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L A N D F O R M E V O L U T I O N I N M O U N T A I N A R E A S

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CHANGES IN ACTIVITY AND GEOMORPHIC EFFECTIVENESS OF DEBRIS FLOWS IN THE HIGH TATRA MTS WITHIN THE LAST SIX DECADES (ON THE EXAMPLE OF THE VELICKÁ DOLINA AND DOLINA ZELENÉHO PLESA VALLEYS)

Abstract. Multitemporal trend analysis of remote sensing data from two model valleys, namely the Velická dolina Valley in the central and Dolina Zeleného plesa Valley in the eastern parts of the the High Tatra Mts, made it possible to outline the temporal trends in the activity and geomorphic effectiveness of debris flows in both valleys in the period 1949–2006. Comparison of trends indicated that the debris flow effectivity was in both valleys rather different, sometimes even opposed, within the earlier decades of this period. It is connected with the local character of extreme precipitation in these years. However, since the 1980s the simultaneous increase in the geomorphic effectiveness of debris flows in studied valleys is observable, though that in the Velická dolina Valley was more marked. This fact can be connected with manifestations of the climate change, expressing itself by the increased frequency and intensity of extreme precipitation events. Increased frequency of extreme rainfall events conditioned the rise in the number of debris flow events, the rising precipitation rates resulted in the increase of the geomorphic effectiveness of particular debris flows.

Key words: temporal trends, geomorphic effectiveness, debris flows, extreme precipitation events, climate change, High Tatra Mts.

INTRODUCTION

Debris flows are one of the most dynamic and intense exogenic geomorphic processes in the cryonival morphogenetic system of the Slovak Carpathians, in particular in the High Tatra Mts. They belong to the group of gravitational (slope) processes. Debris flows, representing a serious natural hazard, have often significant destruction effects and that is why they play key role in changes of the land cover pattern. The mapping of the spatial distribution of debris flows is the fundamental supposition for the location prognosis of their possible activation.

The aim of the article is to contribute to the knowledge on the geomorphic response to debris flow activity in the High Tatra Mts, namely on the example of two model areas — the Velická dolina Valley and the Dolina Zeleného plesa Valley.

On the basis of the multitemporal trend analysis of remote sensing imagery there was assessed an occurrence of debris flows and development of their operation in the model areas in time and space with a special attention to the changes in their geomorphic effectiveness within the period 1949–2006. The authors try to refer to the close relation of the occurrence of this phenomenon to extreme precipitation events.

From among the Slovak and Czech works that deal with the topic of debris flows in Tatra Mts, we leaned on the works of M. Lukniš (1956, 1968, 1973), J. Košťálik (1958), M. Ingr and I. Šarík (1970), J. Kalvoda (1974), T. Mahr (1976), A. Nemčok (1982), R. Midriak (1983a, 1984, 1994c, 1995, 2004), J. Hreško (1994, 1997, 2000), J. Hreško et al. (2003, 2005), M. Boltižiar (2001a, 2007, 2009), but mostly on the work of J. Kapusta (2009). As a significant information sources served also widerly concipated works evaluating the geomorphic response to current relief-forming processes in Slovakia (Stankoviansky and Midriak 1998, Minár et al. 2006, Stankoviansky and Barka 2007) and also some works of the landscape ecological character (Boltižiar 2001b, Hreško 2002). Alongside the above mentioned works we gained a lot of knowledge mostly from the works of the Polish geomorphologists (eg. Krzemień 1988, Kotarba 1994, 2004, 2005, 2007a, b, Rączkowska 2006). At an elucidation of the linkage of the occurrence of debris flows to extreme precipitation events the works of E. Fussgänger and D. Jadroň (2001), M. Kopecký (2001), H. Chen (2006) and I.J. Larsen et al. (2006) were taken into account.

STATE OF THE ART OF INVESTIGATION OF DEBRIS FLOWS IN THE TATRA MTS

Landforms of the Tatra Mts are mostly relic, their characteristic features were created above all in the Pleistocene in different climatic conditions than rule today. These relic landforms are intensely transformed by present-day exogenic geomorphic processes (Midriak 1983b, 1994b). According to A. Kotarba (2007a), the dominant high-energy gravitational processes, that are modifying the Tatra Mts's relief at present, are debris flows. This process transports plenty of material from slopes to valley bottoms and thus connects slope and valley systems (Rączkowska 2006).

Debris flows in the Slovak part of the Tatra Mts were already described by M. Lukniš (1956), J. Košťálik (1958), Q. Záruba and V. Mencl (1969). However, as the essential works referring to the occurrence of debris flows in the Slovak Tatra Mts we can consider the works by M. Lukniš (1968, 1973), A. Nemčok (1982), R. Midriak (1984, 1995, 2002) and J. Hreško (1994, 1996, 1997), containing also the maps of the spatial distribution of this phenomenon.

According to M. Lukniš (1973), the debris flows originate in the Tatra Mts either in rocky troughs when extreme rainfalls water-bear a debris in such a way that it bursts out moving and superimposes on alluvial cone, or on alluvial cones themselves when such a big torrents of water pour on them that due to the water-bearing also the cone debris bursts out moving in the form of the flow. Flows use at their movement mostly topographical predispositions (rocky troughs and other slope hollows deepened in slopes due to erosion acting of water and snow avalanches, but above all tracks of preceding debris flows) and often also channels of mountain torrents (Midriak 1983a, 1984).

Debris flows in the Tatra Mts reach an average length of 1 km, their maximum length is approximately 2 km. They are simple or branching. The mean width of debris flow channels is cca 10–40 m and average depth 1–3 m. They originate above the upper timber line, almost exclusively above continuous dwarf pine stands. The basic elements of debris flow in the sense of K. Krzemień (1988) are source, transport and accumulation zones, while the last of them is according to J. Hreško (1994, 1997) called erosion-accumulation zone. Erosion (erosion-accumulation) zone is typical for the fall of energy of the flow what results in its stopping. Unsorted sediments accumulate in this zone in the form of talus cones. They originate always below the more important branching rocky troughs that deliver not only debris but also concentrate water from more extensive area. Debris flows often bifurcate into 2–3 branches forming characteristic lobes (Krzemień 1988, Ondrášik and Rybář 1991, Hreško et al. 2003, 2005). It is possible to observe locally how they originate by gradual accumulation of material of debris flows. In the framework of this process, the newer debris flows are superimposed lobe-likely on older accumulations (Záruba and Mencl 1969, Kalvoda 1974, Kotarba 2004, 2005).

Debris flows do not originate always on new places. In most cases they renew or originate on places where already occurred sometimes in the past. Thus, younger flows originate by reactivation of older ones especially due to extreme rainfalls (Krzemień 1988, Kotarba 2007b). According to K. Krzemień (1988), the tracks of older debris flows can be reactivated each 1–10 years, locally even each 1–5 years.

In general, in the Tatra Mts there are extraordinarily favourable conditions for formation and development of debris flows (Mahr 1976, Midriak 1994a, c, Kotarba 1976). Tectonically disturbed rocks (mostly in mylonitized saddles and rocky troughs) provide a formation of sufficient amount of clastic material. Also poor to missing vegetation, insufficiently stabilizing slopes, some rocky troughs and cones, enables an occurrence of debris flows (Lukniš 1973, Boltižiar 2009).

The main cause of debris flow formation in the Tatra Mts are extreme precipitation events of the high intensity, reaching great efficiency during relatively short space of time. Debris flows thus originate during or immediately after such efficient rainfall episodes, when internal friction in scree bodies falls due to their sudden water-saturation (Záruba and Mencl 1969, Lukniš 1973, Midriak 1983a, 1984, 1995, 2004, Hreško 1997, 2002, Kotarba 2004, 2007a). J. Kalvoda (1974) refers to the fact that debris flows are seasonal phenomenon and originate in the late spring and summer periods after a disappearance of snow from rocky troughs.

Some of above mentioned works consider extreme precipitation even for the only possible cause of debris flow formation in the Tatra Mts. However, according to R. Ondrášik and J. Rybář (1991) and J. Hreško (1994, 1997), debris flows can be initiate beside extreme rainfalls also by sudden summer melt of abnormal amount of snow, as well as by earthquakes. Also A. Kotarba (2004) admits that earthquakes can trigger debris flows, but he refutes the similar role of snowmelt in the Tatra Mts.

Though the influence of extreme precipitation on activation of slope movements is generally accepted, it manifests itself differently in reation to geological, geomorphic and vegetation conditions. Thus, the geomorphic effect of debris flows conditioned by the precipitation of the same intensity can differ from place to place (Krzemień 1988, Fussgänger and Jadroň 2001, Kopecký 2001, Kotarba 2007a).

Efficient rainfalls in the Tatra Mts occurr mostly in summer. That is why the most frequent occurrence of debris flows is just in the summer period, as a continues snow cover keeps in the higher positions of the Tatra Mts up to the middle of June (Hreško 1997). Recurrence intervals of extreme rainfalls range from 2 to15 years in this mountain massif (Midriak 1982).

