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Analysis of rainfall preceding debris flows on the Smědavská hora Mt., Jizerské hory Mts., Czech Republic

Abstract In August 2010, extreme rainfall affected the north of the Czech Republic and caused regional floods and landslides. Three torrential debris flows originated in the Jizerské hory Mts., close to Bílý Potok on the north slope of the Smědavská hora Mt. The rainfall situation which triggered the debris flow was analyzed and compared with the rainfall situation in 1958 when a debris flow occurred in the same area. The rainfall data were obtained from rain gauges of the Czech Hydrometeorological Institute. Four rain gauges were chosen close to the Smědavská hora Mt. with data of daily amounts from 1983 to 2013 and 10-min intensity or hourly amounts from the specific period. The data from 1958 were available from three different rain gauges (only daily amounts). The data series were not complete so linear regression was applied to interpolate them. A number of analyses were carried out including daily rainfall, 2-day/3-day moving values, antecedent precipitation index (API) of 5/10/30 days, 10-min intensity, and hourly amounts, and the trigger factor of the debris flow in the study area was also investigated. It was determined that for the triggering of debris flows, both high API values as well as high-intensity short-duration rainfall is needed. It was documented that in cases of solely high API indices or high-intensity short-duration rainfalls, no debris flows were initiated.

Keywords Debris flow · Rainfall pattern · Rainfall thresholds · Jizerské hory Mts · Czech Republic

Introduction

The origin of mass movement depends on the geological and geomorphological setting, the thickness of vegetation cover (Iverson 2000), and the porosity and permeability of the local regolith; however, the crucial trigger factor of debris flow is the rainfall intensity and duration (Wieczorek and Glade 2005), chiefly in the temperate climate of Central Europe (Rybář and Novotný 2005). There is a close relationship between the type of rainfall and the occurrence of extreme events (Starkel 1979). Rainfall intensity and duration, antecedent rainfall, and their combination determine the rainfall pattern resulting in differences in debris flow occurrences. Storms of very high intensity but relatively short duration may cause high surface runoff but insufficient infiltration for the high pore-water pressure required to trigger shallow landslides (Wieczorek and Glade 2005). Starkel (1979) states that the high intensity and short duration of rain cause low infiltration, thus these heavy downpours give rise to slope wash and debris flow. According to Iverson (2000), rapid infiltration of intense rainfall causes soil saturation and an increase in pore-water pressure, which generates debris flow. Rybář and Novotný (2005) add that the seasonal and multi-annual cycles of rainfall and temperature changes help to prepare conditions for the activation of debris flow. On the contrary, low-intensity and lengthy rainfall lasting a few days may increase groundwater levels but often results in insufficient pore-water pressure within near-surface soils for triggering shallow landslides (Wieczorek and Glade 2005).

Determination of rainfall thresholds is crucial for prediction of debris flow initiation, which leads to risk and hazard mitigation. The accuracy of the prediction depends on the accuracy of the determination of the thresholds, which is conditional on the placement density of the rain gauges and the accuracy of the obtained rainfall data as well.

Rainfall thresholds can be defined as global, regional, or local (Guzzetti et al. 2007). Global rainfall thresholds are independent of local morphological, lithological, and land use conditions or the history and patterns of rainfall and have been proposed by many authors, i.e., Caine (1980), Crosta and Frattini (2001), and Cannon and Gartner (2005). Regional rainfall thresholds are determined by Wilson (2000), Jakob and Weatherly (2003), and Gariano et al. (2015) for areas from a few to several thousand square kilometers of similar meteorological, climatic, and physiographic characteristics (Guzzetti et al. 2007). Local rainfall thresholds (Marchi et al. 2002; Peres and Cancelliere 2014) consider the local climatic regime and geomorphological setting in an area from a few to hundreds of square kilometers (Guzzetti et al. 2007). Analysis has demonstrated that local rainfall thresholds are higher than regional and global thresholds. Low-average rainfall intensity is required to initiate landslides in the mountainous areas of central Europe (Guzzetti et al. 2007).

