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Conditions and morphogenetic role of the 2018 and 2021 debris flows in Starorobociański Cirque, Western Tatra Mts.

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Abstract: In this study we used geomorphologic mapping, precipitation analysis and archival photomaps to study debris flows in the Starorobociański Cirque, which were renewed in 2018 and 2021. Debris flow in 2021 was most likely the largest single flow recorded in the Polish Western Tatras in the twenty first century. It reached a length of about 870 m and it covered an area of 0.62 to 0.65 ha. We set July 14, 2021, as the date of debris flow initiation and 52.1 mm·d^{-1} as its threshold value. This is one of the lowest values provided in the literature for such flows in the Western Tatra Mts. On the contrary, debris flow which occurred July 18, 2018 was linked to threshold value of 150.5 mm·d^{-1}. On the basis of former debris flow occurrence as well as precipitation analysis we interpret the appearance of debris flow in 2021 as an effect of short and intense rainfall.

Key words: debris flow, rainfall threshold, Starorobociańska Valley, Western Tatra Mts.

Introduction

Debris flows represent events when poorly sorted, unconsolidated mineral material saturated with water flows downslope at high speed (Iverson 2005). Their occurrence is associated with the presence of debris on the slope and the exceedance of so-called threshold precipitation values, i.e. the amount of precipitation above which rock mass is liquefied (Hungr 2005).

Debris flows currently represent the main geomorphologic process shaping slope relief in the Tatra Mountains in Poland (Rączkowska 2006). They transport material from valley heads downslope, fossilizing glacial deposits and building up mixed alluvial-colluvial cones (Libelt 1988, Kłapyta 2012, Krzemień, Kłapyta 2018). The movement of material takes place in a pulsating manner, producing wavelike flow, leading to the emergence of lateral levees, while furrows are carved out along the flow path (Rączkowska 2006). The debris flows observed in the Tatra Mountains are a good example of hillslope flows. This type of flows forms when debris accumulated within chutes is saturated with rainwater and flows to the foot of rock walls (Kotarba et al. 2013). However, in the research literature, flows that always occur in the same channel, outgoing from the gullies, were also called valley-confined debris flows (Kotarba 2004).

Basically, the long profile of a debris flow is divided into three zones: initiation (source area), transport (track zone), and accumulation (accumulation zone) (Krzemień 1988, Hungr 2005). In the Western Tatras, Krzemień (1988) identified three types of debris flow depending on the initiation zone and flow path. Type A represent flows originating in upper slopes, moving through rock walls and end on debris slopes. This type of flows originating in areas featuring regolith has the highest potential energy because of the highest elevation of initiation zone. Type B refers to flows occurring on steep slopes with unconsolidated deposits of different origin without rock wall section. The third one, type C, is the most common type of flows occurring in the Western Tatras. Flows of this type originate in a rock gully and end within the debris slope below. This classification was expanded and supplemented with a fourth type in a paper by Jurczak et al. (2012) – type D. This type refers to the smallest flows which occur when material within a debris cone becomes liquified and starts to move. Currently, debris flows in the Tatras are capable of moving 0.7–1.5 m clasts over a distance of more than 1 km and depositing them in channels with a depth of 3–4 m and a maximum width up to 10 m. The volume of the transported material ranges anywhere from 100 to 25,000 m^3 (Rączkowska 2006 and references therein).

In recent decades researchers studying debris flows in the Tatra Mountains have been focusing mainly on their morphogenetic role (e.g. Kotarba 1988, 2007, Kapusta et al. 2010). However, only a few events of this type have been documented in the literature (Jurczak et al. 2012). Problems with observing flows led to the development of post-event research, carried immediately after them, and attempting to determine the conditions for the formation of debris flows. Pioneering studies by Kotarba (1976) on the Polish side of the Tatras and Lukniš (1973) on the Slovak side initiated a period of greater interest in these processes in geomorphologic research. For the first time in the Tatras, flows were being experimentally studied on the slopes of Skrajna and Żółta Turnia in the High Tatras (Kotarba et al. 1979, 1987). Studies addressing temporal and spatial changes in local debris flows based on detailed geomorphologic maps were conducted by Kotarba et al. (1987) and Kapusta et al. (2010), and in more recent years by Dlabáčková and Engel (2022) and Rączkowska and Cebulski (2022).

In addition, the geomorphologic studies were always accompanied by attempts to determine precipitation thresholds for debris flow occurrence. These were given for the High and Western Tatras on both sides of the massif. The lowest values were determined for the Polish part by Kotarba (1992, 2007) and equalled 25 mm and 30 mm, both values for the High Tatras (Kotarba 1994). In this particular paper, it was also stated that debris flows covering the entire length of the slope are initiated by precipitation of 35–40 $mm \cdot h^{-1}$ and at least 80–100 $mm \cdot d^{-1}$. These values were determined based on a 20-year observation period in the High Tatras (Kotarba 2004). Slightly lower values of around 20 $mm \cdot h^{-1}$ were given in studies from the Slovak High Tatras (Kapusta et al. 2010) and Western Tatras (Janačik 1971). In turn, the most recently published lowest value is found in a paper by Dlabáčková and Engel (2022) and refers to a flow that occurred in Smutná Valley in the Slovak Western Tatras in 2014 equalling 60 $mm \cdot 29h^{-1}$. This threshold corresponds directly to values given by Krzemień (1988) for a flow recorded on July 20, 1985 in Dudowy Cirque, which is located near Starorobociański Cirque, 5 km from Smutná Valley. In studies conducted directly in our study area, threshold values of 50 $mm \cdot d^{-1}$ (for the flows of different size occurring between May and July) and 82.3 $mm \cdot d^{-1}$ for large flows reaching the bottom of the Starorobociański Cirque were recorded (Krzemień 1988).

The consensus reached over the last fifty years of research is that debris flows have the greatest impact on shaping the slopes of the Tatra Mts. However, in the Polish Western Tatra Mts. no geomorphological mapping of debris flows landforms has been made since 1980s, despite the availability of photomaps and digital elevation model. What is more, only a few rainfall thresholds have been proposed. These aspects – geomorphologic record and precipitation analysis – are crucial to set specific conditions for debris flow initiation, and examine how exactly these events contribute to the contemporary evolution of high mountain relief. To answer these questions, we investigated a debris flow track which was renewed in 2018 and 2021 in Starorobociański Cirque. The latter event was probably the largest single flow recorded in the Polish Western Tatras in the twenty first century. Particularly, we analyze:

- the geomorphological record of the 2021 flow and precipitation conditions for both flows,
- past temporal and spatial changes in the debris flow gully,
- key parameters of the 2021 flow and precipitation thresholds of both flows to compare with other events occuring in the Tatra region.