According to E. Fussgänger and D. Jadroň (2001), a threshold value of precipitation activating debris flows is represented by downpours of the intensity more than 25 mm/hour that occurr in spring and summer periods. The same threshold value for the Tatra Mts is given also by A. Kotarba (2007a). However, he states that hourly precipitation of just 35–40 mm is sufficient to trigger major flows affecting entire slopes. On the other side he admits that tremendous debris flows can sometimes happen also at lower threshold values. According to M. Konček et al. (1974), the maximum rates of heavy rains in the Tatra Mts range from 19.7 to 48.9 mm/hour and the highest daily precipitation totals range over a span 160–180 mm.

A. Kotarba (2004, 2007b) on the basis of information from chronicles and other historical sources both from Polish and Slovak sides of the Tatra Mts introduces following years within the last four centuries when extreme to disastrous floods and high precipitation totals were recorded in this mountain massif: 1605, 1617, 1618, 1621, 1650, 1651, 1662, 1699, 1700, 1713, 1724, 1725, 1728, 1735, 1743, 1774, 1800, 1813, 1846, 1854, 1865, 1866, 1867, 1869, 1871, 1882, 1884, 1885, 1893, 1900, 1902, 1903, 1910, 1912, 1934, 1956, 1958, 1960, 1970, 1973, 1980, 1997, 2001 and 2003. The author suggests a possibility of formation of big debris flows in these years in the Tatra Mts.

Occurrence and effect of debris flows in the past is confirmed also by analyses of sediments from talus cones and glacial lakes. A. Kotarba (2004, 2007a, b) has found out that in the past the periods with increased and decreased rate of operation of debris flows alternated in the Tatra Mts. The mentioned author refers mostly to a difference between the operation of debris flow during and after the Little Ice Age (1400–1925). Marked climatic anomalies during the Little Ice Age resulted in much more frequent occurrence of debris flows as well as in their higher force and energy in that time than in the later period. Analysis of lacustrine sediments confirmed that the high frequency of high-energy, rapid slope movemets in the Tatra Mts occurred in the period 1400–1860. Acting of debris flows continued until the end of the Little Ice Age, mostly in its final phase, approximately in the period 1900–1925, but already with lesser intensity. The dynamics of debris flows in this period was confirmed besides the analysis of lacustrine sediments also by the lichenometric dating. According to Kotarba (2004, 2007a, b), after the Little Ice Age faded away, the calmer period followed approximately till the 1970s, but within the last decades there is documented again the increased activity of debris flows.

STUDY AREA

Our investigation was performed in the High Tatra Mts, the highest geomorphic subunit of the Tatra Mts and at the same time the highest and the most typical high mountains in Slovakia. Especially characteristic is its relief energy with relative hights ranging from 500 to 1,500 m. The highest peaks exceed 2,600 m in elevation. During the Pleistocene glacial cycle (at least tripple valley glaciation, according to Kotarba 2007a) a classic alpine relief was formed in the High Tatra Mts, characterized by the presence of glacial cirques and troughs separated by pyramidal peaks and arêtes. Glacial erosional forms are filled with moraine and glacifluvial covers originating from the last glaciation (Würm). The current High Tatra Mts are non-glaciated high mountains. The original, relic forms were transformed by geomorphic processes during the Holocene. The significant boundary from the viewpoint of contemporary morphogenesis of the mountains is the upper timber line, oscillating around 1,500 m a. s. l. The territory of the High Tatra Mts situated below this boundary belongs to the temperate forest morphogenetic altitudinal zone (system), the territory above it to cryonival system (Kotarba and Starkel 1972). The High Tatra Mts are built of granitoid rocks of pre-Mesozoic age creating outcroping crystalline core. Prevailing granodiorites are tectonically disturbed on many places. Valley bottoms and lower parts of slopes are covered by thick beds of Quaternary sediments while their thickness reaches locally up to 150 m.

Study area is represented by two High Tatra's valleys, namely the Velická dolina and Dolina Zeleného plesa Valleys (Fig. 1). The Velická dolina Valley is

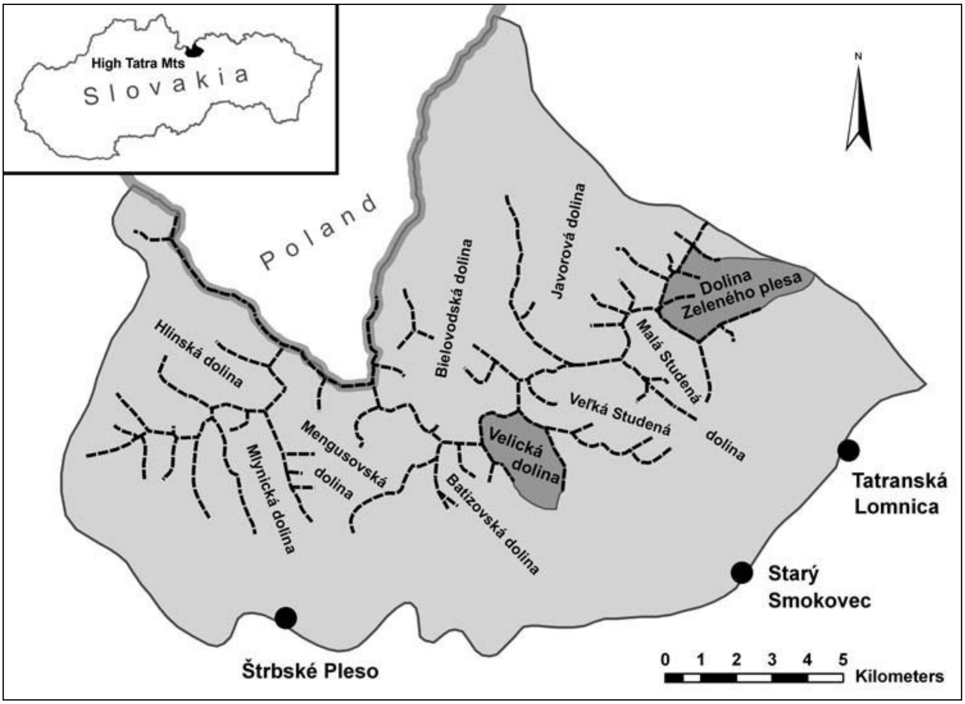


Fig. 1. Study area (Velická dolina Valley and Dolina Zeleného plesa Valley)

deepened in the southern slope of the central part of the mountains. It is situated between the lateral ridge with peaks of Bradavica (2,476 m) and Velické Granáty (2,318 m) and lateral ridge with peaks of Gerlachovský štít (2,654 m), Kotlový štít (2,601) and Kvetnicová veža (2,433). Its glacially transformed bottom is the widest at the beginning of the valley, i.e. below the main ridge of the mountains and it narrows gradually towards the valley mouth at the foot of the mountains.

The Dolina Zeleného plesa Valley lies in the eastern part of the mountains. It represents the right tributary valley of the Dolina Kežmarskej Bielej vody Valley. It is situated between the lateral ridge with the peak of Lomnický štít (2,634 m), protruding to the east from the main ridge of the High Tatra Mts and the main ridge itself in its part between peaks of Baranie rohy (2,526 m) and Jahňací štít (2,229 m).

MATERIAL AND METHODS

The course of the activity and geomorphic effectiveness of debris flows in selected model areas in period 1949–2006 was assessed on the basis of *multitemporal trend analysis of remote sensing data*, comparing according to J. Feranec et al. (2007) the same area over longer time intervals with multiple imagery. Key materials for detection of a spatial distribution of debris flows in this period represented airphotos taken in 1949, 1973, 1986, 1997 and 2003, ortophotos from 1998, 2002, 2003 and 2006 and digital elevation model (DEM). Black and white (panchromatic) airphotos were provided by the Topographical Institute in Banská Bystrica. Photos were well readable and appropriate for a large-scale mapping. DEM and ortophotos of high resolution (40–50 cm/pixel) in an approximate scale of 1:15,000 were provided by Eurosense Ltd in Bratislava. They were infrared (1998) and coloured ortophotos from years 2002 (Velická dolina Valley), 2003 (Dolina Zeleného plesa Valley) and 2006. Data on extreme precipitation to assess the relation of an occurrence of debris flows to extreme rainfall events in the evaluated period were gained from databases of the Slovak Hydrometeorological Institute in Bratislava.

The first step of the assessment, based on the detection of areas of accumulation parts of debris flows on talus cones, was a processing the maps (digital layers) of spatial distribution of debris flows from years when the used photos were taken. The next steps were a quantification of selected parameters of debris flows, identification of the number of their changes (gains and losses) and calculation of their areal extent in temporal intervals between years of the origin of interpreted photos, i.e. 1949–1973, 1973–1986, 1986–1998, 1998–2002/2003 and 2002/2003–2006, using statistical tools of GIS. The last step was an outline of temporal trends of geomorphic effectiveness of debris flows within the whole assessed period 1949–2006.

To analyse changes in the area (increase, decrease) of debris flows in the framework of the temporal intervals in question, the method of *computer aided visual interpretation* (cf. Feranec et al. 2007) of the above mentioned remote sensing imagery was used. All operations and outputs were realised in the environment of the program ArcGIS 9.2. Individual areas of debris flows (as well as of talus cones on which accumulation parts of debris flows were situated), represented by gray to grey-white colours, were digitized by a manual digitizing directly on computer screen approximately in the scale of 1 : 1,000. Talus cones were delimited on the basis of infrared ortophotos. Only such areas of debris flows were indicated on cones that showed signs of fresh surface destruction and therefore could be regarded as active in temporal intervals in question. Inactive flows (flows stabilized by vegetation) were not delimited. As a base for delimitation of debris flows in both valleys served ortophotos. The fact that identification of debris flows based on ortophotos is a reliable material for their further analyses and assessments was confirmed also by the field reconnaisance.

