Rainfall analysis of debris flows in the Obří důl Valley in the Krkonoše Mts., Czechia

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ABSTRACT

Rainfall is the most important triggering factor responsible for the occurrence of debris flows in the Obří důl Valley in the Krkonoše Mts. The critical rainfall conditions for slope failures are not the same for different debris flows, and may be strongly influenced by regional geological and geomorphological conditions. Nevertheless, analysis of hourly intensities, daily rainfall, cumulative data and the antecedent precipitation index (API) revealed that several of the above-mentioned factors are necessary to trigger the debris flow. On the other hand, a significant amount of daily rainfall (e.g. 225 mm) could trigger a debris flow without the support of any other rainfall characteristics in the monitored area and period under review. We used several rain gauges from the study area but the local differences in rainfall were so high that data from more remote stations was difficult to include in the Obří důl Valley. This is why only a limited amount of precise data is available for some years.

KEYWORDS

debris flow; rainfall analysis; Krkonoše Mts.

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1. Introduction

The main aim of the paper was to analyse rainfall data from several rain gauges in order to determine the rainfall threshold for triggering debris flows in the Obří důl Valley in the Krkonoše Mts. They have morphological as well as precipitation preconditions for debris flow occurrence. Due to this fact debris flows were described in the Krkonoše National Park in the frame of inventory of geomorphological features since early 1970s (Pilous 1973). This type of gravitational movement has been described in detail and analysed with respect to the genesis by Pilous (1973, 1975 and 1977). The Obří důl Valley has the largest occurrence of debris flows in the Krkonoše Mts. It is a well-developed glacial valley between Sněžka Mt. (the highest mountain in this range) and Pec pod Sněžkou Mt. The position of the surrounding mountains is clear from Fig. 1. Glacial modelling of headwalls and nivation hollows in the Obří důl Valley was analysed by Šebesta and Treml (1976), who studied debris flows in landscape development.

Debris flow paths in the Krkonoše Mts. are also connected with the occurrence of snow avalanches, which have been observed since the winter of 1961/62 according to the International avalanche classification (De Quervain et al. 1981). This classification was adopted for the Krkonoše Mts. by Spusta and Kociánová (1998), Spusta et al. (2003), Spusta et al. (2006), Kociánová and Spusta (2000), Kociánová et al. (2004), Vrba and Spusta (1975, 1991). The area of the Krkonoše Mts. has also been analysed from the point of view of its susceptibility to snow avalanches (Blahůt 2008; Suk and Klimánek 2011; Juras et al. 2013).

Rainfall is the most frequent triggering factor for shallow slope deformations (Záruba and Mencl 1982; De Vita and Reichenbach 1998; Schuster and Wieczorek 2002; Glade and Crozier 2005). These phenomena usually occur in places where surface and subsurface runoff is concentrated and where a sufficient amount of loose material is located. The most significant debris flows in the Obří důl Valley occurred during extreme rainfall events of 1882 and 1897, when

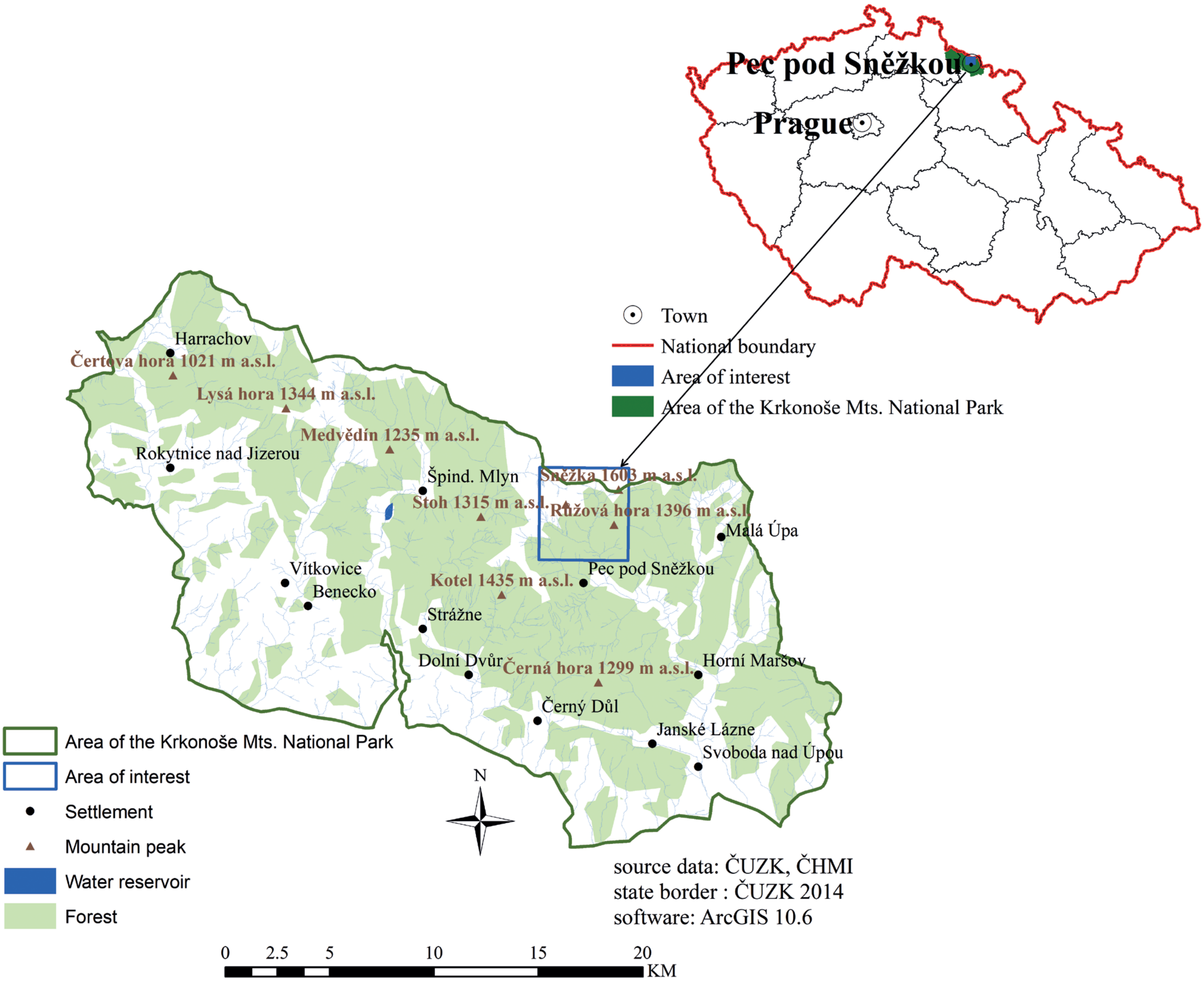


Fig. 1 The study area.

two houses were destroyed and seven people died (Pilous 2016).

In order to analyse landslides generated by rainfall it is important to establish the rainfall threshold, which is often connected with the relation between the duration and intensity of the rainfall (e.g. Turner and Schuster 1996; Novotný 2000; Schuster and Wieczorek 2002). Even rather low rainfall can trigger shallow landslides in the recently deforested areas or arid regions (Schuster and Wieczorek 2002). According to Turner and Schuster (1996) and Guzzeti et al. (2004). It is possible to establish rainfall thresholds for shallow landslides (up to 8 meters) on the basis of the optimal rate between the duration and intensity of the rainfall. Rybář and Novotný (2005) stressed the importance of seasonal and multiannual cycles in rainfall and temperature curves for landslide activity. There are two basic methods to define rainfall thresholds – physical and empirical based models. The physical model is based on the process of the landslide origin and conceptual approach comes out from historical or statistic data (Corominas 2000; Crosta and Frattini 2001; Aleotti 2004; Wieczorek and Glade 2005; Guzzetti et al. 2007). The thresholds can be considered as being global, regional or local (Guzzetti et al. 2004, 2007).

1.1 Antecedent precipitation index (API)

Antecedent rainfall is believed to play an important role in the initiation of debris flows because it reduces soil suction and increases the pore-water pressure (Thach et al. 2002). The API shows the rainfall situation retrospectively and is used to define the antecedent moisture condition (Mishra and Singh 2003). The API is also used to assess the saturation of the watershed. Soil moisture has a considerable influence on the physical properties of soil, e.g., pore-water pressure and shear strength (Zhao et al. 2011), which can affect the initiation of debris flows as discussed by Brand (1989), Marchi et al. (2002), and Wieczorek and Glade (2005). In addition, Crozier and Eyles (1980) consider antecedent climatic conditions to be crucial for the triggering of debris flows. The influence of antecedent rainfall is determined by seasonal variations in rainfall and temperature, which affect evapotranspiration. Intense convective storms occur during the summer when evapotranspiration can quickly remove much of the soil moisture. Consequently, the significance of antecedent rainfall may vary depending upon the regional climate (Wieczorek and Glade 2005). The average level of moisture in a catchment varies daily. It is replenished by rainfall and subsequently depleted by evaporation and evapotranspiration (Mishra and Singh 2003).

1.2 Determination of rainfall thresholds

A rainfall threshold is defined as the minimum rainfall conditions for triggering landslides in a particular region (Guzzetti et al. 2007). The determination of rainfall thresholds for landslide initiation is considered as a basic task in landslide hazard assessment, and various methods have been proposed to establish rainfall thresholds (Crosta 1998; Corominas and Moya 1999; Glade 2000; D'Odorico and Fagherazzi 2003; Zezere et al. 2005; Godt et al. 2006; Guzzetti et al. 2007; Marques et al. 2008; Dahal and Hasegawa 2008; Dahal et al. 2009; Frattini et al. 2009; Saito et al. 2010; Giannecchini et al. 2012).

One of the most difficult tasks in using antecedent rainfall for debris flow prediction is determining the number of days to be used (Guzzetti et al. 2007). A detailed literature review revealed a complex relationship between the number of days of the antecedent rainfall and the triggering of a landslide. Terlien (1998) considered 2, 5, 15 and 25 days for the Manizales area (Colombia). Kim et al. (1991) used 3 days, Heyerdahl et al. (2003) used 4 days, Glade (2000) used 10 days, Aleotti (2004) considered 7, 10, and 15 days, Zezere et al. (2005) used 1, 5, 10, 15, 30, 45, 60, 75 and 90 days., and Polemio and Sdao (1999) considered 180-day cumulative daily rainfall data. In summary, antecedent rainfall of between 3 and 120 days (Pasuto and Silvano 1998) can be used to explain the occurrence of landslides (Dahal et al. 2009). The large variability in the number of antecedent rainfall days may be influenced by factors such as: diverse lithological, morphological, vegetation, and soil conditions; different climatic regimes and meteorological circumstances leading to slope instability; and heterogeneity and incompleteness in the rainfall and landslide data used to determine the thresholds (Guzzetti et al. 2007).

