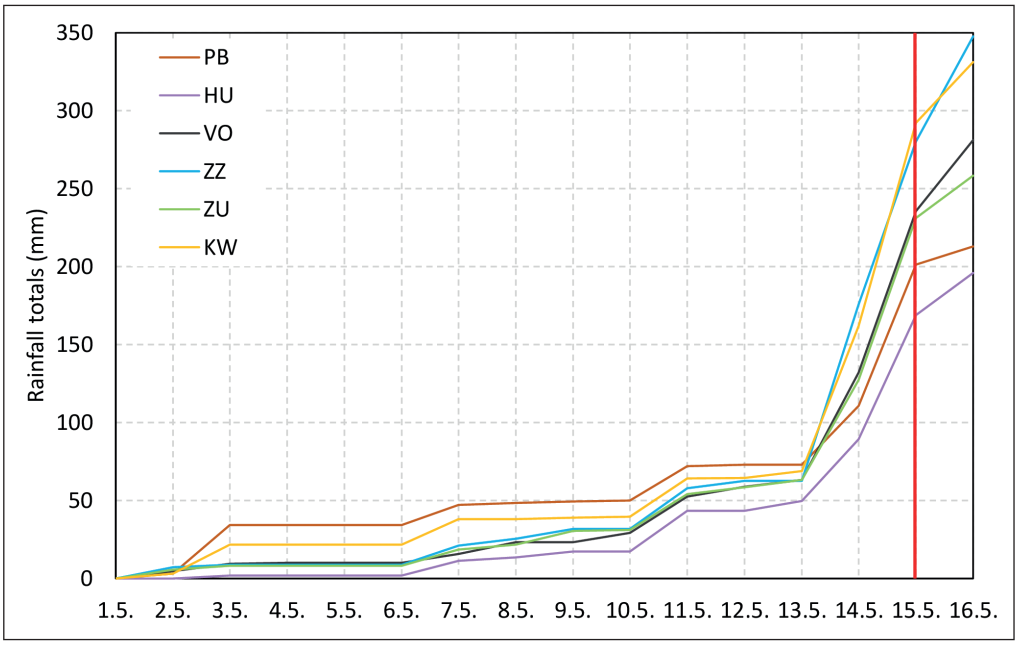

Fig. 5 Cumulative precipitation totals in May 2014.
Note: Red line indicates the occurrence of the debris flow.

>60 mm d^{-1} at the VO and ZU stations or to >90 mm d^{-1} at the KW station. The ZZ station showed the highest total of 113 mm d^{-1} (Figure 5, Table 3). The precipitation was even higher during the following day when the totals >100 mm d^{-1} were recorded at the KW (130 mm), ZZ (104 mm), ZU (104 mm), and VO (103 mm) stations. The debris flow occurred in the morning hours of 15 May 2014. The 24-hour precipitation prior to its formation ranged between 48 mm (HU) and 111 mm (ZZ).

Tab. 3 Precipitation totals before the debris flow formation (15 May 2014).

Station	13 May (mm)	14 May (mm)	15 May (mm)	24 h prior formation (mm)
Zuberec-Zverovka	0	113	104	111
Vitanová-Oravice	5	69	103	76
Zuberec	5	64	104	72
Huty	6	40	80	48
Podbanské	0	38	91	49
Kasprowy Wierch	4	93	130	101

4.4 Rainfall thresholds derived using global rainfall models

Continuous precipitation prior to the formation of the debris flow started at all the weather stations at 7 a.m. on 14 May and continued to 12 a.m. on 15 May. Over 29 hours, 56–135 mm of precipitation was recorded at these stations (Table 4). Corresponding threshold values of 116 mm and 27 mm were derived using the event-duration models proposed by Caine (1980) and Innes (1983), respectively. The threshold value based on the statistical 4σ method (Rebetez et al. 1997) was set at 131 mm.

Tab. 4 Threshold values and precipitation totals derived for the study area.

Station	3-day precipitation (mm)	Threshold value after Rebetez et al. (1997; mm)	Continual event precipitation totals (mm)	Duration of continual precipitation (h)	Threshold value by Caine (1980; mm)	Threshold value by Innes (1983; mm)
Kasprowy Wierch	228	131	***120***	29	116	27
Zuberec-Zverovka	–	–	***135***			
Vitanová-Oravice			*90*			
Zuberec			*86*			
Huty			*56*			
Podbanské			*57*			

Note: The values in bold indicate rainfall totals higher than the Caine's (1980) threshold for debris flow initiation. The rainfalls that exceeded the threshold proposed by Innes (1983) are indicated in italic. Threshold value set by Rebetez et al. (1997) was derived based on the long-term precipitation records for 1989–2014 available only for the Kasprowy Wierch station.