Areal changes of debris flows within individual temporal intervals were visualized in the form of the set of maps. The base layer on these maps demonstrates the areal distribution of debris flows from earlier period (a situation with which the change is compared) and the hatching shows the shape and size of debris flows in newer period (a change in comparison with preceding situation).

Computer aided visual interpretation was based on the *backdating* approach (cf. F e r a n e c et al. 2005). Its basic principle is that the maps of spatial distribution of debris flows elaborated on the basis of older images are compared with the template – the map of debris flows (reference data layer) detected on the newest image of the time sequence (i.e. from 2006), while areal changes in distribution of debris flows were identified. The use of this method enabled us to minimize the risk of inaccuracies and spatial distortions, characteristic for older aerial photos. In spite of the fact that visual change detection relies on subjective aspects of analysis, it is reliable methodical tool for change identification (cf. F e r a n e c et al. 2007).

DEBRIS FLOW ACTIVITY AND GEOMORPHIC EFFECTIVENESS IN RELATION TO EXTREME RAINFALLS IN THE VELICKÁ DOLINA AND DOLINA ZELENÉHO PLESA VALLEYS IN THE PERIOD 1949–2006

According to J. R u b í n and B. B a l a t k a (1986), the debris flows in the Velická dolina and Dolina Zeleného plesa Valleys belong to longest ones in the whole area of Slovak high mountains. The oldest work mentioning also debris flows in these valleys is the book of Q. Z á r u b a and V. M e n c l (1969). Introduced authors document the response to extreme precipitation event of 15 July 1933 when meteorological station in Starý Smokovec recorded between 18:00 and 20:00 hours 45.8 mm, while the maximum intensity was 26 mm/hour. This torrential rain resulted in the formation of a sequence of big debris flows that destroyed on many places talus cones in that time fully covered with vegetation. Mighty debris flows were formed also in our model areas, namely on slopes of the Kežmarský štít in direction towards the Zelené pleso Lake in the Dolina Zeleného plesa Valley and below the lateral ridge with Velické Granáty in the Velická dolina Valley. The fact that this event affected also the northern slopes of the High Tatra Mts, where most of debris flows was triggered in the Bielovodská dolina Valley, testifies that it was not of local character. However, we believe that the actual intensity of this extreme rainfall event was higher than 26 mm/hour, as the meteorological station is located in the marginal part of the affected area.

Detailed geomorphic investigation of debris flows in the Dolina Zeleného plesa Valley was performed by A. K o t a r b a (2004, 2005). He deals with the historical reconstruction of the occurrence of debris flows on the talus cone situated to the south-west from Zelené pleso Lake on the basis of their dating by lichenometric method, as well as on the basis of the analysis of lacustrine sediments. High dynamics of debris flows on this site is confirmed by the fact that no older debris material than from AD 1800 lies on the surface of this cone. In other words, the whole area of the cone is covered by debris flows that occurred in the 19th and 20th centuries. Debris flows in the Velická dolina Valley were studied thoroughly by M. B o l t i ž i a r (2001a, b) who has done also a schematic map of their occurrence. Detailed maps of areal distribution of debris flows both in the Velická dolina and Dolina Zeleného plesa Valleys were prepared by J. Kapusta (2009).

For an elucidation of the real cause of debris flow formation on the given site highly relevant are mostly precipitation data from nearest meteorological stations. That is why we introduce an overview of extreme, intense rainfalls, that exceed both or at least one of treshold values of the rainfall intensity for debris flow generation in the Tatra Mts, namely 25 mm/hour (cf. Fussgänger and Jadroň 2001, Kotarba 2007a), or 80–100 mm/24 hours (cf. Kotarba 1994); the overview is based on analysis of data from the meteorological station Skalnaté pleso Lake in the period 1949–2006 (Tab. 1). The station is situated approximately 2.5 km to the SSE from Zelené pleso Lake in altitude 1,778 m and it is possible to consider it as the most representative for this area. The table is complemented also by some data concerning more significant torrential rains recorded in this station, though they fulfil neither one of above mentioned criteria (however, in the case of daily totals only narrowly, as they range from 75 to 80 mm). The reason to take into account also these rainfall events is coming from our supposal that in the model areas they could fu lfil at least one of criteria.

Thus, at least in years of an occurrence of extreme rainfall events with daily efficiency exceeding 80 mm, or with hourly intensity higher than 25 mm, were exceeded treshold values necessary for debris flow generation. It is very probable that in these years either new debris flows arose (on places where there were not before), or they were reactivated on places where operated in the past (but in the meantime manifestations of their activity disapeared or were masked by vegetation on cones). The proof for this statement is the increase of areal extent of debris flows on airphotos after periods when there were recorded more extreme rainfall events.

Comparing years of the occurrence of extreme rainfall events in Table 1 with years introduced by A. Kotarba (2004, 2007b) we find that for the period 1949–2006 it is not the identical set. In Kotarba's years 1956, 1960, 1980 and 2003 there were not found out extreme rainfall events at Skalnaté pleso Lake. Naturally, extreme rainfalls has often the local character and thus in those years they were probably recorded in other parts of the High Tatra Mts. On the contrary, in years 1949, 1957, 1959, 1962, 1964, 1965, 1966, 1967, 1968, 1975, 1983, 1988, 1992, 1995, 1996, 1999, 2000 and 2002 that A. Kotarba (2004, 2007b) does not mention, there were exceeded threshold values for muddy flood generation at Skalnaté pleso Lake, in some cases even very markedly. Thus it is probable that also in some of these years debris flows could be triggered. Moreover, taking into account already mentioned Kotarba's (2007a) 35–40 mm/hour threshold value for the generation of significant debris flows affecting entire slopes, we assume that at least in years 1959 and 1988, when this threshold value was exceeded, marked flows could be generated in the surroundings of Zelené pleso Lake.

Table 1

Extreme rainfalls (1949–2006) (Skalnaté pleso) (over 75 mm/24 hours or 25 mm/hour)

Date	Daily precipitation [mm/24 h.]	Intensity [mm/h.]
30.6.1949	80.0	< 25
17.8.1949	45.7	26
5.8.1955	77.8	< 25
19.6.1957	62.1	36
29.6.1958	170.0	25
21.7.1959	71.8	49
1.6.1962	58.3	26
17.6.1962	88.5	< 25
18.7.1962	140.0	< 25
26.6.1964	38.0	30
10.6.1965	76.7	< 25
17.7.1965	58.2	33
25.7.1966	81.2	39
3.7.1967	58.2	29
18.7.1968	88.2	< 25
18.7.1970	144.5	< 25
25.7.1970	96.8	< 25
30.6.1973	102.5	< 25
24.6.1975	28.8	26
17.9.1983	83.3	< 25
16.8.1988	91.7	42
17.10.1992	108.1	< 25
30.5.1995	31.4	26
3.6.1996	36.5	27
8.7.1997	76.3	< 25
18.7.1997	103.6	< 25
3.6.1999	40.1	33
17.6.1999	36.5	32
15.6.2000	39.4	25
16.7.2001	79.6	< 25
20.7.2001	34.4	25
16.7.2002	75.0	33
18.7.2002	34.4	25
6.8.2002	33.3	25

Data of Slovak Hydrometeorological Institute, Bratislava

VELICKÁ DOLINA VALLEY

In the Velická dolina Valley there were identified and in the map indicated in all 38 debris flows on the basis of detailed analysis of airphotos taken in 2006. Comparing situation from 2006 with older airphotos we can state that no new tracks of debris flows arose in this area during the assessed period 1949–2006. As the number of debris flows in the whole period was not changed, their tracks (transport parts) were probably regularly renewed. In reverse case, in the course of time the older flows should not be visible. It is very probable the result of relatively frequent reactivation of debris flows. However, the debris flow tracks renew also by acting of fluvial processes after each more intense rain, not exceeding treshold values necessary for debris flow formation.

Though new tracks of debris flows did not arise in the valley, relatively numerous there were changes of debris flows on talus cones, what concerns both their gains and losses. The number of gains (losses) of debris flows on cones refers to the increase (decrease) of their activity as well as spatial distribution in time. Gains were manifesting in the form of new erosion-accumulation parts of flows (gullies, lobes, tongues). During the whole assessed period in the Velická dolina Valley there were registered in all 56 changes of debris flows that were manifested on 27 alluvial cones. 33 cases of these changes were gains, 23 were losses.

The most of losses (16) occurred in the temporal interval 1949–1973. However, it is necessary to stress that this interval is also the longest one (24 years) of assessed intervals. The results of airphoto analysis suggest that on some places of the valley there are not visible manifestations of debris flows as early as after roughly 5–12 years.

