

Chapter 14

Recent Debris Flows in the Tatra Mountains

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Abstract This chapter results from the interpretation of the data collected by field studies of debris flow events including geomorphological effects, of an Ikonos satellite image from 2004, and the DEM prepared for the entire Tatra massif. Based on about 20-year-long field observations, the rainfall thresholds necessary to trigger debris flows have been identified. Such thresholds, however, vary with lithology and relief. As it is illustrated by the lack of debris flows associated with the extreme weather events in May and June of 2010 in the Tatras, there is no clear relationship between periods of high daily precipitations and the triggering of this type of mass movement. The most spectacular topographic impacts of debris flows are observed in the middle section of the vertical profile of the mountains. Debris flow activity is strongly conditioned by relief (topography and substrate properties) that resulted from Pleistocene glacial and periglacial morphogenesis.

Keywords Debris flow • Typology • Geoecological and morphodynamic zones • Rainstorms • Tatra Mountains

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14.1 Introduction

Debris flows belong to most important geomorphic processes in the Tatra massif, south Poland, evidenced by numerous debris flow tracks formed or renewed in recent years. Similarly to other alpine regions, we assume a relationship between debris flow triggering and observed changes in rainfall intensities. In the high-mountain environment of the Tatras, rapid mass movements are favored by direct and indirect causes. Steep slopes and unconsolidated weathering mantles of glacial and periglacial origin promote erosion, while specific hydrometeorological conditions – intensive rainstorms or several-days-long precipitation followed by an intensive, short-lasting rainfall event – are direct triggers of debris flows. In recent years the frequency of debris flow incidents has increased in the Carpathians. In order to assess a role of debris flows in the present-day modeling of the Tatra relief, monitoring has been launched at several research stations on both the Polish and Slovakian side (Kotarba 2004; Hreško et al. 2008; Kapusta et al. 2010). Ikonos satellite images of 2004 have been interpreted, and a Digital Elevation Model (DEM) has been prepared for the entire Tatra massif.

14.2 Relief Features and Geocological Zones

The Tatras (of 785 km² area and 53 km length) are the highest mountain group in the whole Carpathian arc. This region of diverse *relief* is traditionally divided into three landscape units: the High (Eastern) Tatra, Western Tatra, and Belianske Tatry (the smallest area of ca 70 km²) (Fig. 14.1). In the High Tatra several summits rise above 2,500 m elevation (Gerlachovský štít 2654.4 m), the Western Tatra is ca 400 m lower (the highest point is Bystra, 2,248 m), while the Belianske Tatry also has some summits rising above 2,000 m (Havran 2151.5 m). The Tatra landscape is controlled by various rocks, tectonic features, and differentiated relief remodeled by Pleistocene glaciers (Nemčok et al. 1994).

The most resistant granite occurs in the crystalline core of the High Tatra *batholith*, while the less competent pegmatite-aplite granite is present in a marginal zone. The granite core is densely dissected by joints and faults. The Tatra horst of east–west strike is built up of crystalline rocks. Mylonites, which promote formation of deep troughs and passes (Grochocka-Piotrowska 1970), occur in dislocation zones. Metamorphic rocks – gneisses, amphibolites, and biotite schists – predominate, and white granites (alaskites) also occur in the Western Tatras. The entire Belianske Tatry is built up of *nappes* of Mesozoic sedimentary rocks, which are also present on the northern slopes of the Tatras (Nemčok et al. 1994).

Geologic structures, climatic conditions, and vegetation are differentiated both vertically and horizontally. A characteristic feature of the Tatras, high mountains not glaciated at present, is the *vertical zonation* of climate and vegetation with the accompanying geomorphic processes. Determined by elevation above sea level, particular parts of the Tatras are subjected to various climatic conditions: nival,