4.5 Temporal changes of the debris flow track

The analysis of historical aerial photographs identified four debris flow events in the investigated track between 1973 and 2015 (43 years), including the debris flow described in this study (Figure 6). The most extensive debris flow over the entire period was recorded in the 1973 aerial photograph (the erosion-accumulation zone was by ~14% larger than in 2015). The front of this accumulation extended ~355 m from the foot of the slope, whereas it was ~330 m in 2015. The length of the whole erosion-accumulation zone was ~624 m in 1973 as opposed to ~593 m in 2015. In contrast, aerial photographs from 1986 and 2003 show a new debris flow extending only to the foot of the slope. An extensive debris flow path from 15 May 2014 is recorded on the 2015 orthophotos. Based on the remotely sensed data, the recurrence interval of the debris flows is nearly 11 years.

5. Discussion

5.1 Morphology of the debris flow

The extent of the source and erosion-accumulation zone of the Smutná valley debris flow is greater than that of other debris flows in the Roháčská valley and its tributary valleys (including the Smutná valley; Dlabáčková 2018). As one of the few debris flows in the Roháčská valley area, it extends from the debris flow fan to the valley floor filled with the body of a rock glacier. However, it is rather an average debris flow in the Western Tatra Mts. in terms of the elevation of the source and erosion-accumulation zone or the volume of the transported material (Kotarba et al. 2013; Kotarba 1992). Its source zone located at 1657–2123 m a.s.l. is within the elevation range of 1293–2217 m a.s.l. of source zones of debris flows in the Western Tatra Mts. set by Kotarba et al. (2013). Similarly, the average elevation of the source zone of 1892 m a.s.l. is close to the average elevation of 1817 m a.s.l. reported by Kotarba et al. (2013). The head of the debris-flow erosion-accumulation zone, situated at an elevation of 1503 m a.s.l., is among the lower debris-flow heads, but also within the interval of the average values (1213–2095 m a.s.l.) determined for the Western Tatra Mts. (Kotarba et al. 2013). Slightly above average is the compound elevation range of the source and erosion-accumulation zone of the debris flow of 620 m compared to the average value of ~500 m reported for the Western Tatra Mts. (Jurczak et al. 2012; Kotarba et al. 2013). By contrast, the length of the debris-flow erosion-accumulation zone of 593 m is well above the average length in the Western Tatra Mts. estimated at 200 and 166 m by Kotarba et al. (2013) and Jurczak et al. (2012), respectively. Yet, the observed length of the debris-flow erosion-accumulation zone falls into the most common debris-flow lengths in the Western Tatra Mts. set by Midriak (1993) at 500–1000 m. Likewise, the average path width of the debris flow erosion zone of 12 m is also within the interval of average debris-flow widths set by Midriak (1993). The estimated volume of the