2. Geological and geomorphological settings

The lithology of the area is not uniform. The northern slopes of the Obří důl Valley are composed of Krkonoše crystalline complex from the early Proterozoic – several hundred-meter-thick successions of beds of grey mica schist are interbedded with quartz, erlan and gneiss (Chaloupský and Teisseyre 1968). The weathered mantle on the slopes also varies in thickness. In the area of the rock outcrops, the mantle is limited only on local depressions, while in other areas it fluctuates between 20 cm and 2 meters. Talus deposits under the rock walls or talus cones on the foothills represent an even greater thickness (Pilous 1973). Boulders and stones prevail over gravel and sand; nevertheless, smaller particles (up to clayey) are also included. The largest boulders are around 2 meters in diameter but can vary from 20 to 100 cm (Pilous 1973). Debris flows have occurred in sediments with various grain-sizes, e.g. in stony-debris (the Nad Kovárnou site) as well as in areas where sandy fractions prevail (the Rudník site). Rankers have evolved on the top of the silicate rocks (Horník et al. 1986) at different sites, e.g. on crests, slopes or deluvial deposits, and most are covered with forest vegetation (Hraško et al. 1991).

The processes of erosion and denudation has gradually transformed the original Palaeozoic Variscan mountain range into a planation surface (i.e. slightly protruding highlands with softly undulated landforms) that reflect the structural conditions of the bedrock (Pilous 2016). According to the latest research based on the thermochronological analysis of samples from the Krkonoše Mts. (Danišík et al. 2010) erosion was responsible for the removal of between 3.6 and 6 km of rock between 100 and 75 Ma.

Research of neotectonic processes and the resulting landforms has long been focused on the Polish side of the Krkonoše Mts. (Migoń 1992). Its results support older opinions (Ouvrier 1933) that the Krkonoše Mts. represent a segmented horst. In the case of the Czech part of the Krkonoše Mts., tectonic processes have only been mentioned in relation to the landforms as a general background or in a very few case studies (Migoń and Pilous 2007). New research shows that their influence is probably much greater than first thought (Lysenko 2007). Hard rocks of the contact zone have also had an impact on the appearance of the landforms. Their extremely steep slopes create a typical hogback shape in the area of Čertův hřeben Ridge (Pilous 2016).

Glaciation of the Krkonoše Mts. is the feature most commonly studied by geomorphologists. Partsch (1894) and Migoń (1999) drew attention to the important role of the periglacial landscape, and particularly the extent and compactness of deflation zones on summit planation surfaces in the Sudetes mountain range. The latest and most complex findings on the extent of glaciation within the Krkonoše Mts. have been presented by Engel (1997, 2003, 2007). Glacial features dominate the relief of the central part of the Krkonoše Mts., where cirques and troughs are deeply incised into summit plateaus (Engel et al. 2014).

Contemporary research mainly involves cross-sectional and longitudinal profiling, radiometric dating and macroscopic analysis of glacial sediments, which, among other things, are performed to contribute to the correlation of moraines on both sides of the mountain range (Engel et al. 2010, 2014). The latest findings of Engel et al. (2014) show that only small cirque glaciers occurred during the last glaciation period.

The periglacial landforms in the Krkonoše Mts. were described by Králík and Sekyra (1969). These landforms and their genesis particularly in the last two decades were also studied by Sekyra and Sekyra (1995), Křížek (2007), Treml et al. (2010), Křížek and Uxa (2013). The most conspicuous and largest landforms are cryoplanation terraces occurring at various extents, lengths and perfections on almost every peak in the Krkonoše Mts. (Pilous 2016). The landforms on Studniční hora Mt. and Sněžka Mt. jutting above the alpine timberline are perfectly developed (Dvořák et al. 2004). Nivation forms can be found in the Obří důl Valley (Pilous 2016).

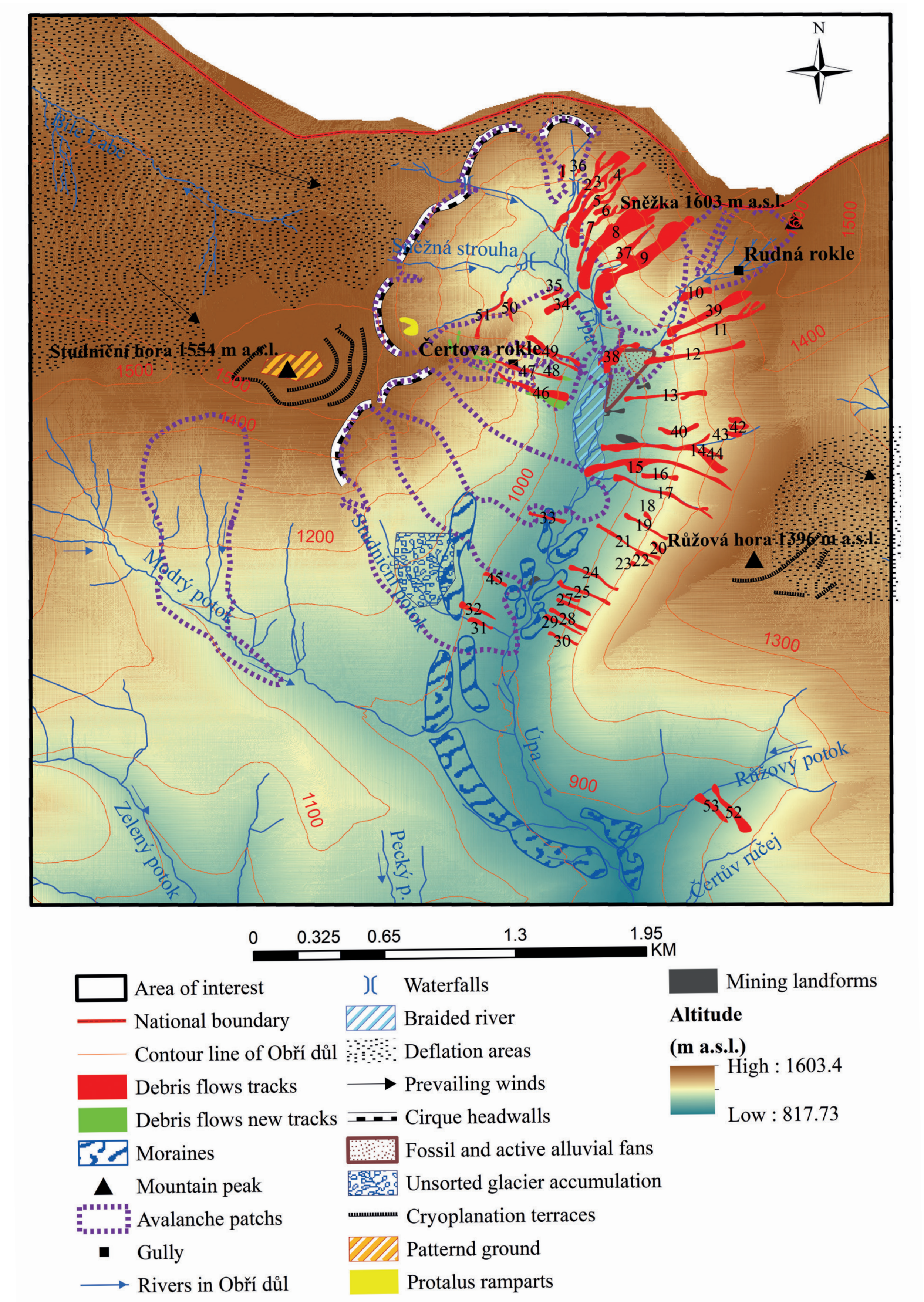
The analysis of factors determining the occurrence of debris flow can be divided into: geological, geomorphological, climatic and vegetational. The occurrence of debris flow is probably more connected to the ability of layers to contain water rather than the differences in grain-size distribution (Pilous 1973). The presence of mica in rocks supports the sliding process especially in the zone of saturation. The water from the flat area of the Krkonoše Mts. (levelled surface) infiltrates into the weathering mantle and through the system of joints and tectonic fractures into the massif and supports the saturation of loose material on the slopes of deeply incised valleys like the Obří důl Valley (Czerwiński 1967).

Geomorphological factors include: inclination and aspect of the slope, relative height, possible presence of snow avalanches and windward (or leeward) effect. The average slope inclination of the debris flow scarp and transitional area varies between 24° and 46°; however, at Čertova zahrádka and Čertova Gorge it can be between 33° and 90°. The vertical differentiation between the source and accumulation area is between 925 and 1460 m, while the length is from 30 to 680 m (Pilous 1977). The slope aspects with relation to prevailing winds were analysed by Sokol and Vavřík (1971) who revealed that the west oriented slopes (NW–W–SW) are the most affected in this area. A total of 83% of debris flows are fixed to these slopes in the Obří důl Valley (Pilous 1973). In terms of time distribution, most of the debris flows occur in June when the weathered mantle and soil are still well saturated from melted snow and storms can happen (Sokol and Vavřík 1971). Most of the debris flow scarp areas are below the timber line (Pilous 1977) where the vegetation is shallowly rooted (spruce), and trees can work during strong winds as crowbars.

3. Historical overview of debris flows

Debris flows in the Krkonoše Mts. are the largest and oldest, according to literature descriptions and documentation. The oldest engraving is from 1804 in Rudník, where one debris flow path can be documented. Other engravings and lithography are from the mid-19th century (Tittel 1830; Knippel 1850 and Tauber around 1850) and the locations are again Rudník and additionally Sněžka Mt.

In the first stage of the inventory, 35 debris flow paths in the Obří důl Valley were identified (Pilous 1973). The next inventory from 1977, which was based on the analysis of photos, field inspections, monitoring and more accurate data from the first inventory, revealed 51 events (Pilous 1973, 1977). In one particular case, more accurate dating appeared, i.e. for 25 August 1938 (Šourek 1977).



source data: KRNAP, ČÚZK, Google Earth, Blahůt et al. (2013-2015), Engel et al. (2014), Pilous (2016)
software: ArcGis 10.4.1.

Fig. 2 Geomorphological map.

Tab. 1 List of debris flows (elaborated according to Pilous 1973, 1977). Colour: yellow and red – first stage of the inventory (Pilous 1973); only red – two houses destroyed and seven people killed (29/7/1897); green – next stage of the inventory (Pilous 1977); blue – the newest origin of debris flows in the Růžová důl Valley (Myslil 1997).