The most of gains (15) were registered unequivocally between years 2002 and 2006. Ortophoto of June 2002 and airphoto of 2003 were available from this valley. However, we did not work with this short time span (only one year) as with the separate time unit. The reason for it was that its comparing with longer temporal interval could bring distorted results. By coincidence, just in this short period, namely in 16 July 2002, the extreme rainfall event of extraordinary intensity happened in tha area of the Velická dolina Valley. As early as M. Boltižiar (2007) referred to its effect, though he did not know its precise date. According to him, tremendous debris flows penetrated in that time as far as in Velické pleso Lake. According to the data of the meteorological station in Tatranská Polianka, the daily precipitation total in that time was 112.7 mm. In connection with the location of this station at the foot of the High Tatra Mts J. Kapusta (2009) supposes that this rainfall event could be in the Velická dolina Valley, situated in higher altitude, substantially more marked. His statement is conjoined with the fact that due to low altitude and considerable distance it is not possible to consider the mentioned meteorolgical station as representative enough for the area of this valley. Thus, the airphotos from 2002 and 2003 enabled us to refer to geomorphic effect of debris flows originated during the only extreme rainfall event. Just this particular event resulted in mentioned 15 gains of flows of large extent. Later, between years 2003 and 2006, no changes of debris flows occurred in the valley.

As it was already stated, the number of changes of debris flows in given time interval refers to their activity and distribution, but it does not reflect their geomorphic effect expressed by the actual areal extent of these changes on talus cones. The precise and objective picture of spatio-temporal changes of debris flow operation in individual temporal intervals of the assessed period 1949–2006 can be gained only on the basis of comparison of calculated values of areal extent of their increase or decrease.

The actual areal extent of the active debris flows in the Velická dolina Valley (status from 2006) is more than 113,000 m^2 (ca 0.11 km^2) what represents 2.8% of the total area of the valley. In the framework of the assessed temporal intervals in the period 1949–2006, the highest areal extent of debris flows on talus cones (but also in the whole valley) was in the interval 2003–2006. The area of debris flows on cones in that time reached 58,138 m^2 (6.8% of the cone area). Increase and decrease of the area of debris flows (in %) on cones in individual temporal intervals in comparison with their areal extent in the preceding interval is shown on Figure 2. The graph suggests that in the interval 1949–1973 the area of debris flows on cones diminished by 29.3%, what testifies on their low activity in that time. In the following interval (1973–1986) the areal extent of debris flows on cones remained unchanged. It indicates that debris flows in these years operated on places of their occurrence in the preceding time interval and they had to renew obviously on the

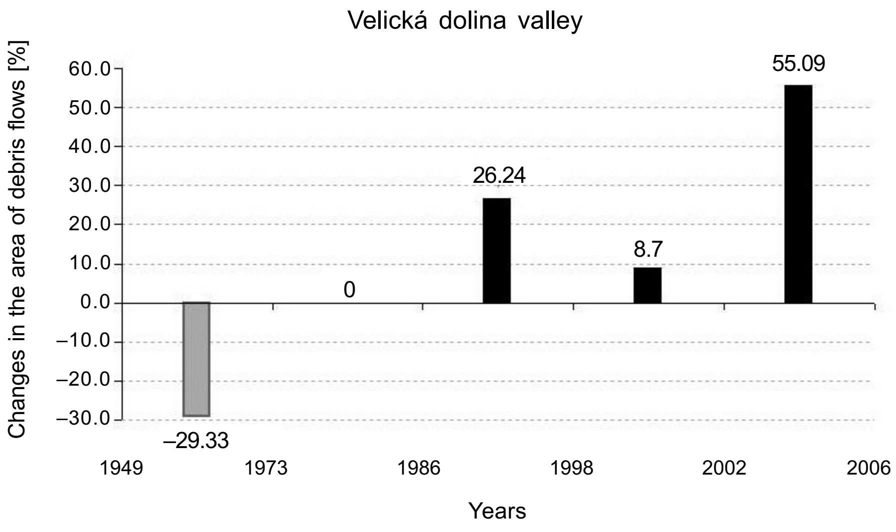


Fig. 2. Increase (decrease) of the area of debris flows in the Velická dolina Valley in particular temporal intervals of the assessed period 1949–2006

same places. Since 1986 it is visible the increase of areal extent of debris flows on talus cones in each following temporal interval in comparison with the preceding period. Marked increase was for instance in years 1986–1998 (26.2%), but especially in the interval 2002–2006 (55.1%). As it was already stated, it was the concequence of the only extreme rainfall event in 2002 (cf. Figs. 4a, b, 5 and 9). The development of spatial distribution of debris flows in the Velická dolina Valley in individual intervals of assessed period is shown on Figures 5–9.

Temporal trend of the geomorphic effectiveness of debris flows in individual time intervals, based on values of the share of debris flow area from the total cone area, is demonstrated on Figure 3. The graph indicates decreasing effectivity of debris flows in the valley in interval 1949–1973. Their operation was probably so expressionless in those years that their sites from the preceding period lost typical character of flows. Even if debris flows were locally reactivated, the reactivation occurred probably only in some their parts. In the following interval 1973–1986 the areal extent of debris flows on cones was not visibly changed. It suggests that debris flows, in comparison with the preceding period, started to act more intensely. However, their operation was restricted only to sites of older debris flows, as no enlargement of their distribution on cones arose. In intervals 1986–1998 and 1998–2002 the area of cones destructed by debris flows increased more markedly, what indicates that the geomorphic effectiveness of these flows was in these years still higher than in the interval 1973–1986. In the last interval 2002–2006 the debris flow effectivity in comparison with preceding intervals increased again and reached the maximum within the whole assessed period 1949–2006.

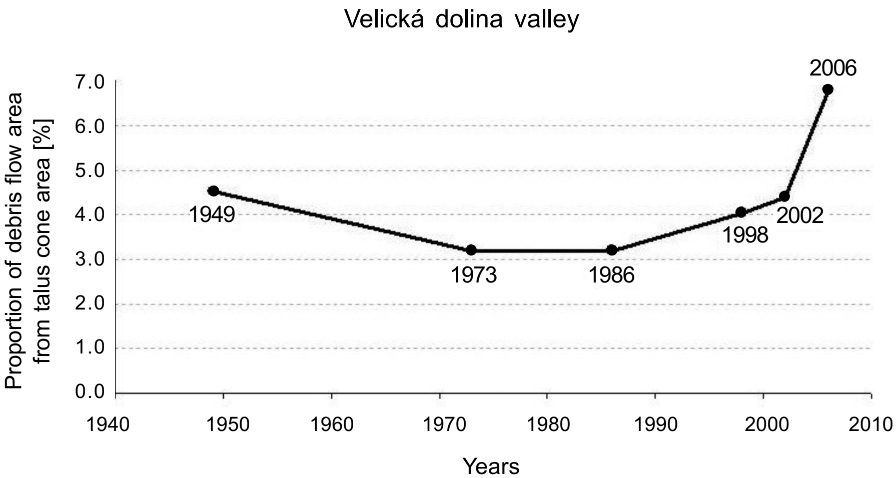
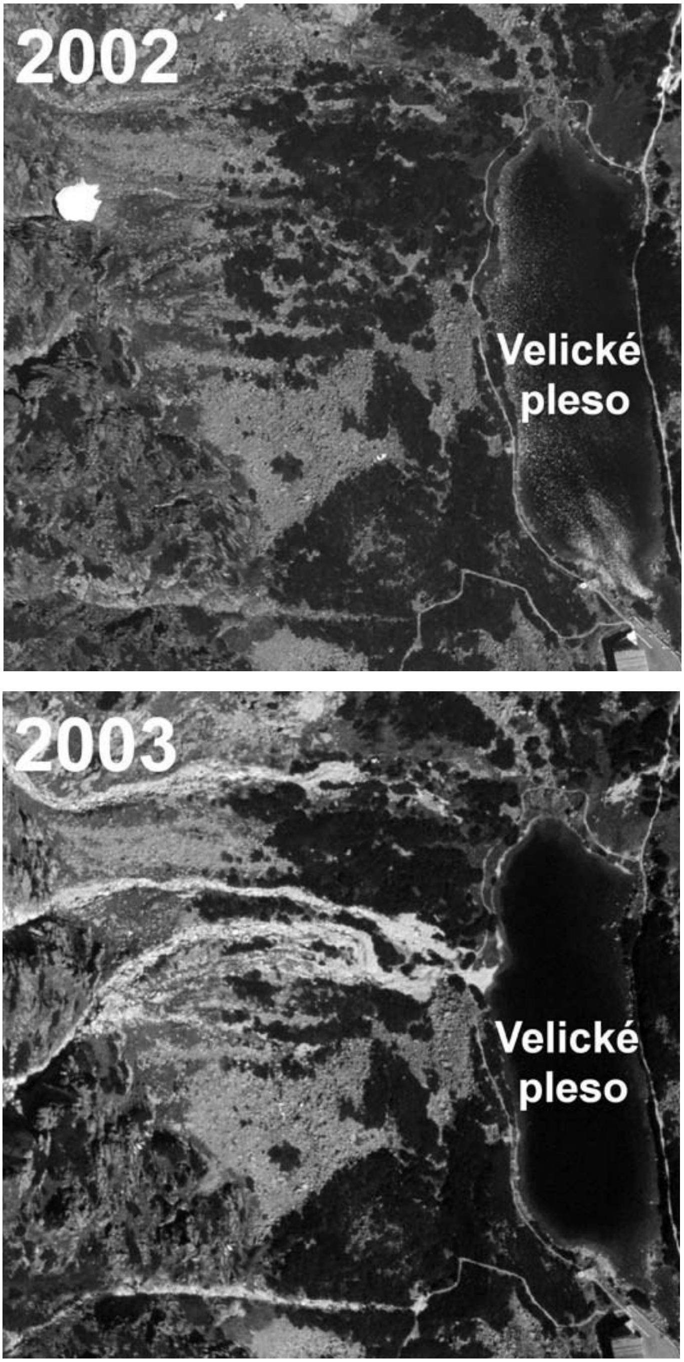