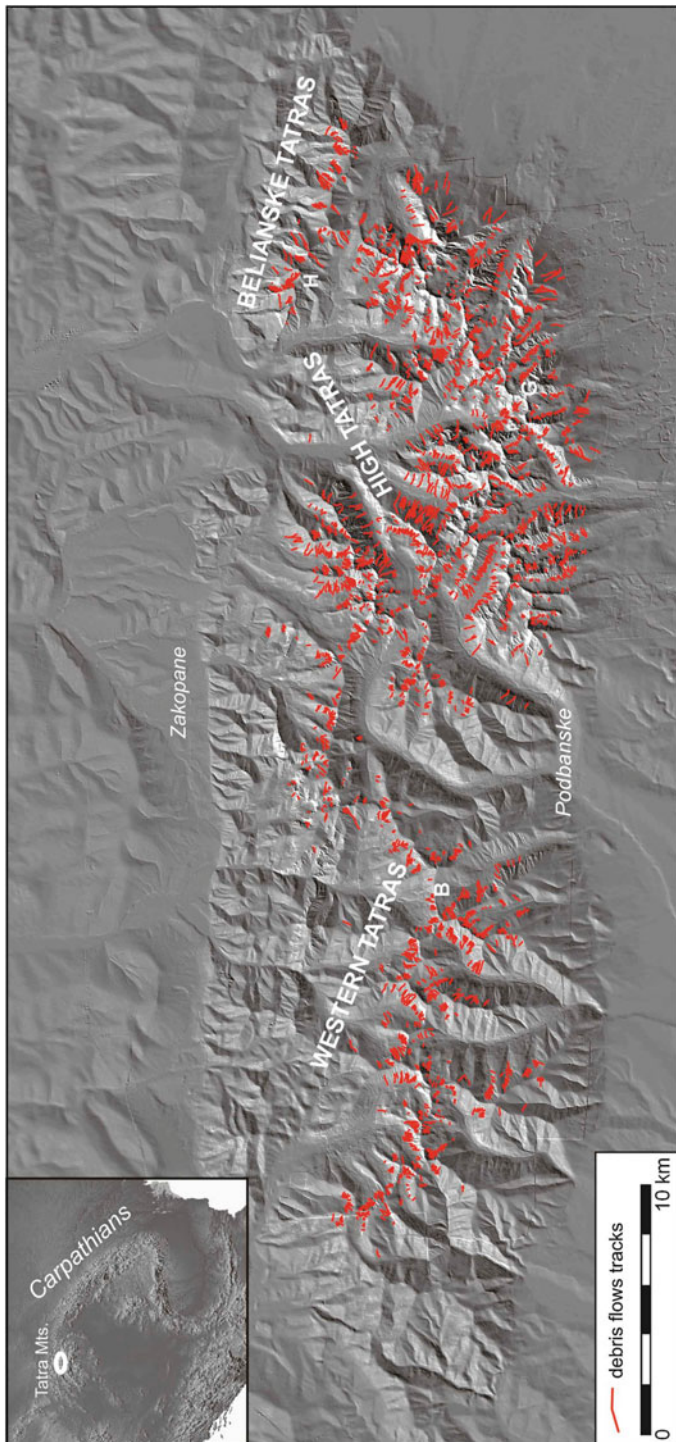


Fig. 14.1 Map of debris flow tracks in the Tatra Mountains (By M Dlugosz)

from 2,200 m to the summits; nival-pluvial (1,550–2,200 m); and pluvial-nival, below 1,550 m (Hess 1965). So water retention in the form of snow lasts for long, snow patches are found above 1,800 m (Wiśliński 1996), and abundant supply of water originates from rainfalls and snowfalls.

The recharge of water resources as well as water circulation is mainly driven by rainfalls (75% of annual precipitation – Łajczak 1966). The highest totals and intensities of rainfalls are recorded in the summer season, i.e., from June to August. The Tatra Mountains receive high annual precipitation (1,100–1,900 mm), with the highest amounts (1,600–1,900 mm) observed on northerly slopes at 1,400–2,000 m elevation (Niedźwiedź 1992, 2003).

The unique features of high mountains are their rise above the present-day timberline and the presence of numerous glacial, nival, and periglacial landform complexes. From a geocological viewpoint, two geomorphological domains are distinguished (Kotarba and Starkel 1972): the *cryonival* or periglacial (Jahn 1958) zone and the *temperate forest* zone, separated by an upper timberline at 1,500 m elevation. There are two *morphogenetic zones* in the cryonival domain: the lower zone with congelifluction processes and the upper zone, reaching to the permanent snow line, where frost sorting processes are observed (Starkel 1980). Small periglacial features clearly actively develop also at present (Rączkowska 2007).

Being the most important geomorphic process, *debris flows* transport weathered material from the rock crests to the bottoms of glacial cirques or troughs. By the end of glaciations, under paraglacial conditions, rapid mass movements dissected the slopes below melting glaciers and formed systems of rock chutes. At present, slopes are still being remodeled by debris flows and avalanches.