No.	Location	Date of origin	No.	Location	Date of origin
1	Úpská jáma Cirque	14/7/1964 (the youngest)	27	SE slope Růžová hora Mt/	(2–3/7/1926)
2	Úpská jáma Cirque	?	28	SE slope Růžová hora Mt.	(2–3/7/1926)
3	Úpská jáma Cirque	?	29	SE slope Růžová hora Mt.	(2–3/7/1926)
4	Úpská jáma Cirque	> 1882	30	Modrý důl Valley	?
5	Úpská jáma Cirque	> 1882	31	Výsluní Modrý důl Valley	?
6	Úpská jáma Cirque	> 1882	32	Výsluní Modrý důl Valley	?
7	Úpská jáma Cirque	> 1882	33	Velká studničná jáma Cirque	?
8	Úpská jáma Cirque	> 1882; 17/7/1882	34	Čertův hřeben Ridge	17/7/1882
9	Zadní Rudník	> 1882 17/7/1882	35	Čertův hřeben Ridge	17/7/1882
10	Rudná rokle	> 1882 17/7/1882	36	Úpička drainage through	?
11	Rudná rokle	> 1882 17/7/1882 (the oldest)	37	Zadní Rudník	?
12	Rudná rokle	(> 1882) 17/7/1882 29/7/1897	38	Rudník	?
13	Pod Kovárnou	29/7/1897	39	SW slope Sněžka Mt. /Rudná rokle	?
14	Růžová hora Mt.	29/7/1897	40	SW slope Sněžka Mt.	?
15	Růžová hora Mt.	29/7/1897	41	Růžová hora Mt.	?
16	Růžová hora Mt.	(29/7/1897)	42	Růžová hora Mt.	?
17	Růžová hora Mt.	(29/7/1897)	43	Růžová hora Mt.	?
18	Růžová hora Mt.	(29/7/1897)	44	Růžová hora Mt.	?
19	Růžová hora Mt.	(29/7/1897)	45	Výsluní Modrý důl Valley	12/7/1937
20	Růžová hora Mt.	(29/7/1897)	46	Čertova rokle	18/6/1974
21	Růžová hora Mt.	(29/7/1897)	47	Čertova rokle	22/6/1975
22	Růžová hora Mt.	(29/7/1897)	48	Čertova zahrádka	18/6/1974
23	SE slope Růžová hora	?	49	Čertova zahrádka	18/6/1974
24	SE slope Růžová hora	?	50	Čertův hřeben Ridge	18/6/1974
25	SE slope Růžová hora	?	51	Čertův hřeben Ridge	18/6/1974
26	SE slope Růžová hora	?	52+53	V Korytech Růžový důl Valley	7/1997

From the debris flow paths identified in the study area the oldest in Tab. 1 are numbers 4, 5, 6, 7, 8, 9, 11 and partially 12. The largest number of events occurred during intensive rainy periods (17/7/1882, 29-30/7/1897, 2-3/7/1926) and affected the whole of the Krkonoše Mts. Two of the above-mentioned events from Růžová hora Mt. (No. 14 and 15) had a direct catastrophic influence on a small settlement at the bottom of the Obří důl Valley, where two houses were completely destroyed and the debris flow left behind seven fatalities. Unfortunately, historical sources do not always provide the precise locations, like after the 1926 rainfall period. Ouvrier (1933) mentioned only that debris flows were identified in all of the larger valleys in the Krkonoše Mts.

Ouvrier (1933) described the debris flows that occurred during the night of 2 July 1926, in the Krkonoše Mts., but without any precise location. If these debris flows originated in the Obří důl Valley, then they were probably in the forested area of the Růžová hora Mt.

4. Data and methods

4.1 Rainfall data

The rainfall data were taken from fourteen rain gauges located near the Obří důl Valley (Fig. 3). The precise amount of rainfall is usually not known in the head scarp of the slope deformation because there are no rain gauges directly in that area. Therefore, we had to use the nearest stations and because of the rainfall variability due to possible orographic effects we also tried to consider the position of the rain gauge compared to the detachment area (detailed data are included in Tab. 2). Eleven rain gauges operated by the Czech Hydrometeorological Institute (CHMI) are located within a distance of 0.5 to 23 km (two of them are located between 0.5 and 5 km) from the triggering area of the debris flows (Tab. 2). Data from the National Center for Environmental Information – National Oceanic and Atmospheric Administration, National Climatic Data Center, U.S. Department of Commerce (NCDC NOAA) are available for stations at Sněžka Mt. and Pec pod Sněžkou for 6 h, 12 h, and daily amounts (see Tab. 2).

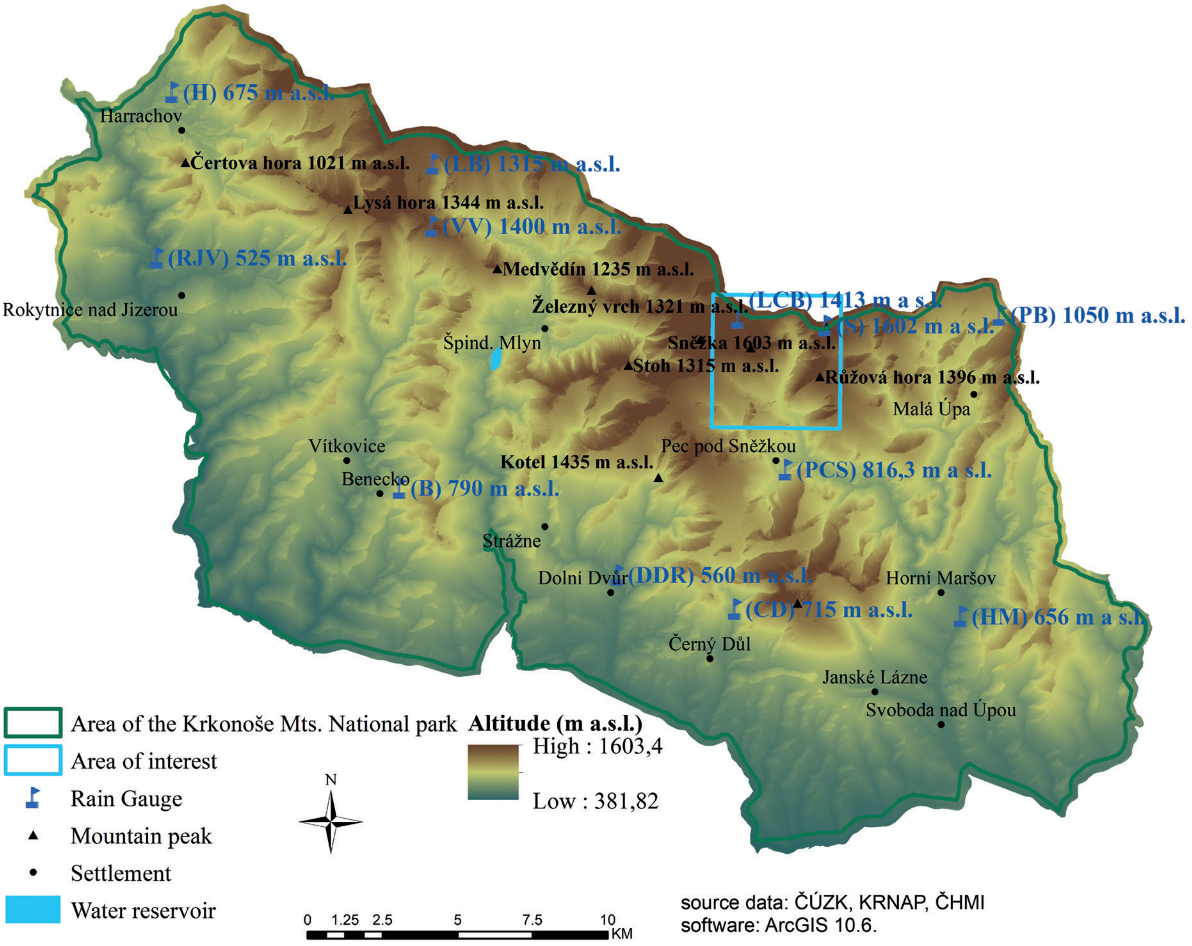
Rain gauges are located in a similar climatic region – very cold and cold with abundant precipitation (Quitt 1971) with the different geological setting – gneisses and migmatites that underwent retrograde metamorphism and biotite metagranites to metagranodiorites and orthogneisses and porphyritic biotite granite (Cháb et al. 2009). Nevertheless, they are at different elevations and windward and leeward slopes have created the variability. The rain gauge on Sněžka Mt. (S in Tab. 2) is the most relevant because of its elevation (1602 m a.s.l.) and close vicinity to the Obří důl Valley. Historical rainfall data are also available from this station (see Tab. 2) (Schneider 1897; Demuth 1901; Jitrasek 1915). Rainfall data were analysed for the available period up to 2006, because data after 2006 suggested rather low rainfall values. The rain gauge at Luční bouda only has available data since 2009 and was also not analysed due to low rainfall values.

4.2 Data analyses

Daily rainfall, hourly rainfall, antecedent rainfall and cumulative rainfall data were used to estimate the rainfall threshold.

4.2.1 Daily rainfall

Daily rainfall data represent the total amount of rainfall measured in the selected CHMI rain gauges (LCB,



source data: ČÚZK, KRNAP, ČHMI
software: ArcGIS 10.6.

Fig 3. Map of rain gauges: (S) – Sněžka, (LCB) – Luční bouda, (PCS) – Pec pod Sněžkou, (PB) – Pomezní boudy, (CD) – Černý důl, (DDR) – Dolný Dvůr-Rudolfov, (HM) – Horní Maršov, (LB) – Labská bouda, (B) – Benecko (according to CHMI).

Tab. 2 Location of the selected rain gauges in the area of interest (according to CHMI and NCDC NOAA); rain gauge: see Fig. 3, type of rain gauge: AWS – automatic weather station; AWS$_3$ – automatic weather station without operator; ACS$_1$ – first-order automatic climatological station; ACS$_4$ – fourth-order automatic climatological station; APS – automatic precipitation station; MPS – manual precipitation station.

Rain gauge	Code	Elevation (m a.s.l.)	Distance from the study area (km)	Measurement period (CHMI)/ Historical data	Measurement period (NCDC NOAA)	Type of rain gauge
(S)	H7SNEZ01	1602	0.5–1.65–2.7	Historical data	01/11/1952–31/12/1963	AWS$_3$
					01/10/1973– 01/11/2017	
(LCB)	HLUCB01	1413	1.6–3	20/01/2009–31/12/2014	–	ACS$_1$
(PCS)	HPECS01	8163	2.4–5	15/06/1962–31/12/1971	01/11/1936–31/12/1941	AWS
				01/02/1988–31/12/2014	01/10/1988–01/11/2017	
(PB)	H1POMB01	1050	6.3–7.5	10/05/1994–31/12/2014	–	APS
(CD)	H1CDUL01	715	7.3–10	24/06/2005–31/12/2014	–	APS
(DDR)	H1DDVU01	560	8.3–10.5	16/05/1894–31/03/1939	–	APS
				01/05/1941–31/07/1945		
				01/04/1963–31/12/2014		
(HM)	H1HMAR01	565	9.4–11.4	01/01/1961–31/12/2014	–	APS
(LB)	H1LBOU1	1315	12.8–14.3	01/01/1961–31/04/1997	–	ACS$_1$
				21/06/1997–31/09/1999		
				01/10/2002–31/12/2014		
(B)	P2BENE01	790	13.5–14.5	01/01/1932–31/12/1937	–	MPS
				01/01/1938–31/12/2014		
(RJV)	P2ROKY01	525	21–22	22/07/1958–31/12/2014	–	MPS
(H)	P2HARR01	675	22–23	01/01/1951–31/12/2014	–	ACS$_4$
(VV)	HVITKO1	1400	12.3–13.3	01/07/1945–31/05/1974	–	–
				01/07/1974–31/12/1978		
(OD)	–	–	–	Historical data	–	–
(SE)	–	–	–	Historical data	–	–

PCS, PB, CD, DDR, HM, LB, B, RJV, H and VV in Tab. 2) and in the selected National Centers for Environmental Information (NCDC NOAA) (rain gauge: S and PCS) during a single day (from 7:00 a.m. of the first day to 7:00 a.m. the next day). These records were provided by CHMI for the period 1894–2014 for the selected rain gauges. Daily rainfall was analysed with the selected maximum values from the rain gauges. We selected data over 100 mm and then compared them with values from other rain gauges, to avoid low rainfall values which were common. For the station on Sněžka Mt. (rain gauge S in Tab 2.) the daily rainfall data were taken from historical chronicles (see in Tab. 2) (Anonymous 1889–1941, 1897a, 1897b; Schneider 1897; Demuth 1901; Jitrasek 1915) and from the National Centers for Environmental Information (rain gauge S$_2$) (NCDC NOAA).