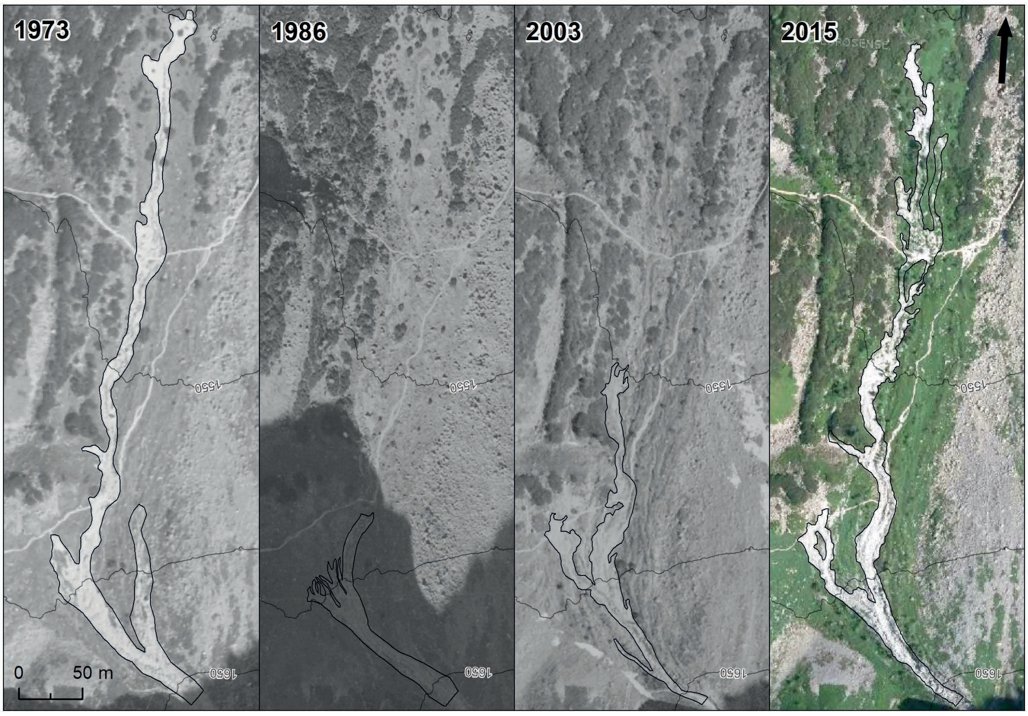

Fig. 6 Temporal changes in the erosion-accumulation zone of the Smutná valley debris flow in the period 1973–2015.

transported material of >1200 m^3 is consistent with the volume estimates for recent debris flows in the Tatra Mts. (Kotarba 1992), representing minor debris-flow events (sensu Jakob 2005). The volume estimates for the largest debris flows in the Tatra Mts. range from 2500 to 5000 m^3 (Ingr and Šárik 1970; Kotarba 1994).

5.2 Triggering precipitation

The rainfall threshold of 27 mm derived using the global event-duration model proposed by Innes (1983) was exceeded at all regional stations. In contrast, the value of 116 mm determined using the event-duration model by Caine (1980) was exceeded only at the stations ZZ and KW (Table 4). These two stations seem to be the most relevant for describing the conditions immediately prior to the 2014 debris flow as both are located at elevations above 1000 m a.s.l. The low precipitation values recorded at other stations are a result of their low elevation, a large distance from the debris flow (HU, PB, and ZU), or the leeward effect of the mountain range (PB). The precipitation threshold of 131 mm derived by the 4σ method (Rebetez et al. 1997) from the KW data proved to be valid as the measured 3-day rainfall total was 228 mm.

Overall, the models proposed by Caine (1980) and Rebetez et al. (1997) are valid for the Tatra Mts. area. On the contrary, model set by Innes (1983) does not seem to be valid for the Tatra Mts. region as the threshold value of 27 mm is too low. Precipitation greater than 27 mm d^{-1} has occurred at KW station approximately 5 times per year during the period 1989–2014 in the months of May to July. This contrasts with the average frequency of one small debris flow per 2–3 years (Krzemień 1988) or one large debris flow event per 15–20 years (Kotarba 1991). The occurrence of debris flows 5 times per year in the Tatra Mts. region thus seems unlikely. In contrast, precipitation exceeding 116 mm d^{-1} occurred approximately once every ten years during the same period, which is close to the published data on the frequency of the formation of debris flows, and information derived from aerial photographs of the monitored debris flow in the Smutná valley. Similarly, 3-day rainfall greater than 131 mm occurred on average once per 2–3 years during this period, which is also consistent with the published data on the frequency of debris flows in the Tatra Mts.

The observed debris flow in the Smutná valley occurred in the morning on 15 May 2014 according to local people. The 6-hour rainfall data from the KW station show that the lowest rainfall of the day (only of 27 mm) was recorded between 6 a.m. and 12 p.m. In contrast, the highest precipitation of 39 mm was recorded between 12 and 6 p.m. (Figure 7). These data indicate that the debris flow may not have occurred during the most intense rainfall.

The precipitation total that led to the 2014 Smutná valley debris flow fits into the rainfall ranges of 60–164 mm d^{-1} and 62–224 mm d^{-1} published for the Western and High Tatra Mts. (Table 5). It was higher compared to the well-described debris flow event on Babia Góra, Poland (>40 mm d^{-1}; Łajczak and Migoń 2007), or debris flows in Southern Carpathians, Romania (74–91 mm d^{-1}; Ilinca 2014). However, it was lower compared to the threshold values of 111–234 mm d^{-1} suggested by Šilhán and Pánek (2010) for the flysch Western Carpathians, Czechia. Outside the Carpathians, debris flows might be triggered after 100 mm d^{-1} in the Jizerské hory