Study area

The Western Tatras with the High Tatra and the Bielskie Tatra mesoregions form the Tatra Mts. – the northernmost high mountain range of the Carpathian mountain arc (Fig. 1A, Solon et al. 2018). Tatra Mts. cover an area of 785 km^2 and have a length of 53 km whereas Western Tatra Mts. cover an area of 360 km^2 (Balon et al. 2018).

The Starorobociańska Valley is located in the Polish Western Tatras, on the northern side of the main water divide, and it is a tributary valley to the main Chochołowska Valley (Fig 1B). It is formed of Carboniferous igneous rocks – i.e. mainly granitoids, diorites, alaskites, and granodiorites – and its metamorphic cover consists of deep metamorphic rocks including migmatite and layered gneiss. Less resistant rocks are found in areas affected by tectonics including cataclasite, tectonic breccia, mylonite as well as phyllonite (PIG 2023). The geomorphological evolution of the valley has occurred along a fault zone with NNW–SSE axis (Gawęda 2001, Kłapyta 2012) at least since the Pliocene (Krzemień 1991), but the main features of its relief such as glacial cirques and deposits formed in the Pleistocene. The Starorobociański Cirque is limited from the south by a main ridge, which culminates in the following three peaks: Siwy Zwornik (1,965 m a.s.l.), Starorobociański Wierch (2,176 m a.s.l.) and Kończysty Wierch

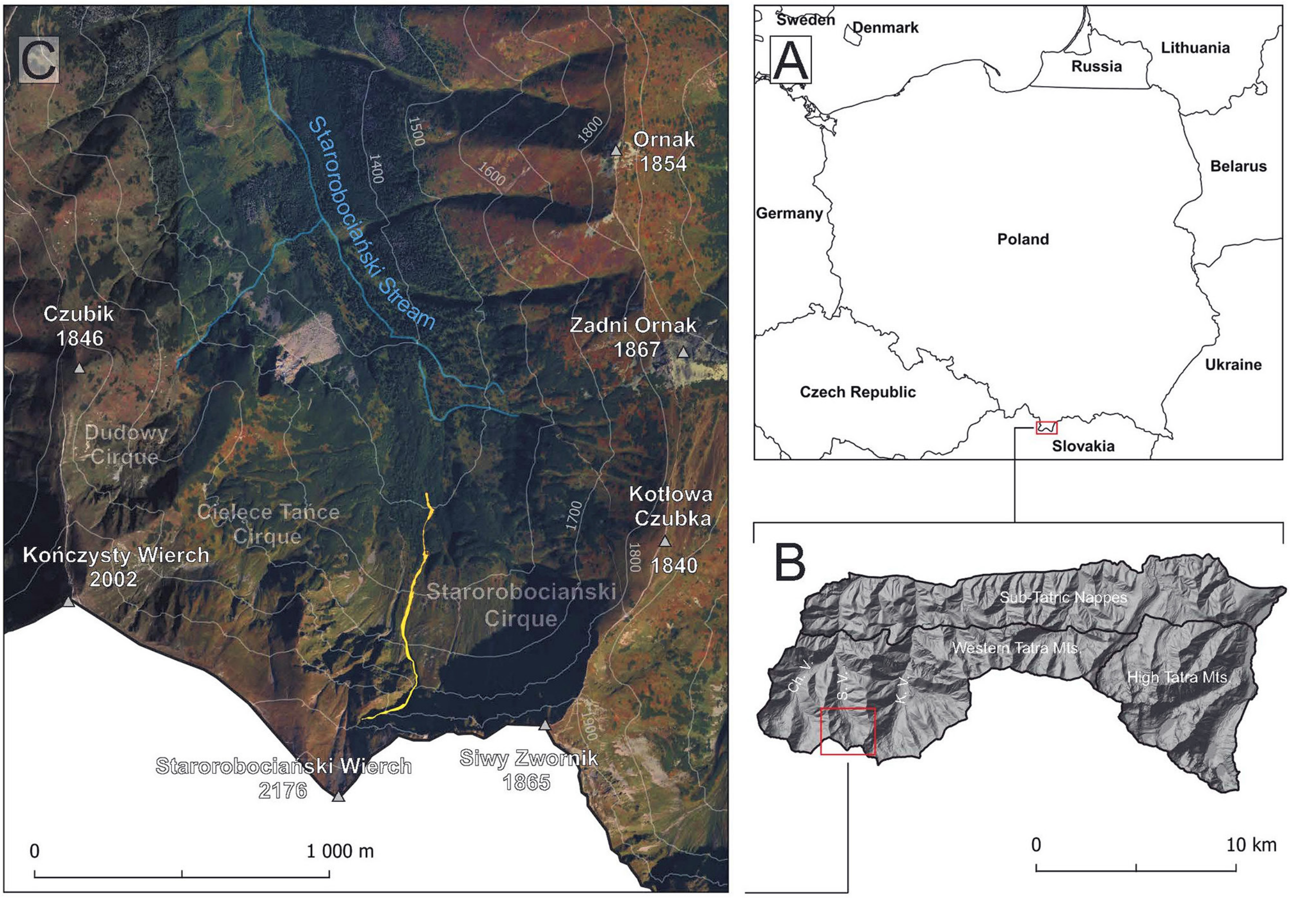

Fig. 1. Study area: A – location of the Tatra Mts. region; B – division of Polish Tatra Mts. according to Solon et al. 2018 with the location of the study area: Ch.V. – Chochołowska Valley, S.V. – Starorobociańska Valley, K.V. – Kościeliska Valley, background: DEM (GUGiK 2023); C – the highest part of Starorobociańska Valley with the extent of the 2021 debris flow marked on the basis of an orthophoto from 2021 (GUGiK 2023)

(2,002 m a.s.l.) (Fig. 1C). From the north, at an elevation of 1,400–1,420 m, the bottom of the cirque terminates with late Pleistocene moraine deposits of the intermediate stage of valley deglaciation – called the Stosy stage (Klimaszewski 1978, Libelt 1988, Kłapyta 2012). The upper, glacially transformed section of the valley is incised by debris flow paths whose source areas are located under the main ridges. Along the slope they continue in the form of chutes or gullies cut into rock walls and weathered covers. Debris-flow cones stretch below rock walls along with loose debris deposited on them by rock falls and avalanches (Fig. 1C).

There are many debris flow tracks in Starorobociański Cirque (Fig. 2B), however two – investigated in this study (marked with an 'Y' in Fig. 2) and the one adjacent to it on the western side (marked with an 'X' in Fig. 2) – are the biggest and most active. They are located in the central-western part of the cirque. The debris flow track investigated in this study became the most significant track in Starorobociański Cirque recently as it is confirmed by events in 2018 and 2021. Based on Sentinel 2 satellite images two dates were adopted as the dates of debris flow occurrence – July 18, 2018 and July 14, 2021. Both debris flows used almost exactly the same flow track, thus the latter erased most evidence of the older one. Despite older debris is partially visible in the field, the range and landforms of the flow in 2018 can be recognized mainly on the photomap.