4.2.2 Hourly rainfall

One-hour, two-hour, two-hour and thirty minute, and four-hour rainfall data were used from historical chronicles (Anonymous 1889–1941, 1897a, 1897b; Schneider 1897; Demuth 1901; Jitrasek 1915) also from the Sněžka Mt. rain gauge. Hourly rainfall data from the other rain gauges were not available. Six-hour and twelve-hour rainfall data were used from the National Centers for Environmental Information (NCDC NOAA) for the Sněžka Mt. and Pec pod Sněžkou rain gauges.

4.2.3 Antecedent precipitation index

The API was firstly expressed by Kohler and Linsley (1951). The equation is generally defined as follows:

$$API_n = \sum_{i=1}^{n} c^i \times P_i \,[mm]$$

Where n is the total number of days prior to the causal rainfall, usually 5, 10 or 30;
i is the number of days counting backwards from the date on which the API is determined;
c is an evapotranspiration constant (for the Czech Republic it is c= 0.93 (Steinhart 2010);
P_i is the amount of precipitation in days prior to the causal rainfall (mm).
The API was calculated for a number of days (n = 5, 10, and 30) from the daily amounts of rainfall in the period when debris flows occurred and selected dates when daily rainfall reached 100 mm.

4.2.4 Cumulative rainfall data

We considered 90-day cumulative daily rainfall data only from the selected CHMI rain gauges (CD, PCS, PB, DDR, HM, LB, B, RJV, H, VV), due to their availability. We compared the cumulative rainfall data from when debris flows occurred with the daily rainfall data over 100 mm from the other rain gauges (during the period between 1897 and 2006). The rainfall values from 2006 to 2014 were relatively low in all of the available rain gauges.

4.2.5 Determination of rainfall thresholds

The rainfall conditions that trigger debris flows can be different. The rainfall thresholds were determined based on daily, hourly, 90-day cumulative rainfall data, and the antecedent precipitation index for 5, 10 and 30 days. It was important to determine the number of days for the antecedent rainfall and to analyse the correlation between the daily rainfall in relation to the debris flows events and the corresponding antecedent rainfall (Zezere et al. 2005) for three periods: 5, 10 and 30 days from two selected rain gauges, Pec pod Sněžkou and Labská bouda.

5. Results

5.1 Daily rainfall

The highest daily rainfall in the years when debris flows occurred and from all the available rainfall data was 266 mm in the Obří důl Valley on 29 July 1897 (see Fig. 4). On the same day, the Sněžka Mt. (S) rain gauge measured 239 mm, whereas the meteorological station at Sedmidolí registered only 93 mm. This means that there were rather large differences over relatively short distances of 0.5–2.7 km (see Tab. 2). Other debris flows (Fig. 4) were triggered during rather low daily rainfall levels (0.2 mm (DDR), 18.5 mm (RJV), 21.6 mm (DDR), 26.5 mm (B), 29.3 mm (B) and 65.7 mm (B)), it which that daily rainfall records could not be considered alone. This is also supported by the fact that we found several days with rather high daily rainfall without any debris flow (Fig. 4). The highest daily rainfall when no debris flow was registered is from 7 August 2006 (193.1 mm at rain gauge B), the second highest rainfall value was measured on 31 August 2002 at rain gauge PB (191 mm). The rainfall recorded at several of the gauges reached the limit of 100 mm. Five of the selected rain gauges (PCS, PB, DDR, LB and VV) recorded 20 days when the daily rainfall levels were up to 100 mm. Rain gauge PB is only 6.3–7.5 km from the study area, which is relatively close.

5.2 Hourly rainfall

First of all, we checked the highest hourly rainfall levels during debris flow events. The highest was registered during 17 July 1882 and reached 45 mm (rain gauge S). The same station also measured very high daily rainfall (see the chapter above). The other debris flow events could not be explained by hourly rainfall extremes. On 18 June 1974, station S measured almost 73 mm in 3 hours during a heavy storm. What is again surprising is that no debris flow occurred on

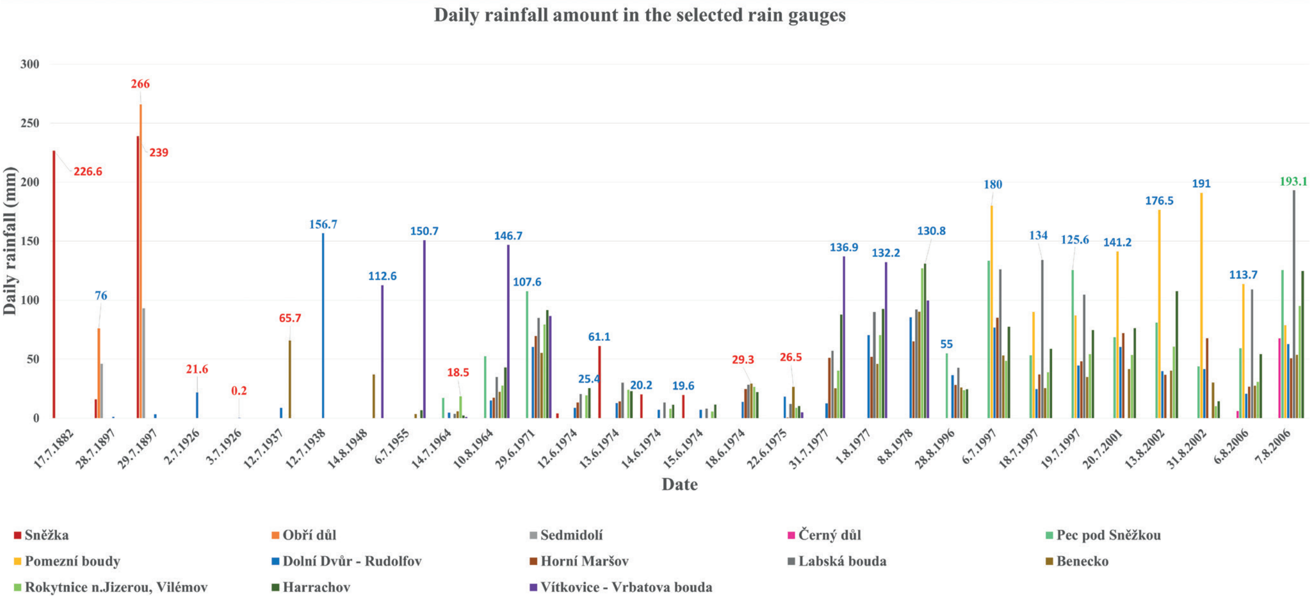


Fig. 4 Daily rainfall levels in the selected rain gauges (Sněžka, Obří důl, Sedmidolí, Černý důl, Pec pod Sněžkou, Pomezní boudy, Dolní dvůr Rudolfov, Horní Maršov, Labská bouda, Benecko, Rokytnice n. Jizerou – Vilémov, Harrachov, Vítkovice-Vrbatova bouda) in the period from 1882 to 2006. Colours: red – occurrence of debris flows (source: CHMI and Anonymous 1889–1941, 1897a, 1897b, Schneider 1897, Demuth 1901, Jitrasek 1915); blue – debris flows did not occur; green – the total maximum daily rainfall when debris flows did not occur (source: CHMI).

Tab. 3 Hourly rainfall levels from the Sněžka Mt. and Pec pod Sněžkou rain gauges in the period from 1882 to 2002. Colours: blue – occurrence of debris flows; white – no debris flows; the number in green is the absolute highest maximum twelve-hour rainfall data (mm); dash – data not available (source: NCDC NOAA).

Date	S						PCS	
	1 h	2 h	2 h 40 min	4 h	6 h	12 h	6 h	12 h
17/7/1882	45.0	–	–	178.0	–	–	–	–
28/7/1897	–	–	–	–	–	–	–	–
29/7/1897	11.0	–	–	–	–	–	–	–
2/7/1926	–	–	–	–	–	–	–	–
3/7/1926	–	–	–	–	–	–	–	–
12/7/1937	–	–	–	–	–	–	–	–
12/7/1938	–	–	–	–	–	–	–	–
14/8/1948	–	–	–	–	–	–	–	–
6/7/1955	–	–	–	–	–	–	–	–
14/7/1964	*storm 48.2	25	–	–	–	–	–	–
10/8/1964	–	–	–	–	–	–	–	–
29/6/1971	–	–	–	–	–	–	–	–
12/6/1974	–	–	–	–	–	5.9	–	–
13/6/1974	–	–	–	–	–	74.9	–	–
14/6/1974	31.0	–	–	–	–	–	–	–
15/6/1974	–	–	–	–	–	17.0	–	–
18/6/1974	–	–	72.9	–	–	70.1	–	–
22/6/1975	–	–	–	–	–	10.1	–	–
31/7/1977	–	–	–	–	1.01	–	–	–
1/8/1977	–	–	–	–	–	80.01	–	–
8/8/1978	–	–	–	–	–	10.9	–	–
28/8/1996	–	–	–	–	–	209.6	–	–
6/7/1997	–	–	–	–	–	14.9	–	0
18/7/1997	–	–	–	–	–	37.1	7.9	–
19/7/1997	–	–	–	–	–	79	7.1	–
20/7/2001	–	–	–	–	–	23.1	–	65
13/8/2002	–	–	–	–	–	13.2	–	–
31/8/2002	–	–	–	–	–	0.8	–	–

28 August 1996 when 209.6 mm were registered at station S during a 12-hour period. Nevertheless, only moderate hourly rainfall was identified (see Tab. 3) at all of the other stations in the region.

5.3 Antecedent precipitation index (API)

The antecedent precipitation index was calculated for all debris flow events and days were selected when daily rainfall levels reached at least 100 mm. No significant values were determined for years when debris flows occurred and on the other hand many high values were identified for the following years without any debris flow. The highest API_5 was recorded in 2006 and did not result in a debris flow, whereas years when debris flows occurred, i.e. 1897, 1926, 1937, 1964, 1974 and 1975, show much lower API_5. The highest API_{10} was also recorded in 2006, but the highest API_{30} was calculated in 1997 (Tab. 4). From this analysis it is clear that the antecedent precipitation index itself (in this area) could not be responsible for any debris flows during the monitored period. We have to look at combinations with daily or hourly rainfall.

5.4 Cumulative rainfall data

Fig. 5 includes selected data of cumulative rainfall – both the highest values when debris flows occurred and did not occur. From the days when debris flows occurred, the 90-day cumulative rainfall reached a maximum of 413.7 mm on 3 July 1926. This value is approximately 370 mm lower than the cumulative rainfall from days when no debris flows occurred. The average amount from all of the calculated cumulative rainfall data is 348.8 mm. Only two values when debris flows occurred (in 1926) were above this cumulative rainfall average, i.e. values in 1897 were comparable and other values were lower. Unfortunately, no cumulative rainfall data were available for the debris flow

Tab. 4 Antecedent precipitation index for 5, 10 and 30 days (calculated from the source data: CHMI) (Blue colour represent debris flow events).