Guzzetti et al. (2007) propose many approaches (see, e.g., Caine 1980; Govi and Sorzana 1980; Bhandari et al. 1991; Corominas and Moya 1996; Wilson 2000) to establishing rainfall thresholds for the initiation of landslides, as follows: thresholds based on intensity duration, total event rainfall, rainfall event duration, and rainfall event intensity. A few authors prefer to define thresholds by daily rainfall, antecedent precipitation, cumulative event rainfall, normalized cumulative event rainfall, or others (Starkel 1979; Rebetez et al. 1997; Rybář and Novotný 2005). Caine (1980) points out that the triggering of debris flows is connected with extreme rather than average rainfall.

All of the mentioned authors deal with threshold analyses separately or a combination of two calculations. Rebetez et al. (1997) use the total rainfall amount over a few days; Nikolopoulos et al. (2014) filter out the short rainfall events because they are very localized and may show uncertainties. Antecedent rainfall thresholds determination varies as well. Cardinali et al. (2005) prefer antecedent rainfall higher than 590 mm over a 3-month period or 700 mm over a 4-month period, Pasuto and Silvano (1989) determine antecedent rainfall over a 15-day period higher than 200 mm and consequently the influence of 2-day rainfall, and Kim et al. (1991) and De Vita (2000) calculate antecedent rainfall for 1–60 days before slope failure and the total daily

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amount for the day of the debris flow. Other establishment of the general range of antecedent rainfall changes from 3 to 160 days (Pasuto and Silvano 1989; Kim et al. 1991; Crozier 1999; De Vita 2000; Cardinali et al. 2005) and a combination of the total amount and intensity of rainfall (Starkel 1979), which best corresponds to this study. Brand et al. (1984), Corominas and Moya (1999), and Aleotti (2004) question the influence of antecedent rainfall in general, but no previous study dealt with a detailed combination of rainfall pattern analyses.

Rainfall data applied in threshold analysis are usually taken from the nearest neighbouring rain gauges. Such rain gauges may be sometimes located far away from debris flow source areas and their weak density distribution is not favorable for the accuracy of the calculation. Mainly in mountainous areas and on rugged terrain where debris flows take place, amounts of rainfall vary due to orography and the uncertainty of rainfall thresholds rises. In the Alps, where the network of rain gauges is dense, the spacing between a single gauging station and the debris flow location is typically between 4 and 15 km (Nikolopoulos et al. 2014) but the distribution of the triggering rainfall varies across distances of up to 5 km (Panziera et al. 2011), thus the real values of the triggering rainfall could be distorted. Uncertainty is also connected with the other causative factors for debris flow initiation mentioned above like bedrock, sediment mantle, andsoil type (Aleotti and Chowdhury 1999).

Event background

In August 2010, intense rainfall hit the Czech Republic and caused local floods and landslides (Fig. 1) in the northern part of the country. The Frýdlant area in the Liberec region was one of the affected areas where the extreme flood situation caused considerable damage to property and road infrastructure (Fig. 2). Three torrential debris flows according to the classification of Nemčok et al. (1972) originated there (Blahut et al. 2012a).

According to the testament of local witnesses, they were triggered on the 7th of August 2010 between 10 and 11 am on the NNE slope of the Smědavská hora Mt. (1084 m above sea level (a.s.l.)) in the Jizerské hory Mts.

The debris flows occurred in gullies created by surface runoff on the slope and were modified by stream erosion. These are the same channels where debris flows also originated in the past. Nevertheless, the only previously dated debris flow occurred there in 1958 (Nevrlý 1976).