The study area is characterized mainly by nival-pluvial conditions (Kotarba et al. 2013), with a division into three climate zones: cool zone up to approx. 1,550 m a.s.l., very cool zone up to approx. 1,800 m a.s.l., and a moderately cold zone up to approx. 2,300 m a.s.l. (Kotarba 1976). Average air temperatures oscillate between 5°C at the nearest (~4 km) weather station on Polana Chochołowska (average from the years 1993–2022, (IMGW 2023) and −2°C on summits (Jodłowski 2007). The Starorobociański Cirque area receives a relatively large amount of precipitation relative to the southern slopes, which is related to the orographic effect and the inflow of polar oceanic air masses from the northwest (Niedzwiedź 1992, Kłapyta 2012). The annual precipitation average for the Polana Cho-

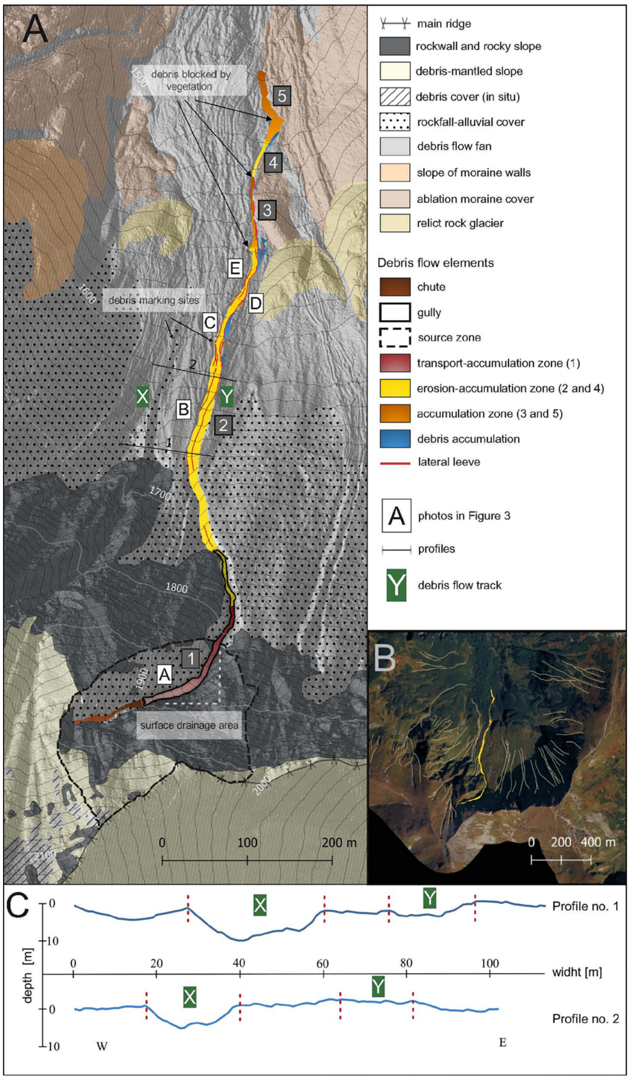

Fig. 2. Debris flow morphology: A – Geomorphological map of the study area with marked segments (1–5 Arabic numerals on the map as well in the legend) and landforms of the 2021 debris flow. Investigated debris flow track is mark with Y while older and dipper one, adjacent to it, with X. Map on the basis of a DEM (GUGiK 2023) and relief landforms after Kłapyta (2012); B – extent of debris flow versus other flows in Starorobociański Cirque on the basis of an orthophoto from 2021 (GUGiK 2023); C – cross-sectional profiles of slopes according to the lines on the geomorphologic map used in the study

chołowska weather station for the period 1971–2022 was 1,611 mm, with a maximum of 2,162.6 mm, and a minimum of 1,091.9 mm. The rainiest month is July with an average of 230.5 mm, while the lowest precipitation is recorded in February, on average 76.1 mm (IMGW 2023). Long-lasting and heavy rainfall occurs usually during stormy days in the summer months. The maximum recorded daily precipitation was noted in June 1973 at 163.8 mm, while the longest precipitation sequences, often combined with thaws, are noted in the spring and summer months. According to Krzemień (1991) snow cover reaches a thickness of up to 1.5 m near the Polana Chochołowska station. However, the most recent studies showed decreasing trend in snow cover in whole Tatra Mts. in the period 1952–2013 (Szwed et al. 2017), although it usually still exceeds 1 m in Chochołowski Stream catchment (Błażejczyk 2019, Płaczkowska et al. 2020). Snow cover remains on the ground in the lower part of the Chochołowska Valley for 137 days, on average, and can last a maximum of more than 200 days. It appears in September/October and disappears at the beginning of summer ultimately. According to an incomplete measurement series from the year 1994 to 2022, snow cover was observable at the Polana Chochołowska weather station for a maximum of 175 days (IMGW 2023).

Methods

Geomorphologic mapping of 2021 debris flow track

Fieldwork was initiated in July 2022 by marking debris in the investigated debris flow track as well as in one adjacent to it on the western side (tracks marked with X and Y on Fig. 2). It was made at the same elevation of 1,595 m a.s.l. in the case of another flow occurrence at the time of research. The geomorphologic field mapping was carried out in September 2022 and September 2023 by using an orthophotomap from 2021 (GUGiK 2023) and Avenza Maps application implemented into a mobile phone with GPS receiver. On the orthophotomap background we marked manually the boundaries of morphodynamic zones and measurement points for selected flow parameters to investigate variability of the debris flow in longitudinal profile. To conclude about flow force, we measured clast length. To do so, we picked at least 15 longest clasts from each morphodynamic zone.

Additionally, we used digital elevation model (DEM) with a resolution of 0.5 m (made available by Tatra National Park – TNP 2023) to obtain the alimentary zone area. It was determined using the Watershed Segmentation Tool based on DEM calculations run using QGIS 3.18.1 software. In places where the boundaries had been incorrectly determined, they were manually adjusted. The length and area of the alimentary zone as well as other key morphodynamic zone parameters were calculated using the Add Geometry Attributes Tool (Dlabáčková, Engel 2022).

Precipitation analysis

Precipitation data collected at the Polana Chochołowska and Hala Ornak stations for the years

1971–2022 were used in the study. The stations are 4.3 and 3.6 km away from the study area, respectively. The said data set was obtained from the Institute of Meteorology and Water Management (IMGW 2023) in Poland and from the European Climate Assessment and Dataset (ECAD 2023). In the present research we used Sentinel 2 satellite images (Sentinel Hub EO Browser 2023) and precipitation data to establish the dates when the said debris flows had most likely occurred in the years 2018 and 2021.