	PCS			PB			DDR			HM			LB			B			RJV			H			VV		
Date/ API	5	10	30	5	10	30	5	10	30	5	10	30	5	10	30	5	10	30	5	10	30	5	10	30	5	10	30
17/7/1882																											
28/7/1897							26.4	33.9	53.1																		
29/7/1897							33.9	57.2	71.3																		
2/7/1926							2.7	11.1	61																		
3/7/1926							2.9	11.3	63.2																		
12/7/1937							11.9	22	35.3							25	25	40.7									
12/7/1938							51.7	63.2	73.2																		
14/8/1948																25.3	31.6	55.2							127.5	14	157.6
6/7/1955																17.6	20.2	30.1				22.5	28.4	39	49.1	59.7	72.3
14/7/1964	2.9	11.7	31.1				6.4	8.6	27.4	12.1	14.5	27.4	14.5	19.4	41	13.7	16.8	33.3	8.3	13.6	24.9	5.6	11.1	28.2	11.9	17.8	42.5
10/8/1964	41.6	60	71				42.1	55.8	74	40.9	48.4	57.4	30.3	43.6	47.8	34.6	50.3	55.1	26.9	44.3	54.9	26.7	47.7	55.6	44.9	56.2	62.7
29/6/1971	16.4	26	47.3				5.1	25.4	43.5	7.2	15.9	31.4	10.9	27.9	50.7	12.4	30.4	55.8	15.5	33.3	56.6	20.7	41.1	67.1	20.8	42	74.6
12/6/1974							6.8	9.7	20.3	9.9	12.7	21.9	6	6	16.9	5.8	9.7	19.5	19.5	27.6	40.8	19.1	22.9	47.4			
13/6/1974							12.4	17.1	26.9	20.5	24.1	32.7	23.1	24.5	34.7	15.8	20.7	29.9	33.9	43.5	55.9	40.2	44.9	67.7			
14/6/1974							19.8	25.2	36.9	28.4	33.4	42.7	46.7	50.7	58.3	26.1	30.1	40.1	47.9	55.8	71.1	50.8	59.6	81			
15/6/1974							24.6	30	39.4	25.7	31.6	38.9	55.2	59.4	65.2	29	33.4	42.1	51.1	59.1	73	56.9	66	83.9			
18/6/1974							26.2	37	42	12.1	26.3	33.1	54.7	70.7	75.8	29.4	33.4	41.1	28.3	52	59.2	35.1	63	76.7			
22/6/1975							22.8	33.2	37.1	16.3	38.5	42.7	17.5	23.6	28.9	30.7	32.3	33.4	15.2	33.1	34.2	19.4	42.2	52.8	12.7	35.7	48.3
31/7/1977							0	15	29.5	0.4	13.4	27.4	0	12.3	29	0.4	11.8	24.3	0.5	16.7	30.6	0.7	17.2	30.5	0.6	14.7	40.2
1/8/1977							11.6	24.6	39	47.4	59.9	72.7	53	64	80	23.9	34	46.1	37.7	52.8	65.7	82.1	97.4	109.9	127.9	140.6	164.2
8/8/1978							2.8	3.9	12.1	8.1	8.6	15	8	8	22.5	4.5	4.6	15.6	9.1	9.1	9.1	16.6	16.7	27	11	11.1	26.8
28/8/1996	7.4	13	54.1				23.4	23.4	42.1	22.4	22.4	44.2	26.4	26.6	73.9	28.5	31.5	52.7	27	29.6	47	18.7	23	42.5			
6/7/1997	34.3	50.9	76.7	45.3	64	78.9	19.5	35	55.5	31	44.6	62.7	56.2	78	86	23.2	35.2	59.8	33.9	39.4	55.9	27.2	33.4	51.4			
18/7/1997	44.4	47.1	163.9	28.9	75	190.2	51	52.8	136.2	21.2	21.2	110	22	24	146.7	36.3	38.3	103.4	8.7	8.7	67.1	6.1	6.2	75.3			
19/7/1997	90.8	93.3	201.9	42.3	42.4	192.3	70.4	72.1	149.6	54.1	54.1	136.4	146	146	261.1	57.4	59.2	117.9	44.1	44.1	97.6	60.1	60.3	124.5			
20/7/2001	14.2	24.6	33.1	21.2	24	41.8	10.8	21.8	44.9	20.5	24.4	38.2				27.8	32.9	54.8	25.9	31.8	55.1	27.4	31.8	57.1			
13/8/2002	14.5	15.5	26	23.6	23.6	42.6	49.2	50.7	63.8	16.1	16.9	41.2				23.2	28.9	38.7	32.9	41.9	50.1	35.7	42.7	54.2			
31/8/2002	10.1	15.1	43	9.9	14.5	75.1	4.9	8.3	33.6	1.7	6.6	23.8				12.9	15.1	33.7	12.7	14.9	43.6	5.3	8.6	51.3			
6/8/2006	44.4	53.2	56.2	119.5	124.5	130.7	19.7	26.5	33.6	31.4	32.8	38.3	89.6	105.7	112.4	18.9	24.2	27.6	24.6	42.6	46.3	40.1	59.1	62.3			
7/8/2006	95.5	104.6	107.3	216.6	221.5	227.3	37.6	44	50.6	53.7	55.3	60.4	183.8	199.6	205.9	43	47.9	51.1	51.6	68.2	71.7	87.6	105.3	108.2			

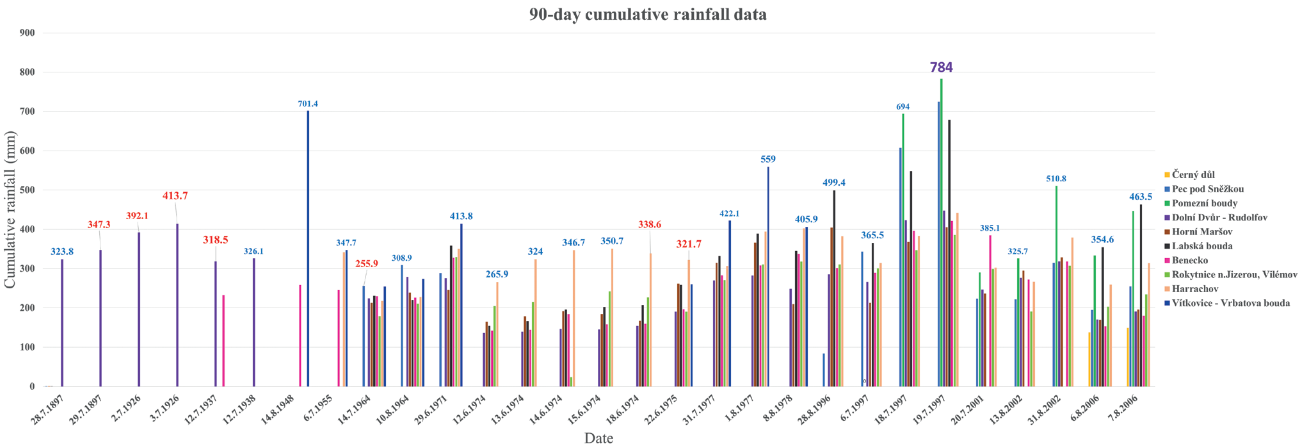


Fig. 5 Cumulative rainfall data for 90 days. Colours: red – occurrence of debris flows; blue – no occurrence of debris flows; violet is the absolutely highest value of cumulative rainfall (calculated from the source data: CHMI).

events (Nos. 5, 7, 8, 9, 10, 34 and 35) – (Tab. 1). In July 1897, July 1937, July 1964, June 1974 and June 1975 when debris flows occurred, values of cumulative rainfall were below the average. In August 1948 and in July 1997 when debris flows did not occur, values of cumulative rainfall were two times higher than the average of all cumulative rainfall data.

5.5 Relation between daily and antecedent rainfall

In order to determine the number of days for the antecedent rainfall, we considered the correlation analysis between the daily rainfalls in relation to the debris flows events and the corresponding antecedent rainfall (Zezere et al. 2005) for two rain gauges, Pec pod Sněžkou and Labská bouda for three periods: 5, 10 and 30 days. The results are shown in Fig. 6. The red points depict the debris flow events whereas the black points show the selected years with high rainfall from a period of 42 years (1964 to 2006). Fig. 6 shows that debris flows occurred after low daily rainfall in combination with small to moderate amounts of antecedent rainfall. On the contrary, high rainfall events in combination with high levels of antecedent rainfall did not create debris flows. We have to stress that debris flow events from the end of the 19th century are not included in Fig. 6, because it was not possible to calculate the antecedent rainfall.

5.6 Combination of different rainfall characteristics

If we consider all of the above analysed factors (hourly and daily rainfall, API, cumulative rainfall), the debris flows from 1882 and 1897 may be explained by the huge daily rainfall amounts, partly supported by hourly rainfall. The influence of API and cumulative rainfall from 1882 could not be evaluated because of missing rainfall data. API data from 1897 are available only for a rain gauge located far from the debris flow source area. The occurrence of the other debris flows in 1926, 1937, 1964 and 1975 is not significantly supported by the available data. Possibly only the 1974 (see Tab. 6) debris flow (18 June 1974) occurred after a combination of moderate hourly rainfall and moderate API, but these values are nothing compared to 1882 and 1897. We have to stress that there were several years over the last few decades when stations registered high values of API and daily rainfall (e.g. middle of July 1997 or beginning of August 2006) but no debris flows were registered. This means that there must be significant differences in the rainfall distribution over rather short distances in the mountainous area of the Krkonoše Mts.

6. Discussion

Debris flows triggered by rainfall have not been studied in detail in the Krkonoše Mts. The majority of the published works are focused on particular debris flow events describing the associated rainfall amounts.

The estimated thresholds for daily rainfall intensity are 225 mm, without the support of API and cumulative rainfall. A comparison of these thresholds with other debris flow studies from the Czech Republic is problematic due to the fact that many of the authors worked on deep seated landslides (Gil and Dlugosz 2006), described isolated events and estimated threshold values for landslide initiation for the Outer Western Carpathians (Bíl et al. 2016). Only a few works focused on individual landslides where numerous events took place (Krejčí et al. 2002; Pánek et al. 2011). However, they did not attempt to estimate the threshold. Work from Smědavská hora Mt. in the Jizerské hory Mts. describes the initiation of debris flows on Smědavská hora Mt. (Smolíková et al. 2016). From this, the authors concluded that for the initiation of debris flows, a combination of API, daily/hourly rainfall and values of short intensities of 10/15 min is far more important than individual extremes. Significant rainfall events have been recorded in the last 30 years without any debris flow events (Smolíková et al. 2016).