The principal triggering factor of the debris flows studied in 2010 was the intense rainfall resulting from a combination of local storm and convective type of rainfall; however the threshold value is not obvious. The rainfall amount in 2010 reached 174.9 mm/24 h with a 1-h intensity of 40.4 mm (CHMI 2010). This was 30 times higher than the long-term daily average calculated for August and three times higher than the long-term monthly average in August (Smolíková et al. 2013). Nevertheless, higher values of daily, monthly, and antecedent rainfall amounts were noted during the years before this event, and they did not result in a debris flow event. Therefore, a series of rainfall analyses was elaborated to help determine the character of the causal rain and the rainfall pattern which resulted in the triggering of a debris flow.

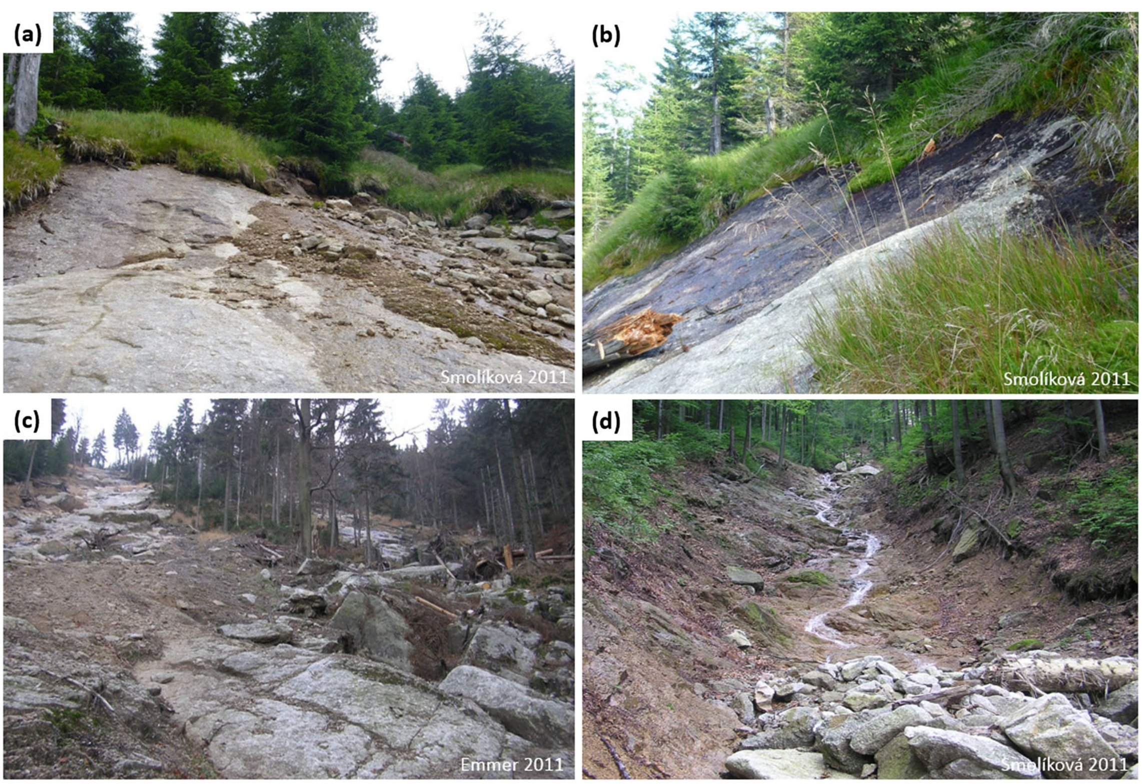

Fig. 1 Torrential debris flow number three on the Smědavská hora Mt. Originated in 2010. **a**, **b** Source areas of the debris flow; **c** transport part and joint of two flows of the debris flow; and **d** transport part of the debris flow