An analysis of antecedent precipitation was conducted for both of the studied events. We summed up rainfall values for the period from the beginning of July to the day assumed as the day of debris flow occurrence. These were 17 days in 2018 and 13 days in 2021, respectively. We also calculated cumulative precipitation values based on event occurrence periods as well as monthly precipitation totals for the period 1971–2022. The calculation of 10-day cumulative precipitation totals was used as the last parameter in the study (Dlabáčková, Engel 2022). It was given only for the event in 2018 due to gaps in data. This parameter included data from the beginning of the climatic winter (December 2017) to July 2018.

In the period 1971–2022 the frequency of rainfall events which exceeded precipitation thresholds of 50 mm·d^{-1} was also investigated and compared with results obtained in the present study. To do so we used daily rainfall totals data collected at the Polana Chochołowska weather station mostly. However, as this data had gaps in the period 1985–1993 we supplemented them by using daily rainfall totals measurements collected at the Hala Ornak weather station. For the year 1990 there was no data at the stations. Both data sets are comparable as it is proven by high Pearson correlation coefficient – 0.92 for data sets in the period 1993–2015 (n=7175).

Spatial analysis of the debris flow track

Photomaps from the years 1955/56, 1977, 1994, 1999, 2009, 2020, and 2021 (made available by TNP 2023) were used to determine spatial and temporal changes in debris flow activity within the investigated track along with an orthophotomap from 2022. The debris distribution was marked on the maps starting at the outlet of the rock chute to the terminus of successive flows.

Results

The geomorphologic record of the 2021 debris flow in Starorobociański Cirque

The studied debris flow reached the examined slope section almost from the main ridge of Starorobociański Wierch (1,900–1,970 m a.s.l.) to the bottom of Starorobociański Cirque (1,489 m a.s.l.). It covered an area of 0.62 to 0.65 ha and had a length of approx. 870 m. The debris flow path is divided into an alimentation zone and five morphodynamic segments consisting of a transport-accumulation zone (segment 1), two erosion-accumulation zones (segments 2 and 4), and two accumulation zones (segments 3 and 5) (Fig. 2). The morphometric parameters of these zones are shown in Table 1.

The alimentation zone or the source zone (including chute and transportation-accumulation zone – segment 1) is located at an elevation ranging from 2,090 to 1,800 m a.s.l. on the northern side of Starorobociański Wierch and covers an area of 3.47 ha. It includes an area directly related to the supply of debris to the rock chute and gully (Fig. 2A). The de-

Table 1. Morphometric parameters of the debris flow in Starorobociański Cirque in 2021

Debris flow section	Maximum elevation	Minimum elevation	Length	Area	Mean slope	Maximum and minimum width of the flow track	Mean size of the largest transported clasts (A axis)
	[m a.s.l.]		[m]	[ha]	[°]	[m]	[cm]
Full debris flow track	1971	1489	800–900	0.62–0.65	40	1.8 / 14.5	52.5
Transportation-accumulation zone (segment 1)	1897	1776	168	0.12	70	3.5 / 12.0	–
Erosion-accumulation zone I (segment 2)	1776	1549	450	0.38	50	3.6 / 14.5	76.0
Accumulation zone I (segment 3)	1549	1522	85	0.03	31	2.0 / 10.3	47.0
Erosion-accumulation zone II (segment 4)	1522	1510	45	0.01	26	1.8 / 5.2	34.0
Accumulation zone II (segment 5)	1510	1489	90	0.08	23	4.8 / 16.0	53.0

Fig. 3. Photos documenting various sections of the 2021 debris flow (see Fig. 2 for the places of taking photos)

bris comes from loose mixed weathering cover found in the summit area and rock walls, mainly on the southern side of the studied gully. The source zone is intersected by minor rock chutes. The debris size here – as in the main gully – is variable, ranging from predominantly medium-sized clasts deposited on a sandy-gravelly substrate to larger ones exceeding 1 m (Photo A in Fig. 3). The morphology of this zone is diversified by bedrock outcrops, creating a stepped profile of the rock chute.

At an elevation of 1,780 m a.s.l. bedrock disappears, and the gully transitions into a typical debris flow path. This is the first erosion-accumulation zone (segment 2), with a surface area of 0.38 ha. In the north-western direction this zone stretches across vegetation-stabilized accumulation areas, then changes direction to the north and continues in an area of older debris flows cones (Fig. 2A). The landforms created by the flow are readily observable across an almost 400 m long section with an average slope of 50°, just below the rock walls (Photo B in Fig. 3). The chute widens locally to 15 m and erosive depressions formed in the course of former flows are present. The debris flow path here was found between older and much wider lateral levees and relatively chaotic deposition of debris is observable. From about 1,650 m a.s.l. debris accumulation areas start to occur due to effect of blocking by single mountain pine bushes (Photo E in Fig. 3). In this section the flow had high morphogenic role as it formed erosive incision reaches 1.8 m (Photo C and D in Fig. 3). The height of fresh lateral levees is different, but usually does not exceed 1 m, and decreases to about 0.5 m along the flow path (Table 1). The largest clasts found outside the studied gully can be found there. Their size ranges between 48 and 120 cm, with an average of 76 cm. Also, clast with fresh fracture was found 20 meters east of the flow path indicates relatively dynamic debris flow. The largest debris deposition areas of 0.02 ha are found in this particular zone.

From an elevation of 1,550 m (segment 3), over a distance of 85 m, flow was depositing the debris mostly, heading north. This is a relatively narrow zone, reaching a maximum of 10 m in width and 30°

in slope, where the movement of debris was slowed down on both sides by mountain pine trees. Distinct lateral levees, reaching 0.5 m, are readily observable on the right side of the flow path. They are formed of clasts of different size, ranging from 25 to 110 cm in size, with 47 cm being the average. In this section, the debris flow reached the ablation moraine, which then shaped its subsequent pattern of movement.

The transition to the next erosion-accumulation zone (segment 4) occurred in an area where the debris flow was severely blocked by mountain pine (approx. 1,550 m a.s.l.). A narrow chute formed between mountain pine shrubs channelled the movement of debris here and became deeper by about 0.5 m. Relatively few big clasts were found in this area, and had a length of 26–60 cm, with 34 cm being the mean size. The length of this zone is small, only 45 m, and its width is only 5 m. In this zone, the debris flow entered another debris flow fan, strongly slowing down and accumulating debris on its eastern side once more. The velocity of debris flow was noticed at this site for the last time.

The formation of the last accumulation zone (segment 5) starting from 1,525 m a.s.l. occurred in the area where ablation moraine deposits occur. The flow here changed its direction to the north. The last studied zone is relatively wide, ranging from 5 to 16 m, and its length is 90 m. Debris disappears between thickets, creating a thin blanket consisting of gravel and sand-size clasts. Although clasts 28–84 cm in size (mean size: 53 cm) were found at this location, it was impossible to determine whether they had come from above or had been torn from the ground by flow in this area.