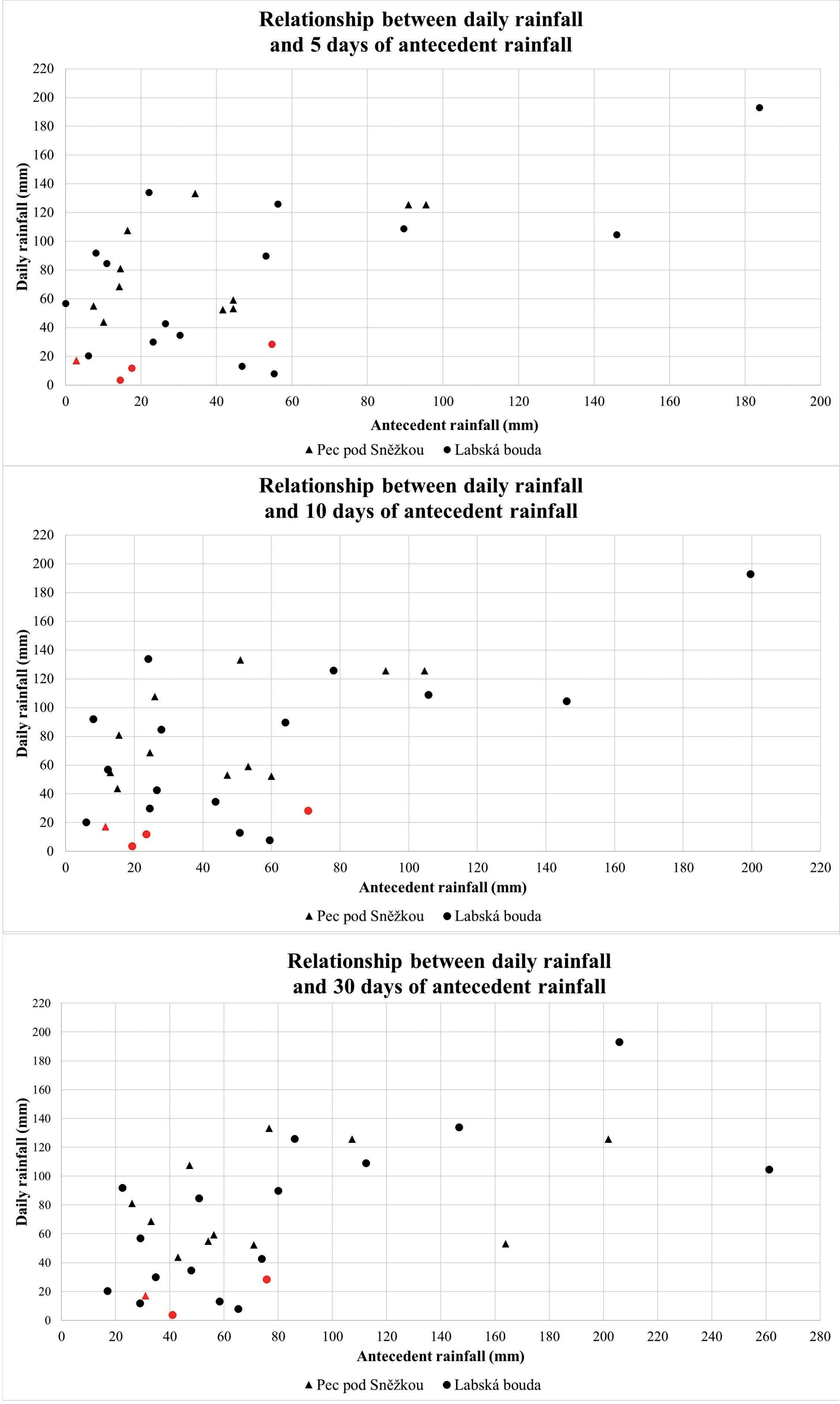


Fig. 6 Relationship between daily rainfall and antecedent rainfall for the period 1964–2006 from Pec pod Sněžkou and Labská Bouda rain gauges. Red points depict debris flow events and black points show years with high rainfall, which did not trigger any debris flows (calculated from the source data: CHMI).

Tab. 5 Daily rainfall thresholds for the initiation of landslides in comparison with our derived value (R > 225 mm).

Continent	Country	Area	Type of landslide	Value of threshold type	Reference
Europe	Italy	Sarno, Campania	All types of landslides	R > 55 mm (lower threshold)	Biafiore et al. (2002)
Europe	Italy	Sarno, Campania	All types of landslides	R > 75 mm (upper threshold)	Biafiore et al. (2002)
Europe	Spain	Llobregat valley, Pyrenees Mts.	Shallow landslide, Debris flows	R > 160–200 mm	Corominas and Moya (1996)
Asia	Japan	Hokkaido	All types of landslides	R > 200 mm	Endo (1970)
		Island			
North America	USA	Alamanda Country	All types of landslides	R > 180 mm	Nilsen et al. (1976)
North America	USA	Los Angeles Area	All types of landslides	R > 235 mm	Campbell (1975)

Tab. 6 Summary of detailed rainfall data in selected dates from all rain gauges (blue lines describe the debris flows events, white – no debris flows; RG is rain gauge; daily amount – the total highest daily value from all rain gauges; hourly rainfall data – 1 h, 2 h, 6 h, 12 h; API 5/10/30 – the total highest API value; 90 days of cumulative rainfall (CR) – the total highest value of CR) (Source data: see previous Chapter 5 and Fig. 4, 5, 6, 7).

	Daily rainfall	RG	1h	RG	2h	RG	6h	RG	12h	RG	API 5	RG	API 10	RG	API 30	RG	90 days CR	RG
17/7/1882	226.6	(S)	45	(S)														
28/7/1897	76	(OD)									26.4	(DDR)	33.9	(DDR)	53.1	(DDR)	323.8	(DDR)
29/7/1897	266	(OD)	11	(S)							33.9	(DDR)	57.2	(DDR)	71.3	(DDR)	347.3	(DDR)
2/7/1926	21.6	(DDR)									2.7	(DDR)	11.1	(DDR)	61	(DDR)	392.1	(DDR)
3/7/1926	0.2	(DDR)									2.9	(DDR)	11.3	(DDR)	63.2	(DDR)	413.7	(DDR)
12/7/1937	65.7	(B)									25	(B)	25	(B)	40.7	(B)	318.5	(DDR)
12/7/1938	156.7	(DDR)									51.7	(DDR)	63.2	(DDR)	73.2	(DDR)	326.1	(DDR)
14/8/1948	112.6	(VV)									127.5	(VV)	31.6	(B)	157.6	(VV)	701.4	(VV)
6/7/1955	15.7	(VV)									49.1	(VV)	59.7	(VV)	72.3	(VV)	347.7	(VV)
14/7/1964	18.5	(RJV)			25	(S)					14.5	(LB)	19.4	(LB)	42.5	(VV)	255.9	(PCS)
10/8/1964	146.7	(VV)									44.9	(VV)	60	(PCS)	74	(DDR)	308.9	(PCS)
29/6/1971	107.6	(PCS)									20.8	(VV)	42	(VV)	74.6	(VV)	413.8	(VV)
12/6/1974	25.4	(H)							5.9	(S)	19.5	(RJV)	27.6	(RJV)	47.4	(H)	265.9	(H)
13/6/1974	61.1	(S)							75	(S)	40.2	(H)	45	(H)	67.7	(H)	324	(H)
14/6/1974	20.2	(S)							31	(S)	50.8	(H)	60	(H)	81	(H)	346.7	(H)
15/6/1974	19.6	(S)							17	(S)	56.9	(H)	66	(H)	83.9	(H)	350.7	(H)
18/6/1974	29.3	(B)							70	(S)	54.7	(LB)	70.7	(LB)	75.8	(LB)	338.6	(H)
22/6/1975	26.5	(B)							10	(S)	30.7	(B)	42	(H)	52.8	(H)	321.7	(H)
31/7/1977	136.9	(VV)					1.01	(S)			0.7	(H)	17	(H)	30.6	(RJV)	422.1	(VV)
1/8/1977	132.2	(VV)							80	(S)	127.9	(VV)	140.6	(VV)	164.2	(VV)	559	(VV)
8/8/1978	130.8	(H)							11	(S)	16.6	(H)	17	(H)	27	(H)	405.9	(VV)
28/8/1996	55	(PCS)							15	(S)	28.5	(B)	31.5	(B)	73.9	(LB)	499.4	(LB)
6/7/1997	180	(PB)							210	(S)	56.2	(LB)	78	(LB)	86	(LB)	343.5	(PCS)
18/7/1997	134	(LB)					7.9	(PCS)	37	(S)	51	(DDR)	75	(PB)	190.2	(PB)	607.5	(PCS)
19/7/1997	125.6	(PCS)					7.1	(PCS)	79	(S)	146	(LB)	146	(LB)	261.1	(LB)	784	(PB)
20/7/2001	141.2	(PB)							23	(S)	27.8	(B)	32.9	(B)	57.1	(H)	385.1	(B)
13/8/2002	176.5	(PB)							65	(PCS)	49.2	(DDR)	50.7	(DDR)	63.8	(DDR)	325.7	(PB)
31/8/2002	191	(PB)							0.8	(S)	12.9	(B)	15.1	(PCS)	75.1	(PB)	510.8	(PB)
6/8/2006	113.7	(PB)									119.5	(PB)	124.5	(PB)	130.7	(PB)	354.6	(LB)
7/8/2006	193.1	(LB)									216.6	(PB)	221.5	(PB)	227.3	(PB)	463.5	(LB)

Rainfall is not the only causative factor for debris flow initiation (Aleotti and Chowdhury 1999), geological, geomorphological, soil and vegetation conditions also have to be taken into consideration. In particular, local climatic and the geomorphological conditions of the geological structure of the area differ from one threshold to another (Guzzetti et al. 2007). Nevertheless, we tried to compare our derived daily rainfall threshold for the Obří důl Valley with others already published (Tab. 5).

The limits of our presented research are also influenced by the following circumstances: the data from 1897 were measured at different rain gauges, thus they may be less significant for determining thresholds. A significant problem was the incompleteness of the rainfall data from the selected rain gauges. The rain gauges are located at different elevations and distances from the triggering area of the debris flows. The orographic effect also has an influence on rainfall distribution.

7. Conclusions

The rainfall analysis for debris flows from the available data revealed that in the area under study daily rainfall above 225 mm could trigger debris flows (e.g. years 1882 and 1897), even without support of API. A combination with hourly rainfall cannot be demonstrated, because we do not have sufficiently accurate data from these years. We have data from the last 40 years from several stations in the surroundings of the Obří důl Valley, which revealed that daily rainfall between 150 and 200 mm/day does not create debris flows, even with the support of API (see Tab. 6). Also, the heavy storm during 28 August 1996 when 209.5 mm/12 hours were measured did not create a debris flow. It seems that the local rainfall threshold is above 225 mm/day, without the possibility to consider its combination with hourly rainfall or API.

The API itself probably has only a limited influence on the triggering mechanism and has to be considered in combination with daily or hourly rainfall. Cumulative rainfall and API are not good indicators for predicting debris flows in our study area as most of the historical debris flows did not occur during the highest cumulative rainfall events or significant API values. A plausible explanation for this is that the infiltration of intensive rainfall is limited by the permeability of the soils. Daily rainfall could result in rapid oversaturation of the weathered mantle and soils and eventually cause the slope to be more susceptible to failure.

There are significant differences in the measured data even over rather short distances. Unfortunately, it did not help us to substitute the data from one station with data from another station. We also have to resolve the issue that some of the debris flows remain undated.