Debris flows occur in all physical-geographic units and geocological vertical zones of the Tatras (Table 14.1, Fig. 14.1), but they differ with respect to type, frequency, and magnitude. The necessary condition for a debris flow formation is favorable terrain configuration: steep slopes and unconsolidated regolith. If these conditions are fulfilled, flow of regolith is possible provided satisfactory hydrometeorological triggers are available. Following Brunsten's classification (1979), we distinguish *hillslope debris flows* and *valley-confined debris flows* in the Tatras (Kotarba 1992). The longest valley-confined debris flows reach the maximum length of over 1,000 m; they amount to 9.3 and 5% of all debris flows in the High and Western Tatras, respectively (Midriak 1984), and transfer the weathering products across geocological vertical zones.

The size, number, and distribution of debris flows depend mainly on topography and substrate properties. The spatial differentiation of the topography of the Tatras results from diverse impacts of Pleistocene *glaciations*. The High Tatra was subjected to the most profound transformation (Fig. 14.2). Within the relief between the highest summits and mountain footslopes of the order of 1,500 m, a vertically distributed system of hanging cirques and glacial troughs has formed. According to Klimaszewski (1988), in the Polish part of the High Tatra, glaciation covered 50% of the area, 21.5% in the Western Tatra, while only minor fragments of the northern slopes of the Belianske Tatry were glaciated.

Table 14.1 Description of debris flows in the Western Tatra, High Tatra and Belianske Tatry Mountains

Region	Lithology	Highest summit (m a.s.l.)	Area (km ²)	Number of debris flows	Elevation of debris flow starting zone (m a.s.l.)			Elevation of debris flow frontal zone (m a.s.l.)			Height difference (m)		Debris flow length (m)		Distribution of debris flows by slope aspect (%)				Distribution of debris flows by slope inclination (%)				
					Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	N	E	S	W	N	E	W	15–25	26–36	37–55
Western Tatra	Gneisses, granitoids, limestone, dolomites	2,248	379	1,127	2,217	1,293	1,817	2,095	1,213	1,711	519	15	106	966	38	200	34	31	8.7	26.3	15	47	35
High Tatra	Granitoids,	2,654	341	2,300	2,396	1,291	1,936	2,350	1,044	1,828	633	11	111	1,410	36	212	21	30	20	29	15	45	33
Belianske Tatry	Limestone, dolomits, sandstones	2,152	67.5	153	2,101	1,449	1,786	1,906	1,260	1,622	638	27	163	1,163	47	274	40	31	6	21	5.5	29	60

Fig. 14.2 View of the Medena Dolinka valley, Slovakian High Tatra, with hanging cirque and glacial trough, a suitable setting for the development of gullies and levees of valley-confined debris flows, which transport material from ridge to valley bottom through subnival, alpine to subalpine belts (Photo by B. Gądek)



The varied influence of glacial and periglacial action in the Pleistocene differentiated *slope morphology*. In the High Tatra, granite narrow crests, slopes, and rockwalls inclined above 40° predominate. The latter are strongly dissected by rocky chutes ($8\text{--}17 \text{ km km}^{-2}$ density) along their entire lengths (Klimaszewski 1988). At footslopes, heaps and debris taluses were formed, so the slope profile consists of two sections (Fig. 14.2). In the Western Tatra, less remodeled by glaciers, the slopes consist of three or four segments (Fig. 14.3). Ridge culminations, gradually change from gently inclined near-ridge slope segments, remodeled by Pleistocene periglacial processes, into rocky slopes dissected by chutes (density of chutes ca. 6 km km^{-2}), which vary in size depending on the properties of metamorphic rocks and on slope aspect. Talus heaps rarely occur, but footslopes are formed by alluvial fans or alluvial-avalanche fans.

The Belianske Tatry has a shape of a huge mountain ridge of *crête* type, enclosed with subsequent valleys of the Biela voda and the Medodolský potok streams. A fundamental feature of this sloping morphostructure is a north–south *asymmetry*, alternatively with southeastern slopes. Consequent valleys on the north face were initially carved by glaciers. In addition, the longitudinal profile of valleys contains several rock bars and steps. The northern slopes are rockwalls, while the southern side of the main ridge combines smooth slopes with horizontal intersection belts of walls and towers of compact quartzites and limestones (Fig. 14.4 – Lukniš 1973).