Precipitation conditions directly related to the 2018 and 2021 debris flows

The dates July 18, 2018 and July 14, 2021 were linked to the maximum precipitation height noted during a continual event precipitation – 150.5 mm·d^{-1} (2018) and 52.1 mm·d^{-1} (2021) – which lasted 5 (July 16–20) and 7 (July 14–20) days, respectively. During these periods, cumulative precipitation values were 244.1 mm in 2018 and 127.9 mm in 2021. The cumulative precipitation totals in the period immediately preceding the occurrence of flows, i.e. from the beginning of July to July 15, 2018 and July 13, 2021 were 158 mm and 34.2 mm (Table 2).

Long-term precipitation conditions before the debris flows

An analysis of cumulative precipitation totals for 10 days for the 2018 flow showed that the highest precipitation value was associated with a period when debris flow occurred in July 2018 (246.2 mm in the period 08–18.07.2018, Table 3). High precipitation values were also noted during select periods in June, 2018 – 114.5 and 137.3 mm, while the lowest values were recorded in the first ten days of March, 2018 (1.4 mm) and in the second ten-day period in April (9.8 mm).

Our analysis of monthly precipitation totals for July in the 1971–2022 period shows that the value 379.1 mm obtained for July 2018 significantly devi-

Table 3. Cumulative precipitation totals for 10-day precipitation periods prior the 2018 debris flow

Date (the last day of 10-day period)	Cumulative precipitation totals
10.12.2017	29.2
20.12.2017	14.9
30.12.2017	47.9
09.01.2018	15.9
19.01.2018	18.2
29.01.2018	19.2
08.02.2018	30.0
18.02.2018	19.9
28.02.2018	4.7
10.03.2018	1.4
20.03.2018	18.0
30.03.2018	10.8
09.04.2018	54.4
19.04.2018	9.8
29.04.2018	19.7
09.05.2018	22.0
19.05.2018	49.8
29.05.2018	41.9
08.06.2018	114.5
18.06.2018	99.5
28.06.2018	137.3
08.07.2018	72.4
18.07.2018	246.2

Table 2. Precipitation totals for debris flow events in Starorobociański Cirque in 2018 and 2021

The day with maximum rainfall during continual precipitation event	Precipitation totals in the day with maximum rainfall	Precipitation totals from the beginning of July without maximum rainfall	Precipitation totals from the beginning of July with maximum rainfall	Duration of continual precipitation event	Continual event precipitation totals
		[mm]		[d]	[mm]
18.07.2018	150.5	158	308.5	5	244.1
14.07.2021	52.1	34.2	86.3	7	127.9

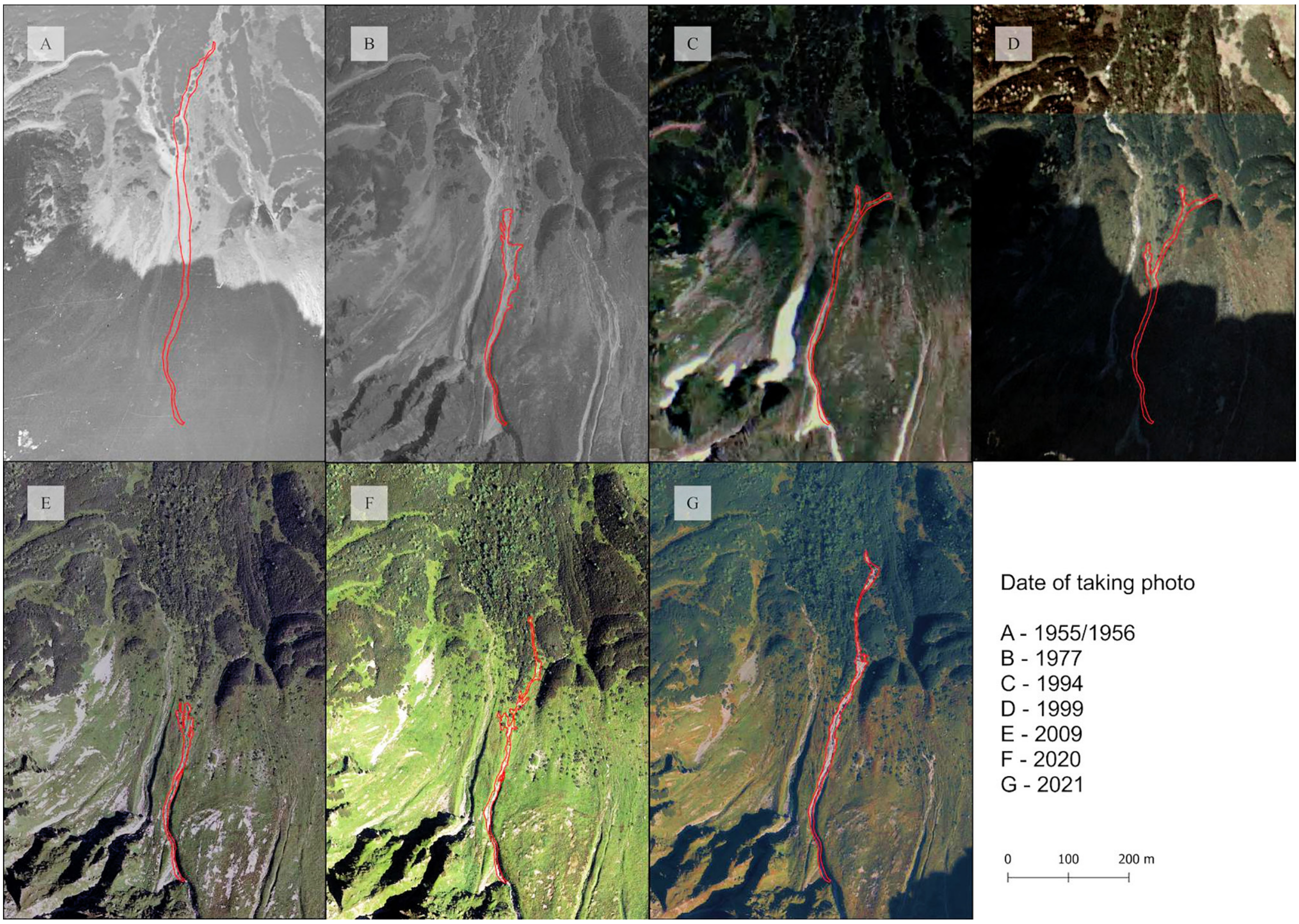

Fig. 4. Archival photomaps of the debris flow in Starorobociański Cirque. At least 6 events (apart from the 2021 debris flow) can be observed. Source: TNP 2023, GUGiK 2023

ates from the multi-year average, which is 230.5 mm. Higher precipitation totals were recorded only a few times in the years 1980, 1997, 2001, 2008, 2010, and 2016. The average monthly precipitation total for July 2021 was 209.5 mm, and it is rather a moderately high value compared to monthly totals in the period 1971–2022. In a measurement series lasting 42 years, exactly half of this period had July monthly totals lower than this value.