The temporal probability of the occurrence of debris flows was directly estimated based on the statistical relationship between the historical debris flow events and rainfall data. The rainfall thresholds were estimated using all debris flow episodes without considering the specifics of the sizes of the debris flows or the number of debris flows in the episodes.

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References

Aleotti, P. (2004): A warning system for rainfall-induced shallow failures. Engineering Geology 73, 247–265, https://doi.org/10.1016/j.enggeo.2004.01.007.

Aleotti, P., Chowdhury, R. (1999): Landslide hazard assessment: summary review and new perspectives. Bull Eng Environ 58, 21–44, https://doi.org/10.1007/s100640050066.

Anonymus (1889-1941): Gedenkenbuch der Gemeinde Gross Aupa, I. Teil.

Anonymus (1897a): Bericht über Hochwasserschäden. In: Der Wanderer im Riesengebirge 17(9), Hirschberg, 130–131.

Anonymus (1897b): Der Wolkenbruch im Riesengebirge. In: Der Wanderer im Riesengebirge 17(9), 131–132.

Biafiore, M., Braca, G., De Blasio, A., Martone, M., Onorati, G., Tranfaglia, G. (2002): Il monitoraggio ambientale dei territori campani a rischio di frane e di alluvioni: lo sviluppo della rete idropluviometrica del Servizio Idrografico e Mareografico Nazionale. Unpublished report.

Bíl, M., Andrášik, R., Zahradníček, P., Kubeček, J., Sedoník, J., Štěpánek, P. (2016): Total water content thresholds for shallow landslides, Outer Western Carpathians. Landslides 13, 337–347, https://doi.org/10.1007/s10346-015-0570-9.

Blahůt, J. (2008): Mapa náchylnosti terénu Krkonoš ke vzniku lavin vytvořená pomocí nástrojů GIS a statisticko – pravděpodobnostních metod. Opera Corcontica 45, 35–44.

Brand, E. W. (1989): Occurrence and significance of landslides in Southeast Asia, In: Brabb, E. E., Harrod, B. L. (eds) Landslides: extent and economic significance. A. A. Balkema, Rotterdam, 303–324.

Campbell, R. H. (1975): Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California. In: US Geological Survey Professional Paper 851, Washington DC: U.S. Government Printing Office 51, https://doi.org/10.3133/pp851.

Chaloupský J., Teisseyre, H. (1968): Geology of the West Sudeten. Guide to Excursion 8 AC, International geolog. congress, XXIII session, Prague 1968, 17–18, Praha.

Corominas, J., Moya, J. (1996): Historical landslides in the Eastern Pyrenees and their relation to rainy events. In: Irigaray, C., Fernandez, T. (eds) Landslides. Chacon J. Rotterdam, A. A. Balkema, 125–132.

Corominas, J., Moya, J. (1999): Reconstructing recent landslide activity in relation to rainfall in the Llobreat River basin, Eastern Pyrenees, Spain. Geomorphology 30, 79–93, https://doi.org/10.1016/S0169-555X(99)00046-X.

Corominas, J. (2000): Landslide and climate. Keynote lecture. In: Proc. 8th Int. Symp. On Landslides (Bromhead E, Dixon N, Ibsen ML, eds.). In: Guzzeti, F. et al. (eds.): Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorology and Atmospheric Physics 98(3–4), 239–267.

Crosta, G. (1998): Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. Environ Geol 35(2), 131–145, https://doi.org/10.1007/s002540050300.

Crosta, G. B., Frattini, P. (2001): Rainfall threshold for triggering soil slips and debris flow. In: Proc. 2nd EGS Plinius Conf. on Mediterranean Storms. In: Danišík, M., Migoń, P., Kuhlemann, J., Evans, Nj., Dunkl, I., Frissch, W. (2010): Thermochronological constraints on the long-term erosional history of the Karkonosze Mts., Central Europe. Geomorphology 117, 78–89.

Crozier, M. J., Eyles, R. J. (1980): Assessing the probability of rapid mass movement. In: Technical Groups, Proceedings of 3rd Australia–New Zealand Conference on Geomechanics. New Zealand, Wellington: 247–251

Czerwiński, J. (1967): Osuwisko w doline Lomniczki w Karkonoszach. In: Opera Corcontica.

Dahal, R. K., Hasegawa, S. (2008): Representative rainfall thresholds for landslides in the Nepal Himalaya. Geomorphology 100(3–4), 429–443, https://doi.org/10.1016/j.geomorph.2008.01.014.

Dahal, R. K., Hasegawa, S., Nonomura, A., Yamanaka, M., Masuda, T., Nishino, K. (2009): Failure characteristics of rainfall-induced shallow landslides in granitic terrains of Shikoku Island of Japan. Environ Geol 56(7), 1295–1310, https://doi.org/10.1007/s00254-008-1228-x.

Danišík, M., Migoń, P., Kuhleman, J., Evans, NJ., Dunkl, I. Frisch, W. (2010): Thermochronological constraints on the long-term erosional history of the Karkonosze Mts., Central Europe. Geomorphology 117, 78–89, https://doi.org/10.1016/j.geomorph.2009.11.010.

Demuth, J. (1901): Der politische Bezirk Trautenau.

D'odorico, P., Fagherazzi, S. (2003): A probabilistic model of rainfall-triggered shallow landslides in hollows: a long-term analysis. Water Resour Res 39(9), https://doi.org/10.1029/2002WR001595.

Dvořák, I. J., Kociánová, M., Pírková, L. (2004): Příklad využití technologií GPS a GIS při studiu kryoplanačních teras na Luční a Studniční hoře. Opera Corcontica 41, 18–24.

De Quervain, M.R. et al. (1981): Avalanche atlas. UNESCO, International Commission on Snow and Ice of the International Association of Hydrological Sciences. Paris: 1–265.

De Vita, P., Reichenbach, P. (1998): Rainfall – triggered landslides: Reference list. Environmental Geology 35(2–3). Springer Verlag, 219–233.

Endo, T. (1970): Probable distribution of the amount of rainfall causing landslides. Annual report, Hokkaido Branch, Govern. Forest Experiment Station, Sapporo, 123–136.

Engel, Z. (1997): Pleistocénní zalednění české části Krkonoš. Przyroda Sudetów Zachodnich 6, 223–234.

Engel, Z. (2003): Současný stav poznatků o pleistocénním zalednění české části Krkonoš. Geografie – Sborník ČGS 102, 288–302

Engel, Z. (2007): Late Pleistocene glaciations in the Krkonoše Mts. In: Goudie AS. Kalvoda, J. (eds) Geomorphological Variations. P3 K. Praha, 269–285.

Engel, Z., Nývlt, D., Křížek, M., Treml, V., Jankovská, V., Lisá, L., (2010). Sedimentary evidence of landscape and climate history since the end of MIS 3 in the Krkonoše Mountains, Czech Republic. Quat Sci Rev 29(7–8), 913–927, https://doi.org/10.1016/j.quascirev.2009.12.008.

Engel, Z., Braucher, R., Traczyk, A., Léanni, L., Asterteam (2014): ^{10}Be exposure age chronology of the last glaciation in the Krkonoše Mountains, Central Europe. Geomorphology 206, 107–121, https://doi.org/10.1016/j.geomorph.2013.10.003.

Frattini, P., Crosta, G., Sosio, R. (2009): Approaches for defining thresholds and return periods for rainfall triggered shallow landslides. Hydrol Process 23(10), 1444–1460, https://doi.org/10.1002/hyp.7269.

Giannecchini, R., Galanti, Y., Avanzi, G. D. (2012): Critical rainfall thresholds for triggering shallow landslides in the Serchio River Valley (Tuscany, Italy). Nat Hazards Earth Syst Sci 12(3), 829–842, https://doi.org/10.5194/nhess-12-829-2012.

Gil, E., Dlugosz, M. (2006): Threshold values of rainfalls triggering selected deep-seated landslides in the Polish flysch Carpathians. Stud Geomorphol Carpatho-Balc 11, 21–43.

Glade, T. (2000): Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical "antecedent daily rainfall model". Pure Appl Geophys 157(6), 1059–1079, https://doi.org/10.1007/s000240050017.

Glade, T., Crozier, M. J. (2005): The nature of landslide hazard impact. In: Glade, T., Anderson, M., Crozier, M. J. (eds): Landslide hazard and risk. Wiley, Chichester, 73–74, https://doi.org/10.1002/9780470012659.ch2.

Godt, J. W., Baum, R. L., Chleborad, A. F. (2006): Rainfall characteristics for shallow landsliding in Seattle, Washington, USA. Earth Surf Proc Land 31(1), 97–110, https://doi.org/10.1002/esp.1237.

Guzetti, F., Cardinali, M., Reichenbach, P., Cippola, F., Sebastiani, C., Gali, M., Salati, P. (2004): Landslides triggered by 23 November 2000 rainfall event in the Imperia Province, Liguria, Italy. Engineering Geology 73, 229–245, https://doi.org/10.1016/j.enggeo.2004.01.006.

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, CP. (2007): Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorology and Atmospheric Physics 98(3–4), 239–267, https://doi.org/10.1007/s00703-007-0262-7.

Heyerdahl, H., Harbitz, C. B., Domaas, U., Sandersen, F., Tronstad, K., Nowacki, F., Engen, A., Kjestad, O., Devoli, G., Buezo, S. G., Diaz, M. R., Hernandez, W. (2003): Rainfall induced lahars in volcanic debris in Nicaragua and El Salvador: practical mitigation. In: Proceedings of international conference on fast slope movements – prediction for risk mitigation, IC- FSM2003, Naples. Patron Pub, 275–282.

Horník, S., Buzek, L., Mičian, Ľ., Pech, J., Trnka, P. (1986): Fyzická geografie II. Státní pedagodigické nakladatelství Praha, 319.

Hraško, J., Linkeš, V., Němeček, J., Novák, P., Šály, R., Šurina, B. (1991): Morfogenetický klasifikační systém pôd ČSFR, VÚPÚ Bratislava, 106.

Cháb, J., Stránik, Z., Eliáš, M. (2009): Geologická stavba. In: Hrnčiarová, T., Mackovičin, P., Zvara. I. et al. Atlas krajiny České republiky. Praha, Ministerstvo životního prostředí ČR, Průhonice: Výzkumný ústav Silva Taroucy pro krajinu a okrasné zahradnictví, v.v.i., 106–107.

Janeček, M., Bečvář, M., Bohuslávek, J., Dufková, J., Dumbrovský, J., Dostál, T., Hula, J., Jakubíková, A., Kadlec, V., Krása, J., Kubátová, E., Novotný, I., Podhrázská, J., Tippl, M., Toman, F., Vopravil, J., Vrána, K. (2007): Ochrana zemědelské půdy před erozí, Metodika. (Protection of agricultural land against erosion, the methodology). Výzkumný ústav meliorací a ochrany půdy, v.v.i., Praha, 76 (in Czech).

Jitrasek, F. J. (1915): Volks – und Heimatskunde des politischen Bezirkes Hohenelbe I. Hohenelbe.

Juras, R., Pavlásek, J., Blahůt, J., Bašta, P., Klose, Z., Vítěslav, M., Balek, J. (2013): New tools for avalanche forecasting in the Krkonoše Mountains. International Snow Science Workshop Grenoble – Chamonix Mont – Blanc.