Fig. 14.3 View of the Starorobociański glacial cirque, Western Tatra. Three-partite slope composed of (from ridge crest to valley bottom) periglacial slope, rocky slope dissected by chutes, and alluvial slope. The active valley-confined debris flows begin in the subnival or alpine belts and continue to the subalpine belt (Photo by Z. Rączkowska)

14.3 Debris Flow Characteristics

Debris flows might differ in shape, size, and mode of movement, depending on their setting, relief, and type of slope cover. Therefore, Krzemień (1988, 1989) distinguished three *morphodynamic zones*: source area of debris and water, track zone, and accumulation zone (zone of debris deposition), which form a system of debris flow. He distinguished three fundamental patterns (types) in the Western Tatras:

- Type *A* – scar → chute → track → lobe
- Type *B* – scar → track → lobe
- Type *C* – chute → track → lobe

These systems were identified in the part of the Western Tatras, where preglacial relief was only slightly remodeled by the Pleistocene glaciers. Glaciers on the interfluvium of the Western Tatras did not cover entire valleys. The *interfluvial crests*, under the influence of periglacial and perinival processes during glaciations (Klimaszewski 1988), protruded above the glaciers. It is the reason why they are mantled with debris often showing pattern ground (Jahn 1958; Rączkowska 2007).

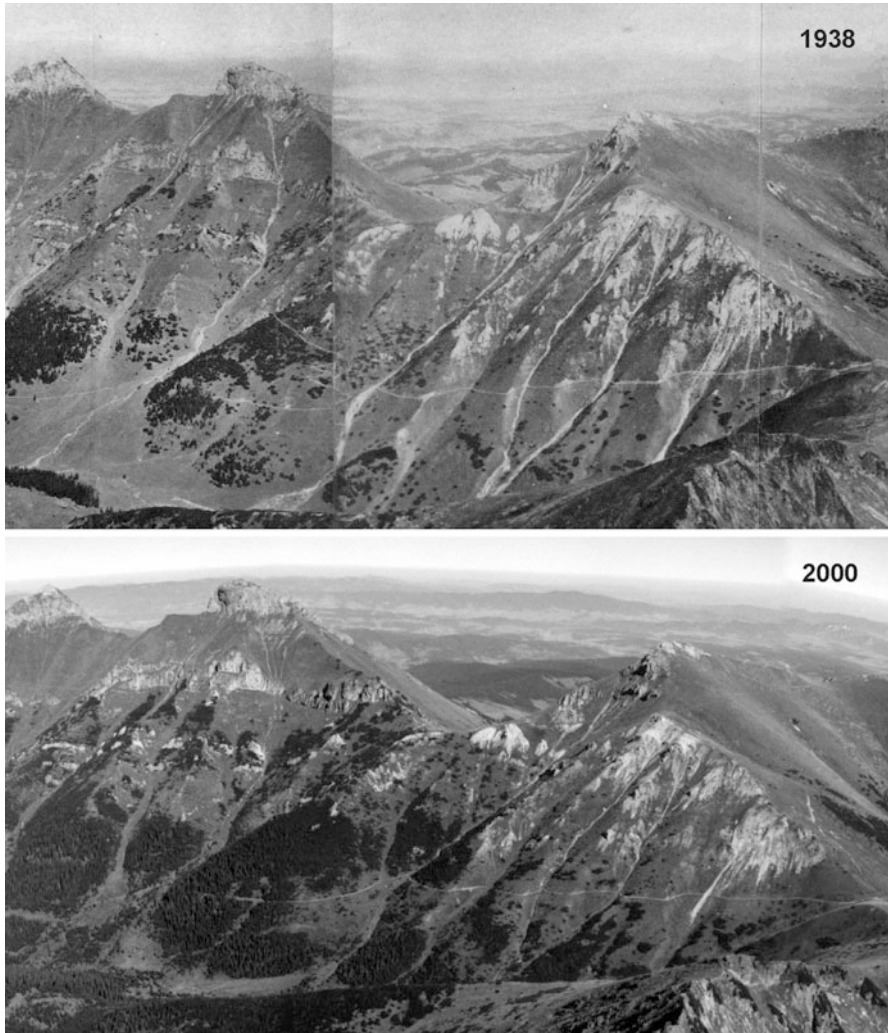


Fig. 14.4 Gullies of long valley-confined debris flows in the Belianske Tatry, documented in 1938, probably formed during a wet period in the 1930s. Recently some gullies are modeled by debris flows, while the majority by avalanches (Photo by M. Boltžiar)