Fig. 3. Temporal trend of geomorphic effectiveness of debris flows on talus cones in the Velická dolina Valley in the period 1949–2006



Figs. 4a, b. Pair orthophotos of 2002 and 2003 from the Velická dolina Valley showing situation before and after the 16.7.2002 extreme rainfall event resulting in the creation of major debris flows (©: Eurosense Ltd. Bratislava)

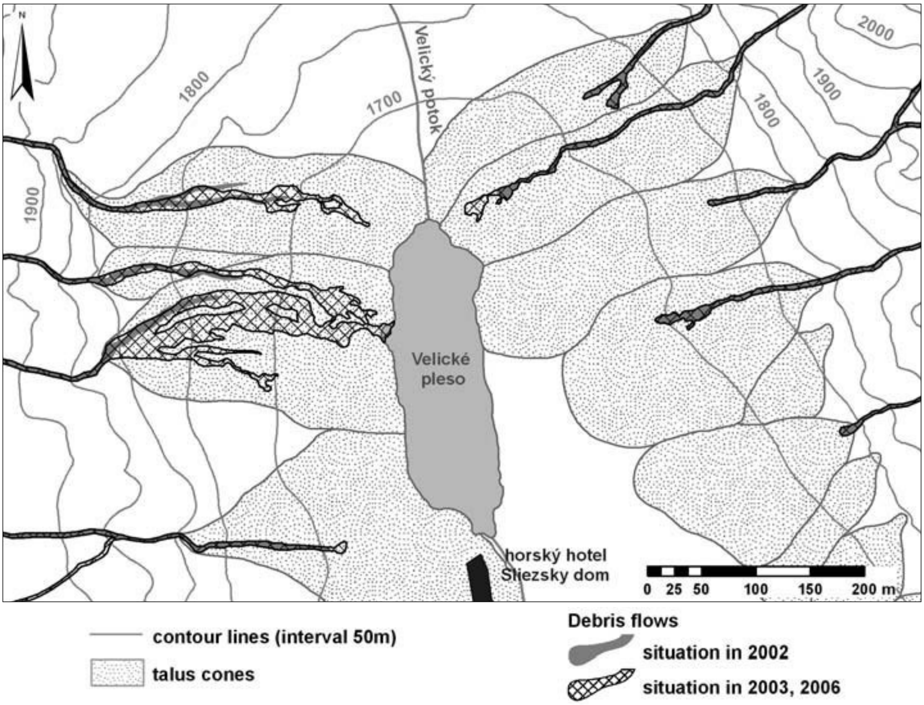


Fig. 5. Changes of debris flows in the Velická dolina valley (the site Velické pleso Lake) in the interval 2002–2006

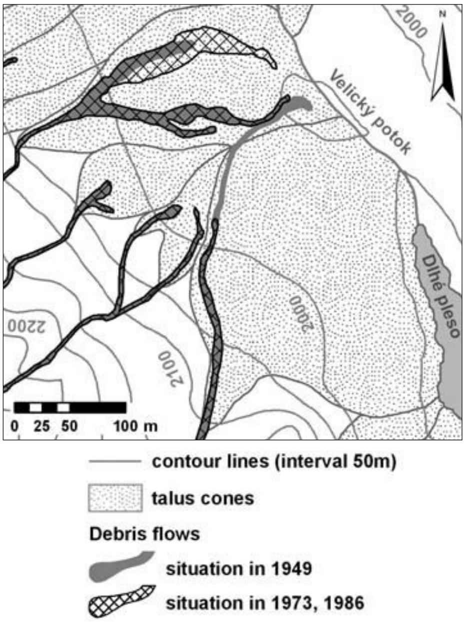


Fig. 6. Changes of debris flows in the Velická dolina valley (the site Dlhé pleso Lake) in the interval 1949–1986

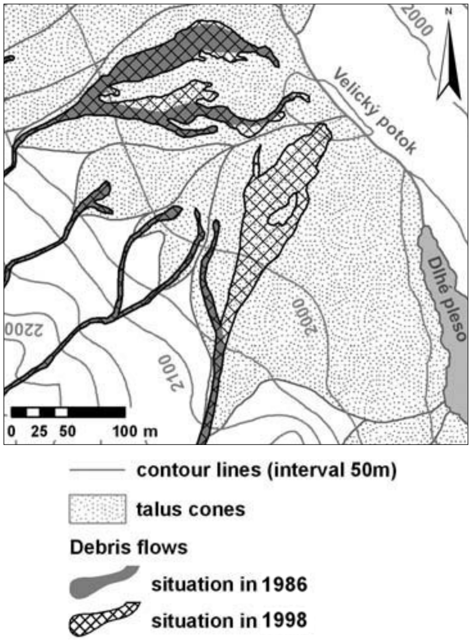


Fig. 7. Changes of debris flows in the Velická dolina valley (the site Dlhé pleso Lake) in the interval 1986–1998

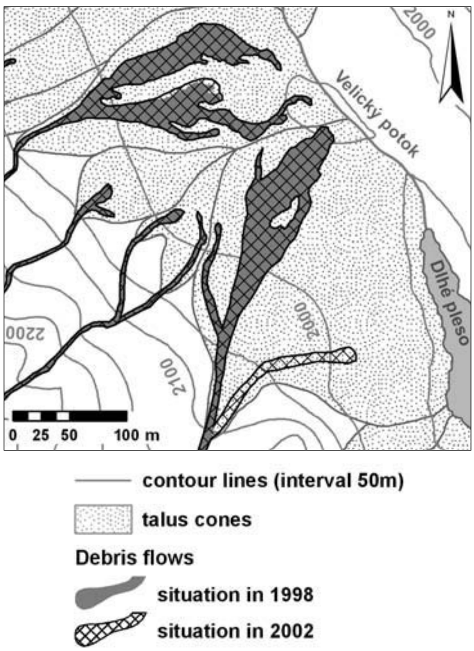


Fig. 8. Changes of debris flows in the Velická dolina valley (the site Dlhé pleso Lake) in the interval 1998–2002

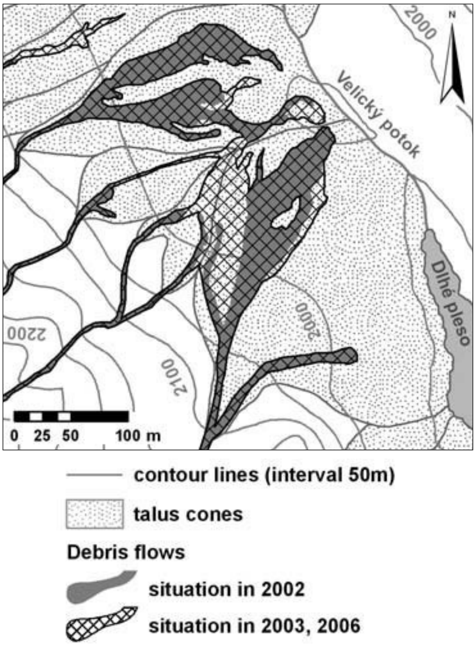


Fig. 9. Changes of debris flows in the Velická dolina valley (the site Dlhé pleso Lake) in the interval 2002–2006

DOLINA ZELENÉHO PLESA VALLEY

Detailed analysis of ortophotos from 2006 enabled us to identify in all 49 debris flows in the Dolina Zeleného plesa Valley to this year. From analyses of older airphotos it is obvious that most of gains of debris flows within the assessed period 1949–2006 is linked with temporal intervals 1949–1973 and 1998–2003. The most of losses is bound with the interval 1973–1986.

Debris flows in this valley cover (status from 2006) the area of 185,000 m^2 (ca 0.2 km^2) what means 3.3% of the total areal extent of the valley. The analysis of airphotos has revealed that the geomorphic effectiveness of debris flows in this valley is higher than in the Velická dolina Valley. It is testified also by the share of the areal extent of debris flows from the total area of talus cones (7.5%).

Development of spatial distribution of debris flows in the valley in individual assessed temporal intervals is shown on Figures 12–16. The highest areal extent of alluvial cones destructed by debris flows was registered in the interval 1973–1986. Debris flows in that time represented 8.3% of the area of cones. The minimum extent of debris flows was in the interval 1986–1998, they covered only 5.8% of the cone area in these years.