Kim, SK., Hong, WP., Kim, YM. (1991): Prediction of rainfall-triggered landslides in Korea. In: Bell, DH. (ed) Landslides. A. A. Balkema. Rotterdam, 989–994.

Kociánová, M., Spusta, V. (2000): Vliv lavinové aktivity na kolísání horní hranice lesa v Krkonoších. Opera Corcontica 37, 473–480.

Kociánová, M., Špatenková, I., Tondrová, A., Dvořák, I. A., Pilous, V. (2004): Základní a smíšené laviny ve vztahu k přemisťování svahovin a dynamice vegetace. Opera Corcontica 41, 86–99.

Kohler, M. A., Linsley, R. K. (1951): Predicting the runoff from storm rainfall. Weather Bureau, US Department of Commerce, Research Paper, 34, Washington.

Knippel, E. W. (1850): Rytina. In: Pilous, V. (1973): Strukturní mury v Krkonoších, I. Část. Opera Corcontica 10, 15–69, Praha.

Králík, F., Sekyra, J. (1969): Geomorfologický přehled Krkonoš, In: Fanta, J. (ed) Příroda Krkonošského národního parku, SZN, Praha, 59–87.

Krejčí, O., Baroň, I., Bíl, M., Jurová, Z, Bárta, J., Hubatka, F., Kašpárek, M., Kirchner, K., Stach, J. (2002): Some examples of deep-seated landslides in the Flysch Belt of Western Carpathians, In: Rybář, Stemberk, Wagner (eds.) Landslides. A. A., Balkema Publishers, Lisse, 373–380.

Křížek, M. (2007): Periglacial landforms above the alpine timberline in the High Sudetes, In: Goudie, A. S., Kalvoa, J. (eds) Geomorphological Variations, P3K, Praha, 313–337.

Křížek, M., Uxa, T. (2013): Morphology, sorting and microclimates of relict sorted polygons, Krkonoše Mountains, Czech Republic. Permafrost Perigl Proc 24, 313–321, https://doi.org/10.1002/ppp.1789.

Lysenko, V. (2007): Morfotektonická analýza Krkonoše pomocí metod dálkového průzkum Země. Opera Corcontica 44(1), 37–42.

Marchi, L., Arattano, M., Deganutti, A. M. (2002): Ten years of debris-flow monitoring in the Moscardo Torrent (Italian Alps). Geomorphology 46, 1–17, https://doi.org/10.1016/S0169-555X(01)00162-3.

Marques, R., Zezere, J., Trigo, R., Gaspar, J., Trigo, I. (2008): Rainfall patterns and critical values associated with landslides in Povoac¸a˜o County (Sa˜o Miguel Island, Azores): relationships with the North Atlantic Oscillation. Hydrol Process 22(4), 478–494, https://doi.org/10.1002/hyp.6879.

Migoń, P. (1992): Tektoniczne formy rzeźby na północnym stoku Karkonoszy. Opera Corcontica 29, 5–24.

Migoń, P. (1999): The role of preglacial relief in the development of mountain glaciation in the Sudetes, with the special reference to the Karkonosze Mountains. Z Geomorp NF Supp 113, 33–44.

Migoň, P., Pilous, V. (2007): Geomorfologie. In: Flousek, J. et al. (eds) Krkonoše – příroda, historie, život. Baset. Praha, 103–124.

Mishra, S. K., Singh, V. P. (2003): Soil conservation service curve number (SCS-CN) methodology. Kluwer Academic Publisher, Dordrech.

Myslil, V. (1997): Zpráva o geologickém průzkumu sesuvů v okrese Trutnov. Geomedia s.r.o. Archív Geofond, Praha, 13.

NCDC NOAA: National Centers for Environmental Information [online]: Available on: https://www7.ncdc.noaa.gov/CDO/cdodata.cmd.

Nilsen, T. H., Taylor, F. A., Brabb, E. E. (1976): Recent landslides in Alamanda County, California (1940–71). US Geological Survey Bul, 1398.

Novotný, J. (2000): Analýza vlivu vody na stabilitu svahu v jílových horninách. Autoreferát disertační práce k získání vědecké hodnosti kandidáta věd, MS, ÚSMH AV ČR, Praha, 27.

Ouvrier, H. (1933): Beiträge zur Morphologie des Hohen Riesengebirges. Veröff Schles Ges Erdkunde. Breslau, 88.

Pánek, T., Brázdil, R., Klimeš, J., Smolková, V., Hradecký, J., Zahradníček, P. (2011): Rainfall induced landslide event of May 2010 in the eastern part of the Czech Republic. Landslides 8(4), 507–516, https://doi.org/10.1007/s10346-011-0268-6.

Partsch, J. (1894): Die Vergletscherung des Riesengebirges zur Eiszeit. Forschungen zur deutschen Landse- und Volkskunde 8(2): 103–194.

Pasuto, A., Silvano, S. (1998): Rainfall as a triggering factor of shallow mass movements, A case study in the Dolomites, Italy. Environmental Geolog 35, 184–189, https://doi.org/10.1007/s002540050304.

Pilous, V. (1973): Strukturní mury v Krkonoších, I. Část. Opera Corcontica 10, 15–69, Praha.

Pilous, V. (1975): Strukturní mury v Krkonoších, II. Část. Opera Corcontica 12, 7–50, Praha.

Pilous, V. (1977): Strukturní mury v Krkonoších, III. Část. Opera Corcontica 14, 7–94, Praha.

Pilous, V. (2016): Krkonoše Mountains: A Case Study of Polygenetic Relief. In: Pánek, T., Hradecký, J. (eds.) Landscapes and Landforms of the Czech Republic. World Geomorphological Landscapes, https://doi.org/10.1007/978-3-319-27537-6_15.

Polemio, M., Sdao, F. (1999): The role of rainfall in the landslide hazard: the case of the Avigliano urban area (Southern Apennines, Italy). Eng Geol 53(3–4), 297–309, https://doi.org/10.1016/S0013-7952(98)00083-0.

Quitt, E. (1971): Klimatické oblasti Československa. Studia Geographica, 16, Geografický ústav ČSAV, Brno.

Rybář, J., Novotný, J. (2005). Vliv klimatogenních faktorů na stabilitu přirozeních antropogenních svahů. Zpravodaj Hnědé uhlí 3, 13–28.

Saito, H., Nakayama, D., Matsuyama, H. (2010): Relationship between the initiation of a shallow landslide and rainfall intensity–duration thresholds in Japan. Geomorphology 118(1–2), 167–175, https://doi.org/10.1016/j.geomorph.2009.12.016.

Sekyra, J., Sekyra, Z. (1995): Recent cryogenic processes. In: Soukopová, L. et al. Artic – alpine tundra in the Krkonoše. The Sudetes. Opera Corcontica 32, 5–88.

Schneider, G. (1897): Die Hochwasserschäden im Riesengebirge von Ende des fünfzehnten Jahrhunderts bis Juli 1897.

Schuster, R. L., Wieczorek, G. F. (2002): Landslide triggers and types. In: Rybář, J., Stemberk, J., Wagner, P. (eds.): Proceedings of the first European conference on landslides, Prague Czech Republic, June 24–26 2002, A. A. Balkema, 59–75.

Smolíková, J., Blahůt, J., Vilímek, V. (2016): Analysis of rainfall preceding debris flows on the Smědavská hora Mt., Jizerské hory Mts., Czech Republic. Landslides 13(4), 683–696, https://doi.org/10.1007/s10346-015-0601-6.

Sokol, F., Vavřík, K. (1971): Vznik a asanace svohových sesuvů v Hrubém Jeseníku. Ochrana přírody 26(4), 84–86.

Spusta, V., Kociánová, M. (1998): Lavinový katastr české části Krkonoš. Opera Concortica 35, 3–205.

Spusta Sen, V., Spusta Jun, V., Kociánová, M. (2003): Snow avalanche cadastre and winter situation in the Czech part of Krkonoše 1998/99–2002/03 (in Czech). Opera Corcontica 40, 5–86.

Spusta Sen, V., Spusta JUN, V., Kociánová, M. (2006): Snow avalanche cadastre of Czech part of Krkonoše 2003/04 at 2005/06 (in Czech). Opera Corcontica 43, 81–93.

Suk, P., Klimánek, M. (2011): Creation of the snow avalanche susceptibility map of the Krkonoše Mountains using GIS. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brinensis 59(28), 237–246.

Steinhart, M. (2010): Application of rainfall-runoff model Boussmo. Diploma thesis, Czech Agriculture University in Prague (in Czech).

Šourek, J. (1977): Monografie obce Pec pod Sněžkou. MS dep. in muz. Trutnov, s.d.

Šebesta, J., Treml, V. (1976): Glacigenní a nivační modelace údolí a údolních uzávěrů Krkonoš. Opera Concortica 13, 7–44.

Tauber, G. (app. 1850): Rytina. In: Pilous, V. (1973): Strukturní mury v Krkonoších, I. Část. Opera Corcontica 10, 15–69.

Terlien, M. T. J. (1998): The determination of statistical and deterministic hydrological landslide – triggering thresholds. Environmental Geology 35(2–3), 124–130.

Tittel, F. A. (1830): Rytina. In: Pilous, V. (1973): Strukturní mury v Krkonoších, I. Část. Opera Corcontica 10, 15–69.

Treml, V., Křížek, M., Engel, M. (2010): Classification of patterned ground based on morphometry and site characteristics: A case study from the High Sudetes. Central Europe. Permafrost Perigl Proc 21, 67–77, https://doi.org/10.1002/ppp.671.

Turner, A. K., Schuster, R. L. (eds) (1996): Landslide – Investigation and mitigation. Special report 247, Transportation research board. Washington D.C., 674.

Thach, N. N., Xuan, N. T., My, N. Q., Quynh, P. V., Minh, N. D., Hoa, D. B., Bao, D. V., Dan, N. V., Thuy, T. V., Hien, N. T. (2002): Application of remote sensing and geographical information system for research and forecast of natural hazards in Hoa Binh Province. National University Hanoi, Hanoi.

Vrba, M., Spusta, V. (1975): Snow avalanche cadastre of Krkonoše (in Czech). Opera Corcontica 12, 65–90.

Vrba, M., Spusta, V. (1991): Snow avalanche cadastre of Krkonoše (in Czech). Opera Corcontica 28, 47–58.

Wieczorek, G. F., Glade, T. (2005): Climatic factors influencing occurrence of debris flows. In: Jakob, M., Hungr, O. (eds) Debris flow hazards and related phenomena. Springer, Berlin, 325–362, https://doi.org/10.1007/3-540-27129-5_14.

Záruba, Q., Mencl, V. (1982): Landslides and their control. 2nd edition. Academia, Praha, 324.

Zezere, J. L., Trigo, R. M., Trigo, I. F. (2005): Shallow and deep landslides induced by rainfall in the Lisbon region (Portugal): assessment of relationships with the North Atlantic Oscillation. Nat Hazards Earth Syst Sci 5, 331–344, https://doi.org/10.5194/nhess-5-331-2005.

Zhao, Y., Wei, F., Yang, H., Jiang, Y. (2011): Discussion on using antecedent precipitation index to supplement relative soil moisture data series. Procedia Environmental Sciences 10, 1489–1495, https://doi.org/10.1016/j.proenv.2011.09.237.