Spatial changes in the debris flow track in the period 1955–2022

The recurrence of debris flows in the investigated track in Starorobociański Cirque was determined based on photomaps – at least one flow event was noted between 1977 and 1994, 1994 and 1999, 2003 and 2009, and also in 2018 and 2021. Selected images showing the extent of the flow (Fig. 4) most likely prove that only the flow noted in 2021 reached an extent almost as large as the flow shown on the 1955/56 photomap. Simultaneously, debris flows occurred in other chutes. This is clearly visible in the neighbouring tracks. The best example of this can be seen on photomaps from 1977 and 2021 (Fig. 4B and G) where fresh debris contrasts with older covers.

The flow shown on the 1955/56 photomap followed a similar path to the flow adjacent to it on the western side (marked by X in Fig. 2) and was the largest event whose geomorphic effects can be observed on the studied photomaps. It was approximately 950 m long maximum which is almost 100 m longer than debris flow in 2021 whose length was approximately 870 m. However, its erosion and accumulation area was 0.7 ha, which was 0.3 ha (43%) more than that in the case of debris flow in 2021.

A debris flow that occurred before 1977 had a very similar area in front of the gully to that of the flow in 2021 – 0.4 ha, but its length was 200 m shorter. Events occurring in the 1990s had a very similar length, and the shortest flow can be observed on a 2009 photomap, where the debris flow path had a maximum length of 600 m and its surface area in the erosion and accumulation sections equalled 0.24 ha. This is quite interesting, as a more recent flow in 2018 had a similar area (0.27 ha below the gully), but its length was rather substantial and only 100 m shorter than that in the case of the flow from 2021.

Discussion

Parameters of the 2021 debris flow

Calculated morphometric parameters indicate that the debris flow in 2021 was one of the largest debris flows observed in the Western Tatra Mts. recently. However, debris flows occurred during LIA were significantly more powerful as they occurred within wider gullies and transported 2 to 3 times bigger clasts (Kędzia, Kotarba 2018). The significance of the 2021 debris flow is evidenced primarily by its length, which reached a maximum of 870 m. This value is therefore very similar to maximum values observed in the Polish Western Tatra Mts.; however, two different lengths are reported in the literature: 960 m (Kotarba et al. 2013) and 857 m (Jurczak et al. 2012). The length of the erosion-accumulation zone is also relatively substantial at about 670 m, which is 70 m more than that in the case of the Smutná Valley debris flow (Dlabáčková, Engel 2022). That flow covered a slope section which was 0.5 km longer and carried clasts of 1.5 to 3.5 m long, whereas in our case we did not have find clasts longer than 1.3 m. However, in the most distant accumulation zone we noted 0.5 m clasts which were much bigger than those in the case of the flow in Smutná Valley, where rather small, up to 15 cm long clasts were found at the same elevation (Dlabáčková, Engel 2022). In comparison, clasts bigger than 30 cm never moved in the 2009–2018 period in Chochołowski Stream in glacial trough in Chochołowska Valley, even when 10–28 $m^3 \cdot s^{-1}$ discharge was noted (Płaczkowska et al. 2020). Other parameters such as the location of the initiation zone, minimum height of material deposited in the accumulation zone, and difference in height between these zones achieved average values observed for debris flows in the Western Tatra Mountains (Kotarba et al. 2013).

Conditions for the occurrence of the 2018 and 2021 debris flows

Only a few specific rainfall thresholds for debris flows are provided in the literature, both for the High and Western Tatras. The last observations on the Polish side of the massif date back to 1993 (Krzemień et al. 1995). Most of the recorded rainfall thresholds were defined as daily precipitation due to the lack of hourly precipitation records. Therefore, we considered it appropriate to combine the maximum daily rainfall during a rainfall event with the occurrence of debris flows in 2018 and 2021 in Starorobociański Cirque. All individual events analyzed in this study (Fig. 4), except for the 2021 debris flow, may be correlated with rainfall of >100 $mm \cdot d^{-1}$ (Fig. 5). The determined maximum daily rainfall value in July 2018 of 150.5 $mm \cdot d^{-1}$ is credible in the context of triggering a debris flow. It directly correlates with the value of 164 $mm \cdot d^{-1}$ recorded in June 1973 for a debris flow in Starorobociański Cirque (Krzemień 1988). Another very similar value, 154.5 $mm \cdot d^{-1}$, was recorded in Zverovca in the Slovak Western Tatras on June 19, 1970 (Ingr, Šarík 1970). However, on the day preceding the debris flow, there was precipitation of 61 $mm \cdot d^{-1}$, which suggests that this event should be considered as an effect of accumulated precipitation. Similar values equal to or exceeding 100 $mm \cdot d^{-1}$ were noted three times in studies conducted in the High Tatras, the last time for a debris flow in the Morskie Oko Lake area in August 2001 (Ferber 2002). Conversely, the 52.1 $mm \cdot d^{-1}$ rainfall threshold established for a July 2021 debris flow should be considered one of the lowest values recorded so far, with respect to flows covering the entire slope length. Previously, within the study area, the values of 82.3 $mm \cdot d^{-1}$ (26.07.1982) and 91.6 $mm \cdot d^{-1}$ (23.07.1980) were recorded (Krzemień 1988). The closest rainfall values were reported for Dudowy Cirque at 60 $mm \cdot d^{-1}$ (20.07.1985, Krzemień 1988) and for Smutná Valley debris flow, where rainfall values ranged from 60 to 135 mm/29h^{-1} (111 $mm \cdot d^{-1}$, Dlabáčková, Engel 2022). However, the latter was based on precipitation records from the Zuberec-Zverovka and Kasprowy Wierch weather stations, which are located 5.8 km and 17.2 km, respectively, away from the site of the debris flow occurrence. Based on precipitation data from the Kasprowy Wierch station the Czech authors suggested that the debris flow occurred before the maximum rainfall event. Nonetheless, this is difficult to confirm, given the large distance between the measuring stations and the site of debris flow occurrence.