Increase (dicrease) of the area of alluvial cones affected by debris flows (in %) in the valley in particular assessed intervals in comparison with their areal extent in the preceding interval shows Figure 10. This graph indicates that in the years 1949–1973 the area of debris flows on cones was enlarged by 25%. The reverse tendency arose in the interval 1973–1986 when the area of debris flows decreased by 29.5%. Since this time the areal extent of flows was only increasing until the end of the study period. However, the increase of geomorphic effectiveness of debris flows on cones was not the same in individual assessed intervals of the

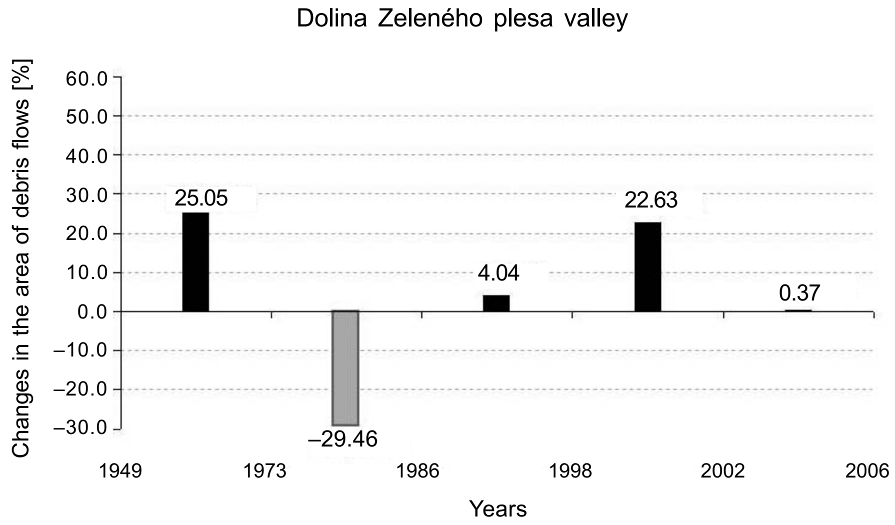


Fig. 10. Increase (decrease) of the area of debris flows in the Dolina Zeleného plesa Valley in particular temporal intervals of the assessed period 1949–2006

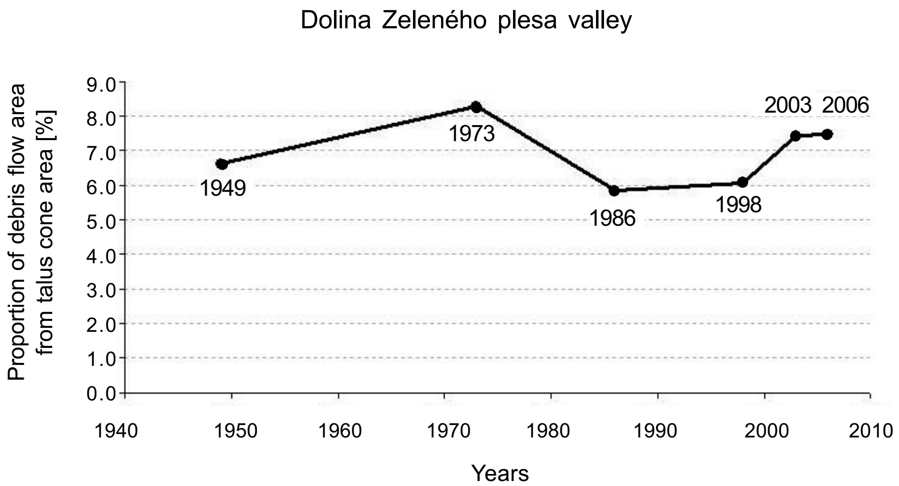


Fig. 11. Temporal trend of geomorphic effectiveness of debris flows on talus cones in the Dolina Zeleného plesa Valley in the period 1949–2006

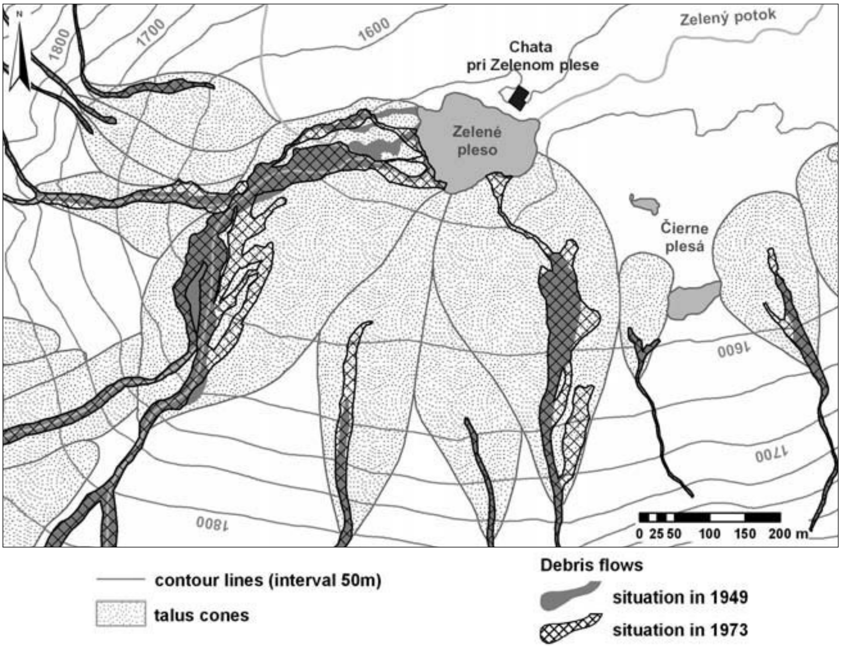


Fig. 12. Changes of debris flows in the Dolina Zeleného plesa Valley (the site Zelené pleso Lake) in the interval 1949–1973

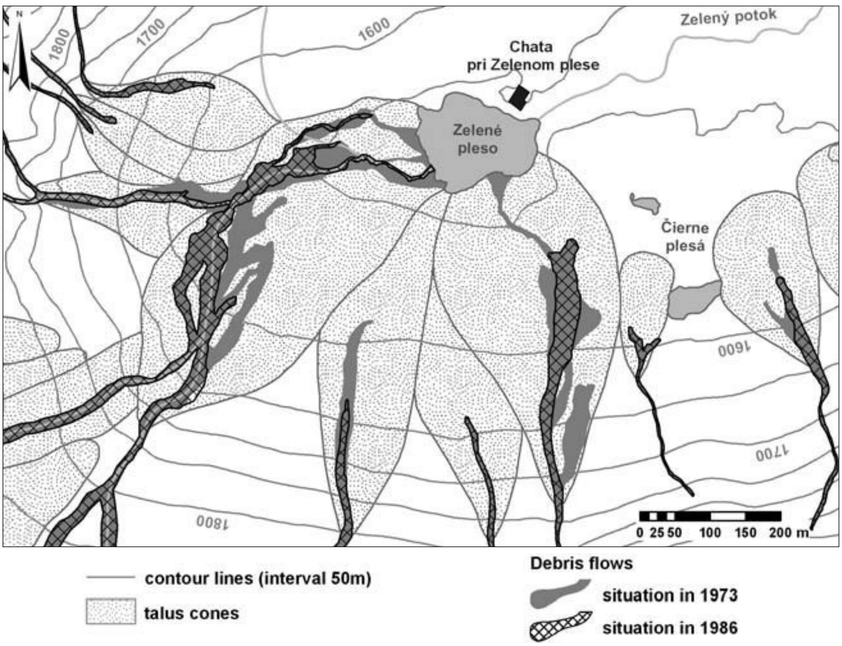


Fig. 13. Changes of debris flows in the Dolina Zeleného plesa Valley (the site Zelené pleso Lake) in the interval 1973–1986

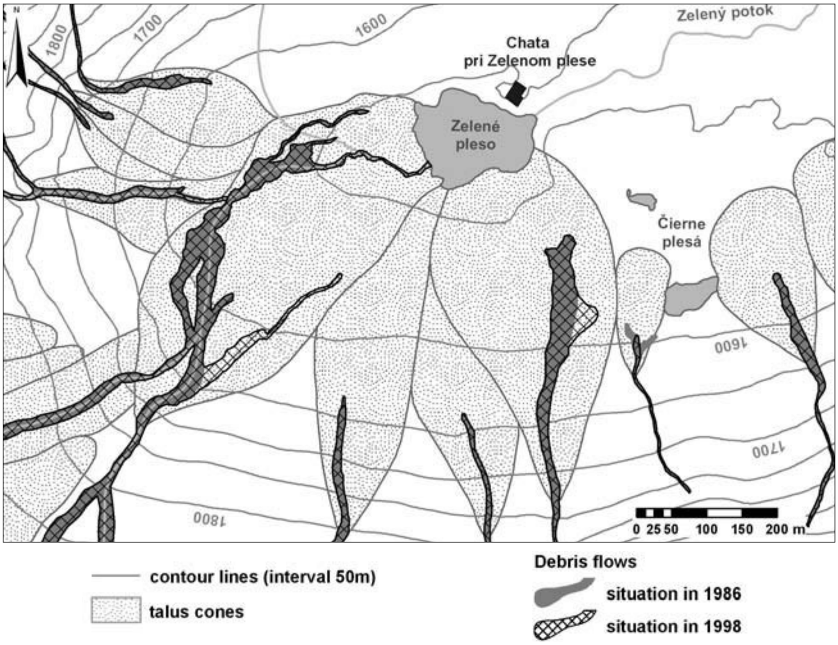


Fig. 14. Changes of debris flows in the Dolina Zeleného plesa Valley (the site Zelené pleso Lake) in the interval 1986–1998