In the *interfluvial* zone, singular or, more often, complex rock-debris niches developed, which initiated *chutes* formation on rocky slopes after glacier melting. Huge talus heaps, with gullies, levees, and tongues, formed at the foot of rocky slopes. Such system, named type *A* by Krzemień (1988, 1989), reaches up to 1,000 m. The type *B* system occurs on rocky slopes and reaches up to 750 m in length. It starts with gullies incised in relatively thin (ca up to 1.5 m thick) weathering mantles of the rocky slopes. The type *C* system comprises three elements – chutes, gullies (tracks), and tongues – and, without possessing a niche, its lengths vary from 100 to 700 m (Krzemień 1989).

Fig. 14.5 Overland flow on the rockwall of Maly Kežmarský štít peak on 17 July 2001, triggering a debris flow which affected the whole length of debris slopes. Rainfall intensity was 64 mm in 6 h (Photo by G. Bugár)



In the High Tatra, the systems of debris flows are more complicated. The Pleistocene glaciers formed classical, alpine-type valleys. In the highest regions, a debris flow is triggered by rainwater concentrated in chutes which flows rapidly onto gravitational talus heaps and talus cones (Fig. 14.5), forming typical *hillslope debris slopes*. As rock steps and exaration depressions with tarns occur, the longitudinal profiles of the main valleys are graded. In the High Tatra, debris flows start in the highest located cirques and continue downvalley. During extreme precipitation events in summer months, debris flows are set into motion, producing a complex system (Fig. 14.2), and weathered material is transferred across two or three vertical climatic zones (Kotarba and Strömquist 1984).

The basic condition of debris flow generation in the Belianske Tatry is a sufficient amount of clastic material detached from rockwalls, eventually from the denuded rocky slopes (e.g., on southern slopes below Hlúpy peak, 2,061 m). Historically grazing has accelerated debris flows in the Zadné Medodoly and the Predné Medodoly valleys.

Debris flow generation is evident in *gullies* or in upper sections of north-oriented valleys (the Nový potok, the Tristárska dolina valleys, and the north kettle below

the Jatky peak) permanently supplied with clastic material by gravitational and fluvio-gravitational processes. Resultant from debris flows, gullies erode the bed-rock or incise in their own deposits. The *bifurcation furrows* with marked lateral mounds were formed in the accumulation zone (Fig. 14.4).

Similarly to other high mountains, debris flow tracks in the Tatra formed directly after glacier melting as outcomes of *paraglacial processes*. Considering the paraglacial environment at the end of the last glaciation, physical weathering (block disintegration and fragmentation of inclined surfaces, formation of tors and minor valleys) was a crucial process (Lukniš 1973; Klimaszewski 1988). The nival niches, which had developed at that time, became areas of melt- and rainwater concentration and promoted the formation of corrasion gullies, which functioned as paths for valley-confined debris flows in the Holocene.

As shown on the map drawn from the interpretation of 2004 *Ikonos satellite images* and the *DEM* (Fig. 14.1), debris flows are not evenly distributed in the Tatras. All forms with clearly noticeable boundaries along the whole longitudinal profiles of the debris flows are depicted on the map. The pixel size of the Ikonos image was 1 m for panchromatic images and 4 m for multispectral images (Guzik et al. 2006), while the grid size of the DEM was 10 · 10 m. The precise terrain model allowed to determine relative and absolute heights of the identified forms and to define their aspects. Based on the DEM, maps of slope gradients and aspects of the Tatras were prepared. All the maps and analyses were made using ILWIS 3.6 GIS software.

This way more than 3,500 features were identified. (For comparison, Midriak (1984) marked 830 debris flow paths in the Slovak Tatras). The majority of debris flows were registered in the High Tatra (2,300), and only half of that number (1,127) were recorded in the Western Tatras. Nevertheless, despite differences in lithology and the Pleistocene remodeling of relief, *debris flow densities* are similar. The smallest number of debris flows (153) with 2.27 flows km⁻² is registered in the Belianske Tatry. This can be attributed to karst-driven water outflow.