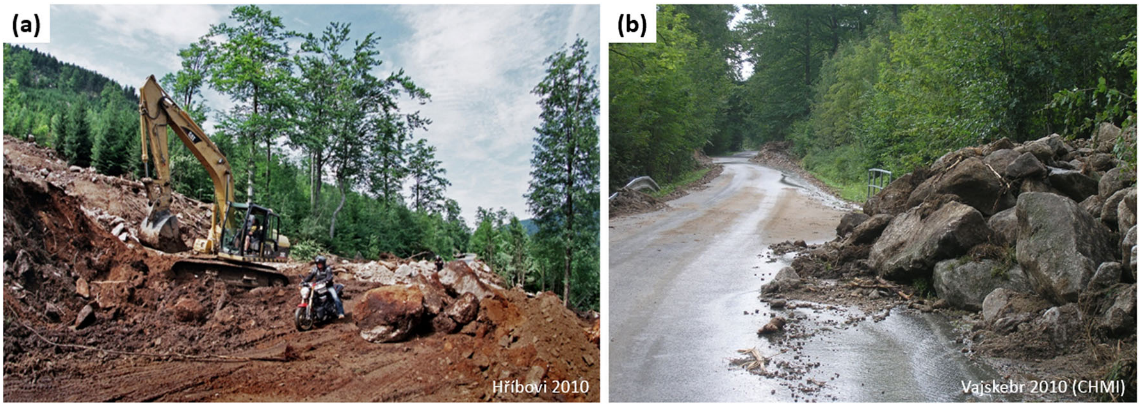

Fig. 2 Consequences of debris flow: **a** the road passes in the place where the motorcycle is crossing; **b** the rest of blocks from debris flow

This study was performed due to the occurrence of debris flows, the availability of detailed rainfall data, and the lack of knowledge of the rainfall thresholds in the area of interest. As a consequence, the principal aim of this paper is to demonstrate how the relation between the triggering of debris flows and rainfall pattern conditions can be determined based on statistics of rain gauge observations.

Study area

The study area is situated in the northern part of the Czech Republic close to the border with Poland, 17.5 km to the NE of the town of Liberec, between the villages of Bílý Potok and Smědava, in the Jizerské hory Mts. (Fig. 3).

The Jizerské hory Mts. are a block-type mountain range. The crystalline basement is formed by biotitic granites belonging to Krkonošsko-jizerský Pluton (Carboniferous age) exposed during the Variscan Orogeny (Chaloupský et al. 1989). The morphology of the mountain range is characterized by a flat denudational surface approximately 1000 m a.s.l. The Tertiary was characterized by peneplainization processes in this area. In the Quaternary, the area was influenced by the nearby continental glaciations and periglacial processes played a major role in their development (see also Nývlt 2000; Černá 2011). The northern structural slopes of the Jizerské hory Mts. are steep, while the southern slopes are moderate and highly dissected by erosional processes.