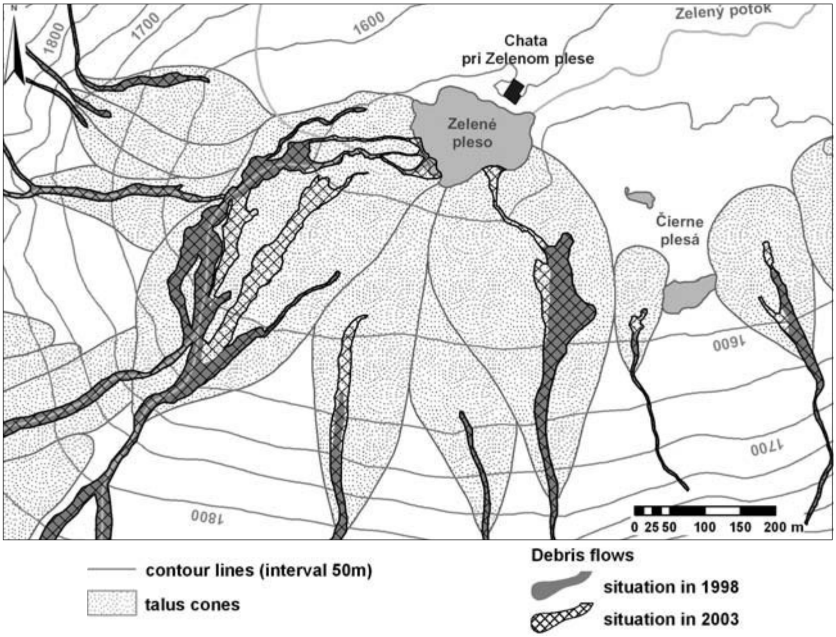


Fig. 15. Changes of debris flows in the Dolina Zeleného plesa Valley (the site Zelené pleso Lake) in the interval 1998–2003

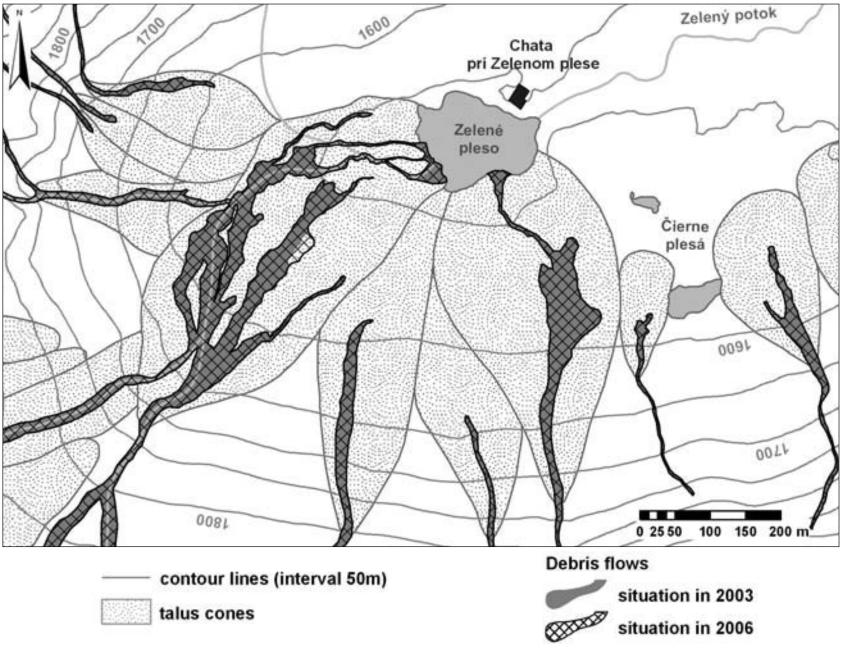
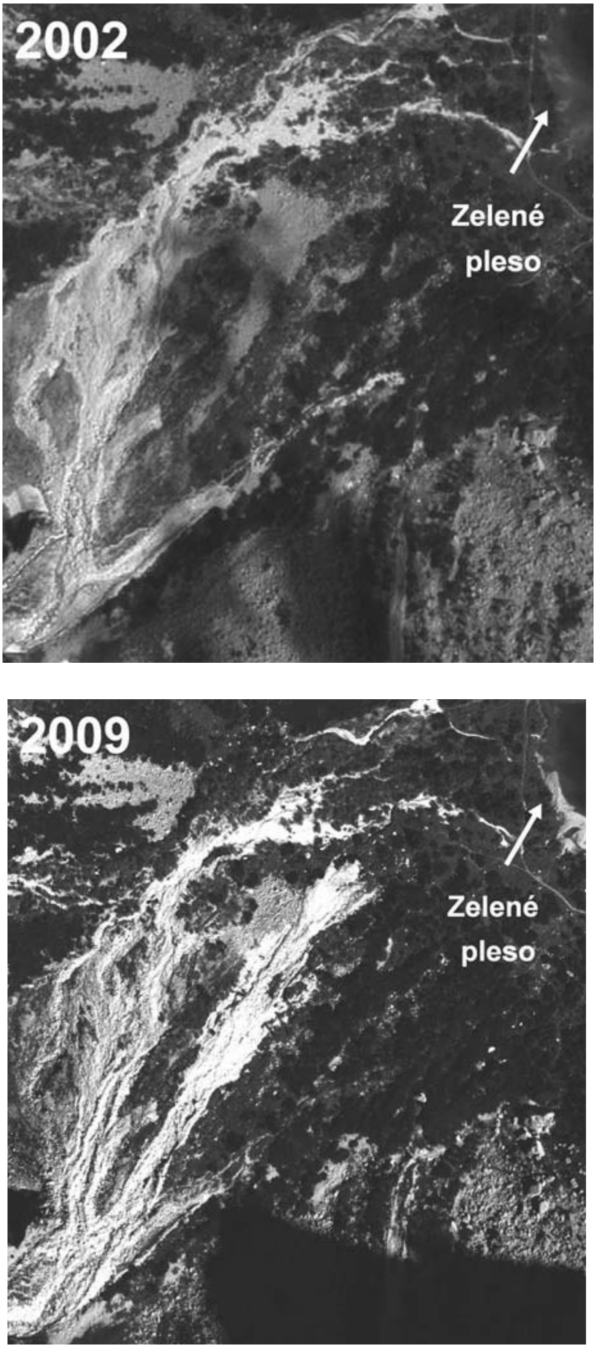


Fig. 16. Changes of debris flows in the Dolina Zeleného plesa Valley (the site Zelené pleso Lake) in the interval 2003–2006

period 1986–2006. The highest rise of debris flow area was registered in the interval 1998–2003 (22.6%), the lowest one in years 2003–2006. On the basis of the analysis of extreme precipitation data from the meteorological station at Skalnaté pleso Lake in years 1998–2003 we can state that mentioned high increase of debris flow area in the Dolina Zeleného plesa Valley is the consequence of extreme rainfall events, namely from 3 June 1999, 17 June 1999, but above all from 16 July 2002, when the threshold value of the debris flow generation was exceeded the most markedly (33 mm/hour). One of the most profound manifestations of the last of mentioned events was a formation of the tongue long approximately 300 and wide 15–40 m (Fig. 17a, b). Pair ortophotos show situation before and after the creation of this tongue (from practical reason of better readability we used the photo of 2009 instead of 2003 as the difference between them is, fortunately, negligible). What was surprising, the daily precipitation total at the meteorological station on Lomnický štít Peak in 16 July 2002 was only 52 mm. On the other hand, the station at Skalnaté pleso Lake registered in this day 75 mm total. However, the precipitation data from Lomnický štít Peak are due to specific location of the station on the peak summit in most cases obviously consideably underestimated. It is connected with the high windiness that results in lower precipitation totals and rates in summit parts of the Tatra Mts (cf. Konček et al. 1974). Thus we consider the meteorological station at Skalnaté pleso Lake as much more representative one for the



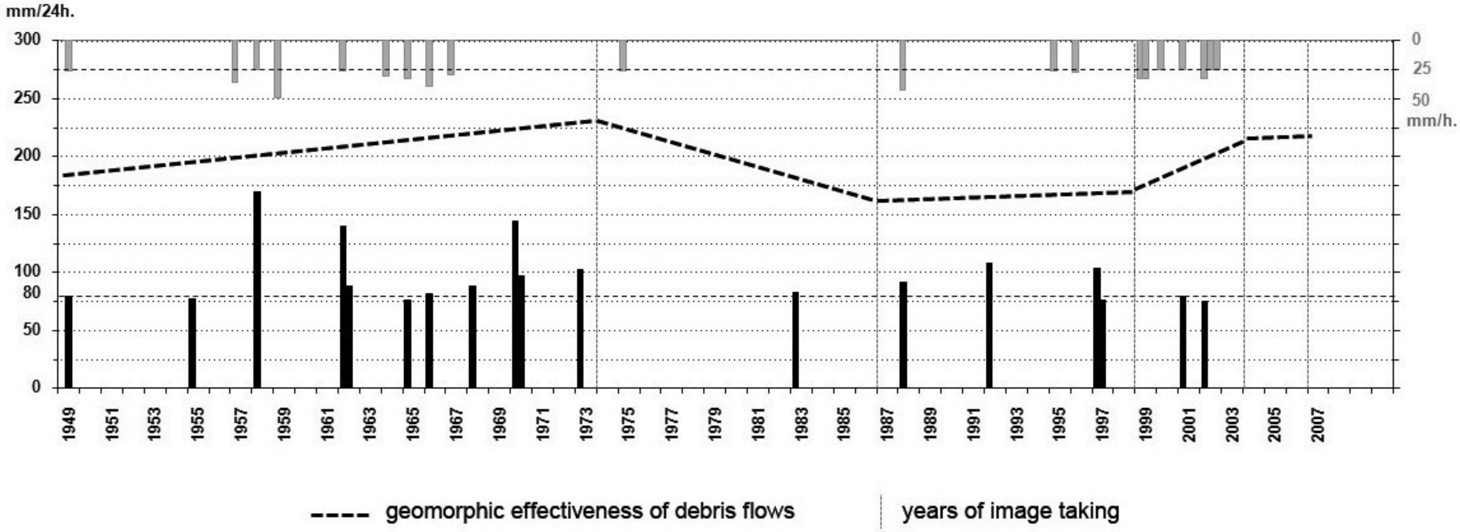
Figs. 17a, b. Pair orthophotos of 2002 and 2009 from the Dolina Zeleného plesa Valley showing situation before and after the 16.7.2002 extreme rainfall event resulting in the creation of major debris flows (©: Eurosense Ltd. Bratislava)