More variation is observed in *debris flow lengths*: 200–300 m on the average and up to 1.5 or 2 km on the northern and eastern slopes of the High Tatras (Lukniš 1973; Nemčok 1982). Debris flows in the lowest number are recorded on south-facing slopes, explained by a faster development and more moderate dissection of such slopes. Such regularity is observable in the whole Tatras. The landforms, located near valley outlets, where denudation processes were initiated shortly after deglaciation, are usually larger in size, for instance, on eastern and western slopes of valleys on the southern side of the Tatra massif. The forms located higher, within the area of cirques, are definitely much smaller in size. It does not apply to north-facing slopes, where the largest debris flows developed in glacial cirque walls.

The debris flows form at elevations of 2,390–1,290 m and their source areas often reach the crests. Midriak (1995) is also of opinion that majority (65%) of debris flows begin at 1,900 m or higher, in the alpine or subnival zones, and continue within rocky chutes on slopes inclined at 26–36 or 37–55°. They end in debris flow gullies and *debris flow levees* developed on debris slopes and alluvial fans with their base at 1,260–1,906 m elevation. The difference in altitude between source and end zones of debris flows vary in the different parts of the Tatras.

As field surveys show, the gullies of recent debris flow tracks are from 3–4 to over 10–20 m wide and at most a few or a dozen meters deep (Kotarba 1989, 1995; Krzemień et al. 1995; Rączkowska 2006). The dimensions depend on slope morphology and substrate properties as well as triggering precipitation amounts and intensities. Debris flow gullies developed during a particular event can also form a complex interconnected network.

Debris flow transport can reach 100 to maximum 25,000 m³ of material during a singular event (Midriak 1984; Kotarba et al. 1987; Krzemień 1991; Kotarba 1995), and, thus, they can be assigned to the second and third categories in Innes' classification (1983).

14.4 Precipitation and Debris Flow Triggering

In the Tatras, debris flows are mainly *triggered* by rainfalls. Snowmelt is almost insignificant because of a high permeability of the slope deposits. Not even a minor debris flow below snow patches has been recorded to date (Rączkowska 1999). The *amount of rainfall* necessary to trigger a debris flow varies with lithology and relief, but it is also different for the debris flow types. Hillslope debris flows, which are bound to the upper part of the debris slope, can be triggered by 30 mm rainfall in the High Tatra (Kotarba 1995) and 20 mm rainfall in the Western Tatra (Janačík 1971). The probability of such precipitation is 5–25% (Cebulak 1983). According to Krzemień (1988), such debris flows can occur at the same spot in the Western Tatra several times in a year.

Based on about 20-year-long observations in the High Tatras, the debris flows which extend over the full length of the debris slope are triggered by *rainfalls* of 35–40 mm h⁻¹ intensity or of at least 80–100 mm day⁻¹ (Kotarba 1992, 1997) with instantaneous intensity of 1.3–1.7 mm min⁻¹ (Kotarba 1995) and 10% probability (Niedźwiedz 2003). The majority of the flows occur on the slopes of the subalpine and alpine zones, whereas stimulating runoff comes from a zone of bare rock (Figs. 14.2 and 14.5). Long-lasting precipitation below 1 mm min⁻¹ intensity triggers mud-debris flows or rill erosion the forest belt close to the upper timberline and on subalpine slopes (Kotarba 1998; Rączkowska 2006).

Debris flows can be either generated by local rainstorms, often confined to a single small valley, or by *prolonged rainfalls* over the Tatra massif or the entire Carpathians as it was the case *in 2010*. In June and July of that year, long-lasting cyclone activity produced high precipitation: in both of the months, 5-day precipitation amounted to 220 and 200 mm in the Polish Tatras, respectively (Fig. 14.6). The automated gaging station located at 1,900 m elevation in Slovakian Western Tatras (Jalovecka Valley) recorded 157 mm rain for the second 5-day period. Nevertheless, debris flow activity did not intensify in response to the high precipitation in May and June 2010, which brought about many changes in the relief of the Polish Flysch Carpathians (see, e.g., Kijowska 2011; Bajgier-Kowalska 2011). Debris flows were not observed even in such locations as the region of the Morskie