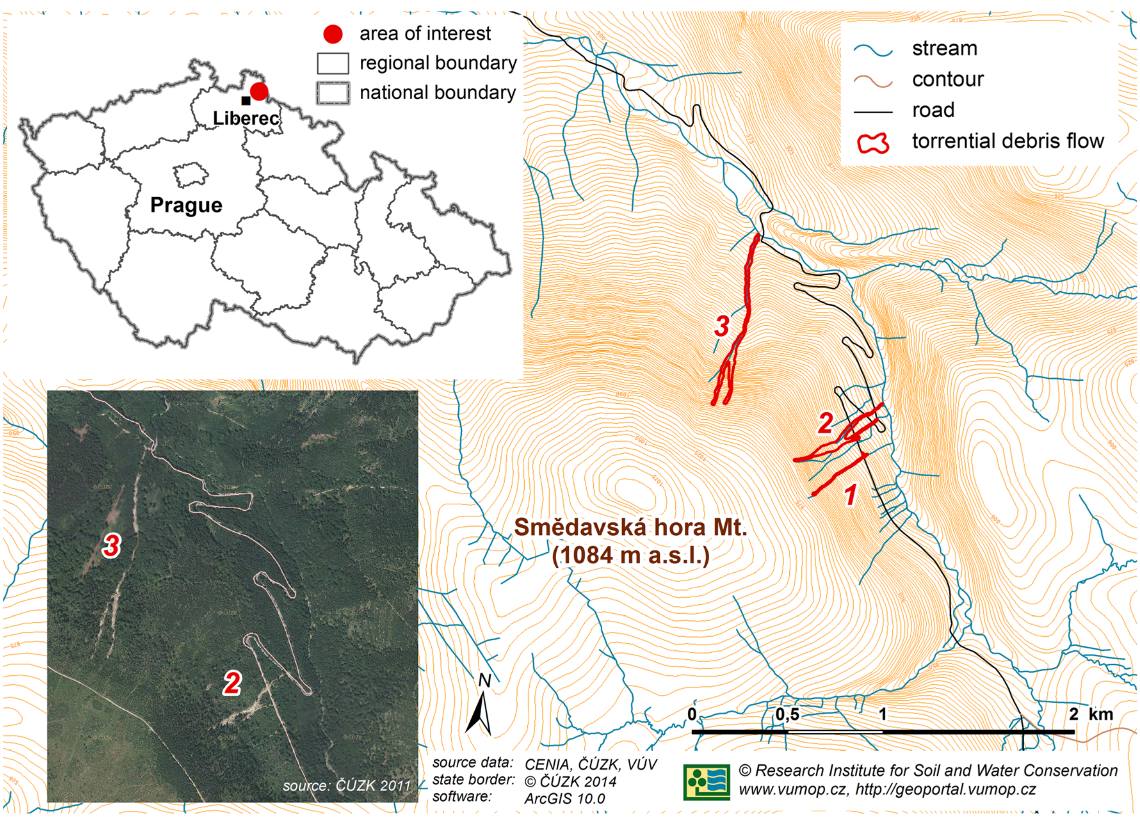

Fig. 3 The area of interest

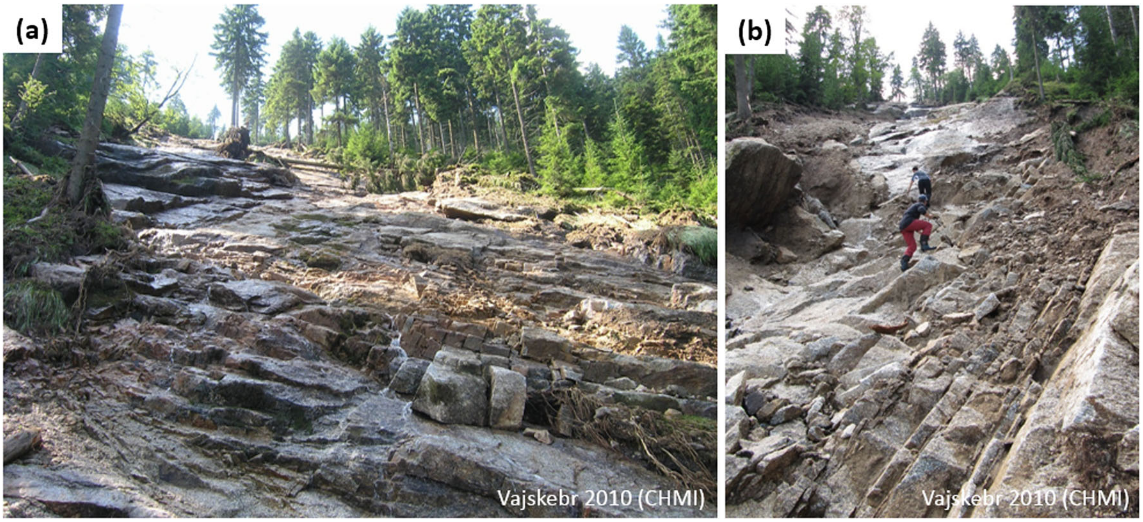

Fig. 4 Granite bedrock exposed by debris flow number three in the transport part

Smědavská hora Mt. (1084 m a.s.l.) is formed by medium-grained porphyric biotitic granite, fractured by three systems of cracks with rectangular disintegration (Fig. 4) (Mrázová and Krupička 2011). Deeper infiltration of water along the system of cracks generates quicker erosion and disintegration of the bedrock. The slopes of the Smědavská hora Mt. are covered by a thin colluvial sedimentary layer with a variable thickness of up to 0.5 m. As a consequence of its very steep slopes (usually more than 30°), the surface of the Smědavská hora Mt. is potentially highly prone to shallow slope movements.