Dolina Zeleného plesa Valley than station on Lomnický štít Peak. Geomorphic effect of this extreme precipitation in the form of new erosion-accumulation parts of debris flows is visible on two photos in the article of A. K o t a r b a (2005). His photos no. 3 (23 August 2001) and no. 4 (20 September 2002) demostrate namely the situation before and after the event from 16 July 2002. Analysis in the GIS environment has revealed that this extreme event resulted in the destruction of at least the area of two football grounds in the area of Zelené pleso Lake. Changes in spatial distribution of debris flows in years 1998–2003 in this area are depicted on Figure 15. As this extreme rainfall event resulted in marked changes of debris flows in both model valleys (see Figs. 5, 9 and 15), it could not have narrowly local character but extensive changes of existing flows and origin of new ones obviously arose also in other valleys in this part of the High Tatra Mts.

We have found out that also Zelené pleso Lake itself is from time to time affected by debris flows. It is manifested by its clogging and consequently by diminishing of its area. During the assessed period debris flows penetrated into the lake in the interval 1949–1973 and in 2002. In the mentioned interval it was clogged by this way ca 523 m^2 of the lake, what represented 3% of its area, in 2002 ca 486 m^2, what diminished the lake by additional 2.9%. It means that during approximately four decades the area of the Zelené pleso Lake was decreased by ca 1,010 m^2 what represents almost 6% of its area from 1949! Similar important role of debris flows in clogging to gradual disapearance of glacial lakes is observable also in upper parts of some other Tatra's valleys, including Velické pleso Lake.

Temporal trend of the geomorphic effectiveness of debris flows in the Dolina Zeleného plesa Valley, expressed by alternations of their area on cones, is shown on Fig. 11. This graph indicates the increase in operation of debris flows in the interval 1949–1973. In the years 1973–1986 their effectivity decreased. Starting with the interval 1986–1998, the continuos increase of the geomorphic effect of flows is observable till the end of the studied period.

Relation between the temporal trend of the geomorphic effectivity of debris flows in the Dolina Zeleného plesa Valley to extreme precipitation events exceeding treshold values of debris flow generation, registered at meteorological station at Skalnaté pleso Lake, shows Figure 18. In the temporal interval 1949–1973, when the trend had rising character, there were recorded more extreme rainfall events. In the following interval (1973–1986), when there was identified the decreasing trend of debris flow effectivity, there were recorded just two extreme events and both exceeded treshold values only minimally. Thus, in this period the torrential rains were not mighty enough to generate more marked debris flows and even they do not suffice either for complete reactivation of already existing flows. In the next interval (1986–1998) more extreme precipitation events occurred. These events markedly exceeded treshold values of debris flow generation what was reflected in the increased trend of their geomorphic effectiveness. Probably only due to greater diffusion of extreme precipitation events in longer time sequence, the graph has more gently increasing course than in the following temporal interval. In years



Legend: curved thick broken line: temporal trend of geomorphic effectiveness of debris flows on talus cones; horizontal broken lines: treshold values of extreme rainfalls for debris flow generation, namely 25 mm/hour (top) and 80 mm/24 hours (bottom); black and gray columns: precipitation data from the meteorological station at Skalnaté pleso Lake exceeding at least one of these tresholds

Fig. 18. Relation of geomorphic effectiveness of debris flows to extreme rainfall events in the Dolina Zeleného plesa Valley in the period 1949–2006

1998–2003 more extreme precipitation events and accompanying debris flow formation occurred in the valley. The area of debris flows substantially increased. These facts confirm unequivocally the close linkage of debris flows to extreme rainfalls.

DISCUSSION

Comparing graphs indicating temporal trends of the geomorphic effectiveness of debris flows in the Velická dolina Valley (Fig. 3) and in the Dolina Zeleného plesa Valley (Fig. 11) we see that they differ each other, especially in the earlier period 1949–1986. In temporal intervals within these decades the effect of flows was really rather different, sometimes even opposed. It is connected with the fact that extreme precipitation, that is the main trigger of debris flows, has in most of cases the local character. However, the situation changed significantly within the last decades. Since the 1980s is observable the simultaneous increase in the activity and geomorphic effectiveness of debris flows in studied valleys, though that in the Velická dolina Valley was more marked. Our period of risen geomorphic effectiveness of debris flows since the 1980s corresponds approximately with the period of their increased activity by A. Kotarba (2004, 2007b), according to which this period lasts since the 1970s until now.

This increase in the activity and geomorphic effectiveness of debris flows can be connected with the climate change, that according to E. Fussgänger and D. Jadroň (2001) since the beginning of the 1980s influences the course of the weather in the world by provoking its sudden changes and fluctuations. According to these authors, fluctuations connected with climate change repeat after rougly each 2–8 years and their manifestations are observable already also in the central Europe. Just the 1980s represents according to P. Faško et al. (2008) the period of the first visible manifestations of the climate change in Slovakia too. To the most important of these manifestations belongs the increased frequency of the occurrence of extreme precipitation events as well as the increased intensity of these events. In the environment of the High Tatra Mts the extreme precipitation events initiate the generation of debris flows that are characteristic by significant geomorphic effectiveness, manifesting themselves in rocky troughs but especially on talus cones. The increasing frequency of extreme rainfalls conditioned the rise in the number of debris flow events, the rising intensity of precipitation resulted in the increase of geomorphic effectiveness of particular debris flows.

CONCLUSIONS

Debris flows represent one of the most dynamically and the most intensely acting exogenic geomorphic processes in the High Tatra Mts and at the same time they constitute the dominant high-energy slope process in the cryo-nival morphogenetic system of this mountain massif. They operate exclusively above the upper timber line where destruct relatively extensive areas. Their geomorphic effects are most marked on talus cones.

The article assesses the occurrence of debris flows and the development of their geomorphic effect in the period 1949–2006 in two model areas (the Velická dolina and Dolina Zeleného plesa Valleys) on the basis of the multitemporal trend analysis of remote sensing data, namely airphotos and ortophotos. The attention is paid to changes in the activity and geomorphic effectiveness of debris flows in temporal intervals between years of the origin of interpreted photos, i.e. 1949–1973, 1973–1986, 1986–1998, 1998–2002/2003 and 2002/2003–2006. Changes were identified and interpreted on the basis of the comparison of areal extent of debris flows on photos from individual temporal horizons. The highest increase of debris flows in the assessed period in the Velická dolina Valley was recorded in the interval 2002–2006, in the Dolina Zeleného plesa Valley in the interval 1998–2003. This increase in the former case represented exclusively, in the latter case mostly the effect of the one and the same extreme rainfall event from 16 July 2002. It resulted in the increase of debris flow area on cones by 55% in the Velická dolina Valley and in the creation of tongue with a length of ca 300 m and average width of 30 m in the Dolina Zeleného plesa Valley. Reconstruction of geomorphic response to this event made it possible to refer to significant effect of the only extreme precipitation event in comparison with the assessment of total effect of more consecutive events in the course of individual temporal intervals in question in the framework of studied period. Determined rate of this extreme precipitation (33 mm/hour) suggests that for the generation of significant debris flows affecting entire slopes in the High Tatra Mts is maybe sufficient the precipitation with hourly intensity ranging between 30–35 mm. As the extreme event of 16 July 2002 manifested itself by marked geomorphic effect of debris flows in both studied valleys, it was not of local character but more important changes of existing debris flows and formation of new ones obviously occurred also in other valleys in this area.

Comparison of temporal trends of the geomorphic effectiveness of debris flows in both valleys in the period 1949–2006 indicates that they differ each other, especially within earlier decades. The course of debris flow effectivity in assessed intervals in years 1949–1986 was in valleys not only rather different, but sometimes even opposed. It is connected with the local character of extreme precipitations in this period. However, since the 1980s the simultaneous increase in the activity and geomorphic effectiveness of debris flows in studied valleys is observable, though that in the Velická dolina Valley was more marked. This fact can be connected with the first manifestations of the climate change, expressing itself by the increased frequency of extreme rainfall events, as well as the increased intensity of these events. The extreme events occur in the Tatra Mts mostly in the summer period. Just summer torrential rains are the main cause of debris flow generation in this mountain massif. The increasing frequency of extreme meteorological-hydrological events conditioned the rise in the number of debris flow events, the rising intensity of precipitation resulted in the increase of the geomorphic effectiveness of particular debris flows.

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