Analysed data indicate that the debris flow in 2021 was most likely the result of heavy rainfall lasting for a reasonably short period of time. We found that between 1972 and 2021 there were 44 years with rainfall of 50 $mm \cdot d^{-1}$ (this value was exceeded 134 times), and on average every two years there was rainfall of at least 82.3 $mm \cdot d^{-1}$ (thresholds according to Krzemień 1988, Fig. 5). Such a large number of potential events that could trigger debris flows was, however, not noticed when observing relief morphology changes. This means that a daily rainfall value and perhaps even its intensity measured at a weather station cannot be readily assumed to represent a threshold value for a site where a flow occurs. Moreover, the exceedance of the thresholds, also in the period between 2018 and 2021 (between the most recent events), usually did not cause debris movement. Flows noted in Starorobociański Cirque (discussed

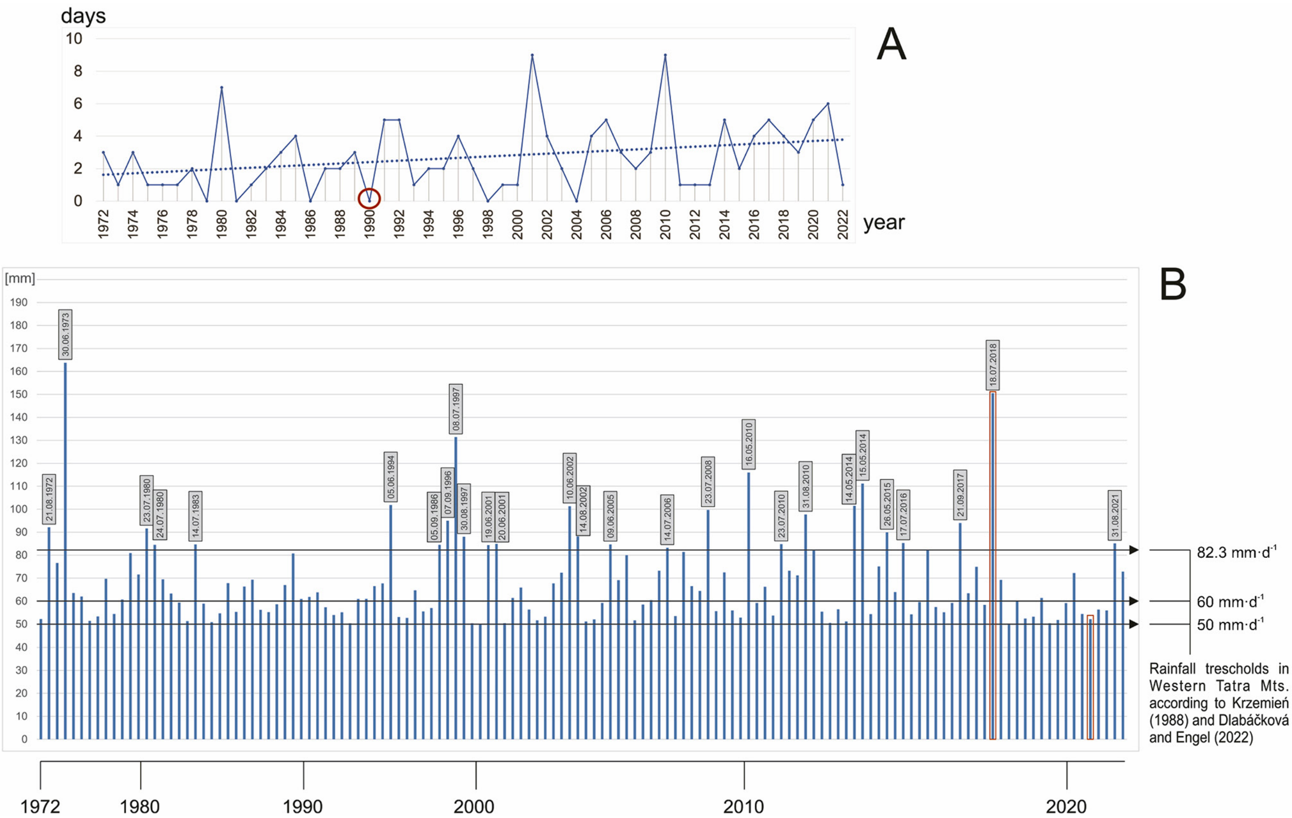

Fig. 5. A – Number of days with exceedance of the threshold value of 50 mm·d^{-1} divided into years; red circle marked year with no data; B – Rainfall precipitation data: Exceeding threshold values given in the literature for the Western Tatra Mts.: 50 mm·d^{-1} – small debris flows in Starorobociański Cirque, 82.3 mm·d^{-1} debris flows covering the full length of the slopes in Starorobociański Cirque, 60 mm·d^{-1} – debris flows in Dudowy Cirque (Krzemień 1988), 60 mm·29h^{-1} – minimum value obtained for the debris flow in 2014 in Smutná Valley (Dlabáčková, Engel 2022); red frame mark threshold precipitation value for 2018 and 2021 debris flows; precipitation data source: (IMGW 2023, ECAD)

below) were rather the result of rainfall characterized by higher daily values of around >100 mm·d^{-1} (Fig. 5). In addition, the debris flow in 2018, despite being assigned a threshold three times higher, had a smaller range. A much higher value was also recorded immediately after the studied event in 2021, on August 31, when precipitation of around 85.1 mm·d^{-1} was recorded at the Polana Chochołowska weather station. In the following year, on August 21, high precipitation of around 72.8 mm·d^{-1} was also recorded at this location. There were several days in 2022/23 when rainfall exceeded the threshold value of the debris flow from 2021. During field observations conducted in September 2022 and 2023 we also found that the marked material in the chutes practically had not moved. Centimetre-sized clasts moved only up to a maximum of 2 m during this time. Gądek et al. (2016) suggested that with rainfall intensity of 1–1.5 mm·min^{-1}, debris flow can occur as early as 15 minutes after the start of precipitation, which gives a rainfall threshold of around 60–90 mm·h^{-1}. This implies that rainfall intensity is much more important than its daily amount, and it means that the rainfall triggering debris flow in 2021 was rather short and torrential. In other parts of the Tatra Mountains debris flows resulting from very short rainfall events of around 35–60 mm·h^{-1} were also observed (Kotarba 1991, 1998, 2007). It is, however, unclear whether the debris flow in 2018 "paved the way" for the 2021 flow. Observations from Karkonosze massif suggest that once the flow is generated it is has less chance to initiate again in relatively short period of time (Migoń 2008). The same author indicates that metamorphic rock are potentially a better source for debris accumulation as they are eroded quicker because they are less resistant than crystalline rocks in general. Indeed, material which is transporting in the Starorobociański Cirque is mostly metamorphic and previous research indicated that large debris flows occurred in the cirque every 15 to 20 years (Krzemień 1988). Despite that, it seems that the 2018 debris flow rather favoured the 2021 flow than reduced its efficacy. First, we cannot assume that all debris accumulated in source area moved in 2018, thus it could have been still available in 2021. Second, even it did, the subsequent flow could have grabbed the material along the way and, increasing mass and accelerating due to high slope gradient, exceed the range of the 2018 flow. Most likely vegetation did not have enough time to stabilize the debris during the 3-year period between events, which facilitated the availability of loose debris in the track and it contributed to the debris flow length.