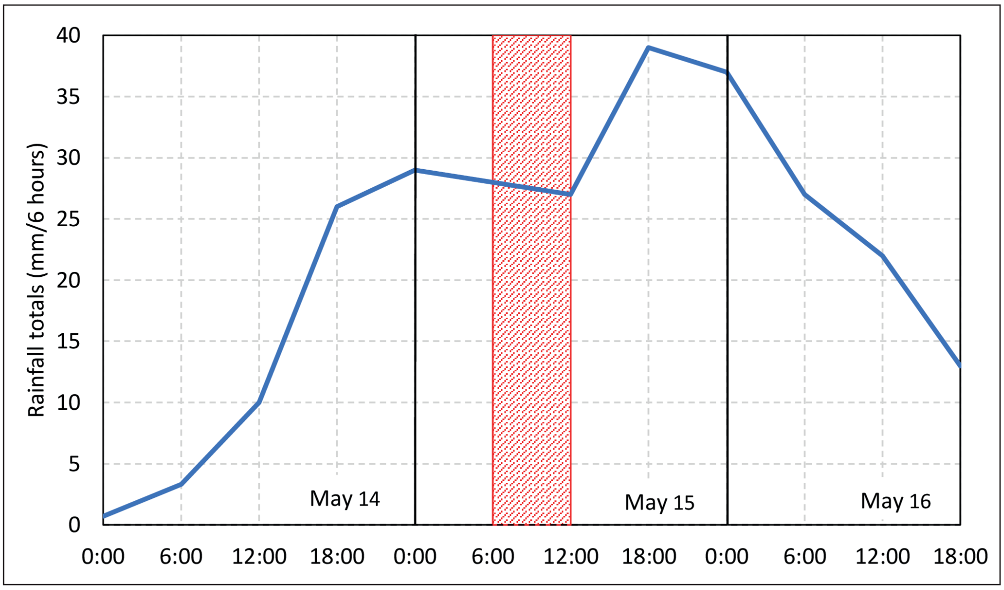

Fig. 7 6-hour precipitation totals recorded at the KW station in 14 May to 16 May.
Note: The approximate time of the debris flow occurrence is indicated by the red hatched area.

Tab. 5 Rainfall thresholds for historical debris flows in the Tatra Mts.

Triggering Rainfall	Location	Date	Author
Western Tatra Mts.			
60–61 mm d^{-1}	Dudowy cirque	20 July 1985	Krzemień (1988)
82.3 mm d^{-1}	Starorobocianski cirque	26 July 1982	Krzemień (1988)
91.6 mm d^{-1}	Starorobocianski cirque	23 July 1980	Krzemień (1988)
215.5 mm 2d^{-1} (61 mm d^{-1} and 154.5 mm d^{-1})	Zverovka	19 June 1970	Ingr and Šarík (1970)
up to 135 mm 29h^{-1} (111 mm 24h^{-1})	Smutná valley	15 May 2014	This study
164 mm d^{-1}	Starorobocianski cirque	June 1973	Krzemień (1988)
73.8 mm 5h^{-1}	Żleb Piszczałki	4 June 1993	Krzemień et al (1995)
High Tatra Mts.			
62 mm d^{-1} (26 mm h^{-1})	Kežmarský Štít Peak	15 July 1933	Záruba, Mencl (1969)
100 mm d^{-1}	Morskie Oko lake	August 2001	Ferber (2002)
118.7 mm d^{-1} (44 mm h^{-1})	Zielony Staw Gasieicowy	16 August 1988	Kotarba (1994)
223.5 mm d^{-1} (330.3 mm 5d^{-1})	Żółta Turnia	8 July 1997	Kotarba (1998)
41.4 mm 1.5h^{-1}	Morskie Oko lake	23 August 2011	Kotarba et al (2013)
60 mm h^{-1}	Żółta Turnia	9 August 1991	Kotarba (1998)

Tab. 6 Overview of the general rainfall intensity thresholds for debris flow (DF) initiation for the Tatra Mts. region.