The area belongs to a cold climatic zone with a mean annual temperature of between 4.4 and 7.1 °C (Vacek et al. 2003) and with average rainfall during the summer (June–August) reaching 600–700 mm. The climate of the area is influenced by prevailing westerly and north-westerly winds, which bring moisture from the Atlantic Ocean. The ridge of the Jizerské hory Mts. forms a barrier to these winds, which results in the highest annual levels of rainfall in the Czech Republic (1705 mm/year in Bílý Potok). The maximum record of 1-day rainfall was recorded in Jizerské hory Mts. at the Nová Louka (345.1 mm) and Jizerka (300 mm) rain gauges on the 29th July 1897. Levels of 1-day rainfall above 300 mm are exceptional in the climate of Central Europe and were recorded only three times within a time span of more than 100 years (Munzar et al. 2011). One-day rainfall of 312 mm was recorded in the Krušné hory Mts. on the 12th August 2002 during the floods in Central Europe. At the same time, 1-day rainfall of 278 mm was measured at the Knajpa rain gauge, close to the site of the 2010 debris flows.

Water from the study area is drained by the Smědá River that flows to the Odra River and belongs to the Baltic Sea catchment. The average discharge of the Smědá River in Frýdlant is 3.09 m^3/s. However, it has significant variance throughout the year. Peatbogs on the Smědavská hora Mt. are essential for the water regime of this region. In dry periods, they are able to retain water and supply local streams; on the contrary, in wetter periods, they can keep large amounts of water to some point. The upper slopes of the Smědavská hora Mt. are covered by podzol soil, which continues with a narrow strip of ranker, and the lower slopes are covered by undeveloped red soil (Tomášek 1995). Table 1 shows the soil granularity.

Data and methods

Rainfall data

The precise amount of rainfall is not known in the places of initiation of debris flows in 2010 because there are no rain gauges directly present in the release area and the real rainfall amounts from the torrential rainfall can vary within 1 km^2 or less due to orographic differences especially in mountainous areas. So, it is important to choose representative rain gauges as close as possible taking into account the orography and data availability.

Four rain gauges managed by the Czech Hydrometeorological Institute (CHMI) were chosen to analyze their rainfall data. All of these gauges are located within a radius of 3 km, with two of them only 1 km from the triggering area of the debris flows, so they offer unique and relatively accurate data. Rain gauges located at Smědava (SM), Smědavská hora (SMH), Knajpa (KN), and Pavlova cesta (PC) (Fig. 5) are in a similar climate zone with the same geologic environment but are at different sea levels and are subject to different exposure with respect to the impact of frontal systems. Unfortunately, rainfall data from the other known debris flow event in 1958 were not available from these rain gauges. Thus, rainfall data from 1958 are taken from the Desná—Souš (DS), Bedřichov (BD), and Mníšek—Oldřichov v Hájích (MN) (Fig. 5) rain gauges situated within a radius of 10 km from the debris flow triggering area, with daily cumulated amounts of rainfall only.