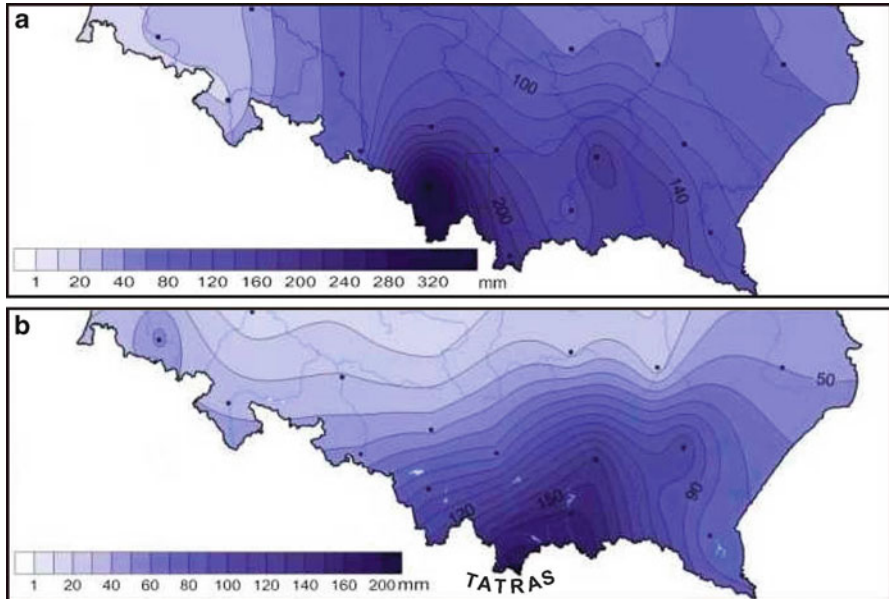


Fig. 14.6 Cumulative totals of precipitation in the Polish Carpathians during spring 2010, for the period 15–20 May 2010 (a) and for the period 31 May to 4 June (b) (After Miętus et al. 2010a, b)

Oko lake, where numerous debris flow gullies evidence that such processes are common (for instance, on the debris slopes of Szeroki Piarg and Zielony Piarg). Three photos, depicting the entire slope, provide evidence for the occurrence of new hillslope debris flows at least once per 10 years. At the same time the photos show that the slope surface was not changed in 2010 (Fig. 14.7). Debris flows were triggered by the 41.4 mm rain lasting 1.5 h on 23 August 2011. Precipitation as high as that was recorded at the valley bottom in 1 km distance from the emerged forms. At the crests, precipitation amounts might have been even higher and intensity above 1 mm min^{-1} .

Precipitation in the Tatras in 2010 was high but mostly in the form of *snow* and happened in a period with almost continuous snow cover particularly at higher elevations. That is the reason why apparent geomorphological effects are lacking.

14.5 Conclusions

1. Debris flows belong to the predominant gravitational processes which model the present-day slopes of the Tatra Mountains. They may develop in any geoeological zone, although their geomorphic role is most apparent *in the cryonival domain above the upper forest line*. The performed inventory showed that over 3.5 thousand modern tracks occur in that relatively small mountain



Fig. 14.7 Hillslope debris flows at the Szeroki Piarg and the Zielony Piarg above the Morskie Oko lake, where fresh gullies evidence frequent debris flow activity in 2001, 2010, and 2011, but no geomorphological impact of the high precipitation in 2010 (2001, photo by T. Ferber; 2010 and 2011, photo by Z. Rączkowska)

- massif, and the most (2,300) and the largest of them are in the High Tatra. Their size, number, and distribution mainly depend on local topography and substrate properties.
2. Extreme summer rainfalls (short-term storms with very intensive convection) confined to small areas are the main trigger of debris flows. Therefore, there is *no clear relationship* between periods of high *daily precipitation* and the *triggering of rapid mass movements* in the Tatras. It is exemplified by the lack of debris flows in May and June 2010. The long-lasting precipitation which resulted in catastrophic landslides observed in the Flysch Carpathians did not generate debris flows in the Tatras. At that time, the snow cover of the last winter was still present in the Tatras and prevented rapid runoff.
 3. The zone of the highest precipitation on the northern side of the Tatra massif (1,400–2,000 m elevation) overlaps with the zone where *debris flows start* (1,290–2,390 m). This fact underlines the role of precipitation in the present-day relief evolution of the Tatras.

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