Threshold value	Region	Debris flow specification	Reference
50–80 mm d^{-1}	Western Tatra Mts.	DF of various sizes occurring between the end of May – end of July (snow patches occurence)	Krzemień (1988)
80–100 mm d^{-1}	Western Tatra Mts.	DF of various sizes occurring in the period of July–October	Krzemień (1988)
60–135 mm 29h^{-1}	Western Tatra Mts.	DF over the full length of slope	This study
80–100 mm d^{-1}	High Tatra Mts.	DF over the full length of slope	Kotarba (1997)
35–40 mm h^{-1}	High Tatra Mts.	DF over the full length of slope	Kotarba (2007)
25 mm h^{-1}	Tatra Mts.	Small-scale DF (apex area of talus slope)	Kotarba (1991)
50 mm h^{-1}	Tatra Mts.	DF over the full length of slope	Kotarba (1991)

Mts., Czechia (Smolíková et al. 2016), having similar geological conditions as the study area in the Western Tatra Mts. Similarly, daily rainfall totals exceeding 50–100 mm can trigger debris flows in the Hrubý Jeseník Mts., Czechia, built by metamorphic rocks (Tichavský et al. 2017). The 24-hour rainfalls that triggered the 2014 debris flow are higher than the threshold of 50–80 mm d^{-1} based on long-term observations of debris flows in the May-July period in the presence of snow patches on slopes. The triggering rainfalls are even higher than the rainfall threshold of 80–100 mm d^{-1} for the initiation of debris flows of various sizes in the Western and High Tatra Mts. (Table 6).

5.3 Temporal changes of the debris flow track

The erosion-accumulation zone of the investigated debris flow from May 2014 was among the most extensive ones in the last 43 years (Figure 6). A larger area of debris flow erosion-accumulation zone occurred at this site only in the early 1970s when shallow landslides occurred frequently in the Tatra Mts. (Kotarba 2004; Gądek et al. 2016). By contrast, only one short debris flow was identified in the same track between 1973 and 1986. The observed decrease in the debris flow surface area confirms the timing of a reduced debris-flows activity reported by Kapusta et al. (2010) from the Dolina Zeleného plesa in the High Tatra Mts. (Figure 1). In contrast, these authors did not detect any significant changes in the area of debris flows in the Velická valley in the High Tatra Mts. Krzemień (1988) states that the number of debris-flow events in the Starorobocianska valley, the Western Tatra Mts., was stable since the 1950s to the mid-1980s.

Aerial photographs taken in 2003 show another debris flow accumulation within the observed track. This debris flow was shorter than the one from the early 1970s but extended to the foot of the slope. Since the mid-1980s to the early 21st century, there was an increase in the area of debris flow erosion-accumulation zones in the High Tatra Mts. (Kapusta et al. 2010; Kedzia 2010). According to Kotarba (1997), this increase may be attributed to more frequent and intense rainfalls in the summer season. The record from the KW station confirms the frequent occurrence of intense rainfall events in the study area during the period 1986–2003. Precipitation >80 mm d^{-1} was recorded at the KW station 15 times over the 18-year period, 8 of which were even >100 mm d^{-1}.

In the period of 2003–2015, the number of days with rainfalls exceeding the threshold value of 80–100 mm d^{-1} decreased to seven at the KW station. Despite the lower frequency of heavy rainfalls, the rainfall totals higher than 130 mm d^{-1} occurred in August 2009 and May 2014. As a result of fewer rainfall events, there was no increase in the area of debris flows at the study site until 2014. Similarly, Kedzia (2010) reported no significant changes of debris flows in the Żółta Turnia, High Tatra Mts., between 2003 and 2009. By contrast, a significant increase in the area of debris-flows in the Velká Studená valley, High Tatra Mts., between 2004 and 2014 is reported by Šilhán and Tichavský (2017).

6. Conclusion

The debris flow in the Smutná valley, Western Tatra Mts., was initiated on 15 May 2014 after continuous precipitation that lasted 29 hours. A corresponding rainfall ranged from ~120 to 135 mm and exceeded the threshold values for debris flow initiation derived from global event-duration models (27 and 116 mm). A 4σ threshold of 131 mm for the accumulated precipitation on three consecutive days prior to the debris flow initiation was also exceeded. The 24-hour rainfall amount of 101–111 mm recorded prior the debris flow is rather high compared to the reported values from the Tatra Mts., Babia Góra, and the more distant Southern Carpathians.

The debris flow that was formed in the Smutná valley in 2014 is one of the largest debris-flow accumulations in the northern part of the Western Tatra Mts. The erosion-accumulation zone extends far to the valley floor, stretching over the length of ~600 m. A similarly long debris flow was identified in this track only in the early 1970s. Two other debris flows deposited in this track between 1986 and 2003 only reached the foot of the slope.

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