High mountain relief affected by temporal and spatial changes in the debris flow path

The most distinct flows in the discussed time period date back to the 1950s. The first photomap from 1955/56 shows the longest observed flow in the studied chute. In that period, the tree-species line, which is the upper limit of scattered mountain pine (Jodłowski 2007), was significantly lower at 1,570 m a.s.l. in the area of the debris flow path. In the lower part, the flowing material used partially the path of a neighbouring flow, bifurcated in the middle part of debris flow fan. The neighbouring track (marked with X in Fig. 2) was more active at least till 1970s, after that time it started to grow over (Fig. 4). The flow visible on the photomap from 1977 was activated probably during the largest recorded rainfall event in the Tatras in 1973 (Fig. 5, Krzemień 1988). This could have also resulted in the occurrence of a debris flow in Smutná Valley, observable on a photomap from 1973 in a paper by Dlabáčková and Engel (2022). These two events correspond to a period of increased human impact in the Tatra Mountains, up until the 1970s, where slope processes were more active due to the lack of vegetation (Kotarba 2004, Rączkowska 2021). Probably since the 1980s, activity in the studied chute has increased, stabilizing the currently observed flow direction. A change in the flow direction occurred in the lower part of the debris flow area, where debris fan furrows and lateral levees do not exceed 0.5 m (Fig. 2C). Despite this, it was enough to change the flow direction, which now seems rather stable. The reason for changing track activity is unknown but the bigger one (marked by X in Fig. 2) was definitely more dynamic and most likely it exists longer. Despite similar lithology (mainly granitoids, gneisses and schists) but slightly different character of source area (less rocky), it is currently functioning less well. The mentioned period coincides with a time of increased debris flow activity documented in the Tatras starting from roughly the mid-1980s (Kapusta et al. 2010, Kędzia et al. 2023). Subsequent flows which occurred probably in the last decade of the 20th century followed a clearly similar path (Fig. 4, Photos C and D). The debris flow in 1994 can probably be directly linked to rainfall event of around 101.8 mm·d^{-1} recorded at the Polana Chochołowska weather station on June 5, 1994 (Fig. 5B). The second debris flow observable on a photomap from 1999 was most likely triggered by rainfall that caused a catastrophic regional flood in Poland in 1997. High rainfall values were then recorded throughout the Tatras (Kotarba 2004, Kapusta et al. 2010). On the other hand, rainfall at that time did not cause significant changes within debris flow gullies in the Hala Gąsienicowa area (Kotarba 1998). Debris flows in 1990s were noticeable shorter, as seen on the photomaps provided in the research study. This clearly demonstrates the inhibitory effect of vegetation and the bifurcation of flow in the final section of the channel. The next flow visible on the photomap from 2009 may be related to rainfall of 99.7 mm·d^{-1} recorded on July 23, 2008 (Fig. 5B). Increasing activity of debris flows has been observed again since 2007, as demonstrated by dendrochronological studies in the Slovak High Tatras (Šilhán, Tichavský 2016, 2017). The flow visible on the photomap from 2009 is, except for the flow on the photomap from 1977, the shortest. However, the terminal accumulation zones in both cases are relatively wide. This example shows that when a flow is shorter, the material tends to move in older channels, which may be related to lower dynamics of the flow itself and lack of blocking effect by forming lateral levees. It seems that this flow path has become more active than its neighbouring path since the year 2009. This finding is confirmed by the last two debris flows in 2018 and 2021 when much more debris was transported in this chute. These flows occurred within a period of only three years, which is not consistent with earlier observations; it was previously determined that large debris flows occur every 15 to 20 years (Krzemień 1988). They occurred in July, which is a month with a large number of days with precipitation exceeding the rainfall threshold of 50 mm·d^{-1} (32 days in the period 1972–2022). For comparison, a debris flow occurred in Smutná Valley in May 2014, which is a month with an average number of such days equalling 14.

In our research, we have observed two contradictory tendencies occurring at the present time. Rainfall data analysis shows a growing trend in the number of rainy days exceeding the given threshold of 50 mm·d^{-1} (Fig. 5A), similar to those presented in paper of Niedźwiedź et al. (2015). It may suggest overall better conditions for debris flow occurrence in the future. This however does not directly indicate debris flow initiation which cannot be simplified to daily precipitation total, as we have shown earlier. The second issue is the rise of the tree-species line – individual mountain pine bushes can now be observed at various locations at an elevation of 1,650 m a.s.l. in the area of the debris flow path, which means that after sheep grazing had ended in the 1970s this line gradually climbed upwards 70 m. It can presumably limit flows to some degree as long as climatic, and especially topographic conditions allow for that. On the other hand, debris flows may sometime overrun mountain pine shrubs, as they have enough force to vanquish the resistance when carrying bigger clasts or to simply move over the trunks. That last situation refers to flows carrying smaller clasts and thus those having rather small effectiveness in generating pronouncing landforms. In both cases rising of the tree-species line will confine smaller flows more readily because affecting large debris flows, like those from 2021, requires more time. This is however a rather quick process because debris is almost always accumulated in the same places – changes are noticeable only in the area of the debris fan (Fig. 4). Perhaps, if debris flow in 2021 were not blocked be vegetation, it can exceed the range of flow from 1950s.

Conclusions

Based on rainfall analysis and satellite imagery, we set July 14, 2021, as the date of debris flow initiation and 52.1 mm·d^{-1} as its threshold value. Previously at least six debris flow events had been recorded in the same gully in Starorobociański Cirque between 1955 and 2023, and were likely triggered by rainfall exceeding the set threshold value of 100–150.5 mm·d^{-1}.

At the same time, between the years 1972 and 2022 the threshold value of 50 mm·d^{-1} was exceeded 134 times and on days with rainfall of 70–85 mm·d^{-1} debris flow did not occur. Therefore, we interpret the appearance of debris flow in 2021 as an effect of short and intense rainfall. The obtained threshold value is one of the lowest values provided in the literature for flows covering an entire slope length in the Western Tatra Mts.

The debris flow in Starorobociański Cirque was one of the longest flows observed in the Western Tatras. It reached about 870 m, almost equalling debris flows observed in the 1950s, whereas other examined flow tracks were noticeably shorter.

Between the years 1972 and 2022 an increasing trend in the number of days with potential conditions for debris flow formation was observed, as well as the rapid rise of the tree-line zone. If climate change will proceed as expected, we can expect a further stabilization of slope covers. Currently, changes occurring within debris flow paths are dynamic, but the accumulation area is mainly limited to existing chutes and fans. Despite this, debris flows are still the dominant morphogenetic process in the Polish Western Tatras.

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Author's contribution

Together with the supervisor of the work, Elżbieta Gorczyca, Dawid Siemek is the author of the concept of work. He conducted field work and developed the text and graphical part of the work. Elżbieta Gorczyca supervised the text as well as took part in figure designing.

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