Table 1 Granularity of the taken soil samples (grain size less than 2 mm)

Sample	Clay (%)	Silt (%)	Sand (%)
1	5.2	20.2	74.7
2	4.1	25.1	70.9
3	4.0	16.2	79.8

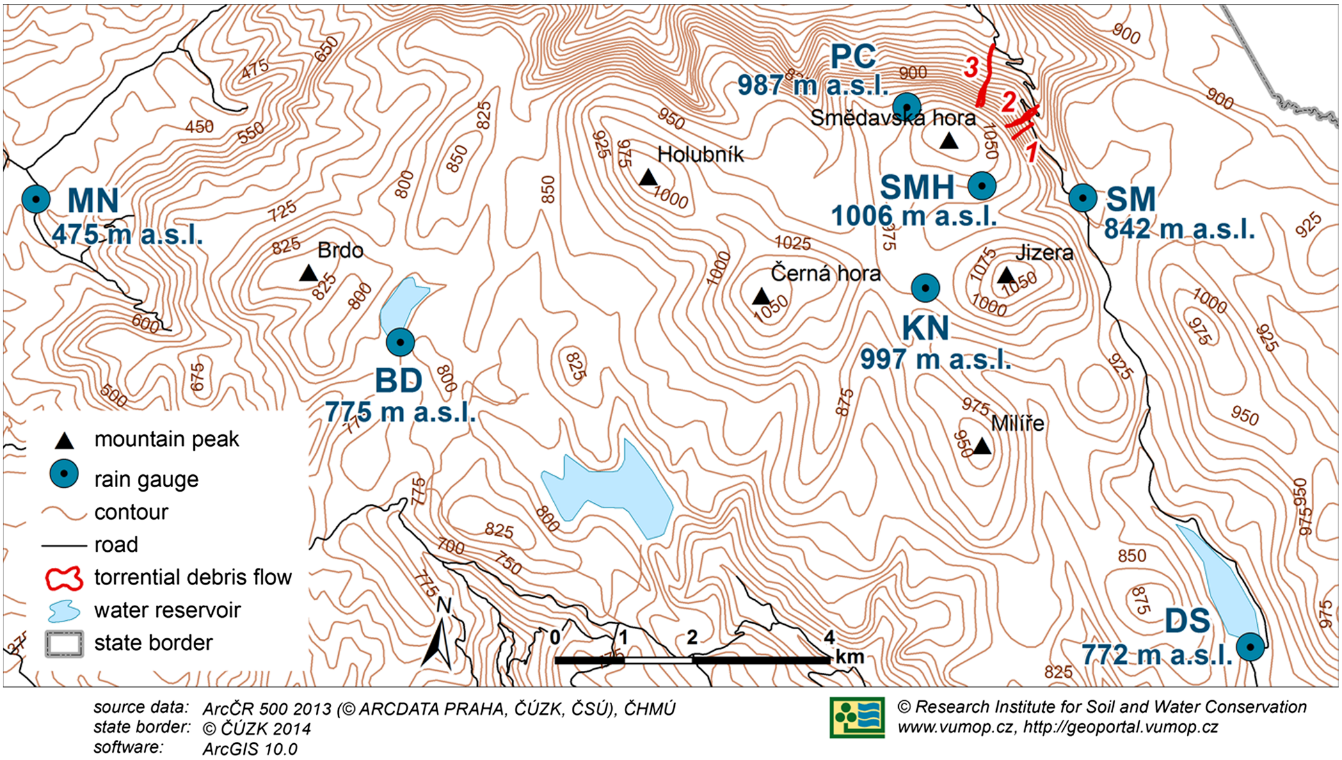

Fig. 5 Localization of the selected rain gauges in the area of interest

The KN, SM, and SMH rain gauges do not have a complete range of rainfall data, and none is a strict representative (due to their orographic position and altitude). They only collect measurement data during the summer period—June–September (1983–1997) and May–October (1998–2013)—and suffer from frequent outages caused by gauge breakdowns. Several years or months in some of the rain gauges are completely missing, so the data set is not coherent. Data on short intensities has been available since 1996, after the installation of automatic stations. Prior to 1996, only daily rainfall data are available.

Rainfall data were analyzed for the period June–August 1983–2013 due to their availability and also as they represent rainfall corresponding to the occurrence of 80 % of erosional rain or torrential rainfall in the Czech Republic (Janeček et al. 2007). The period June–August also corresponds to the wettest months in the study area. In addition, according to Nikolopoulos et al.

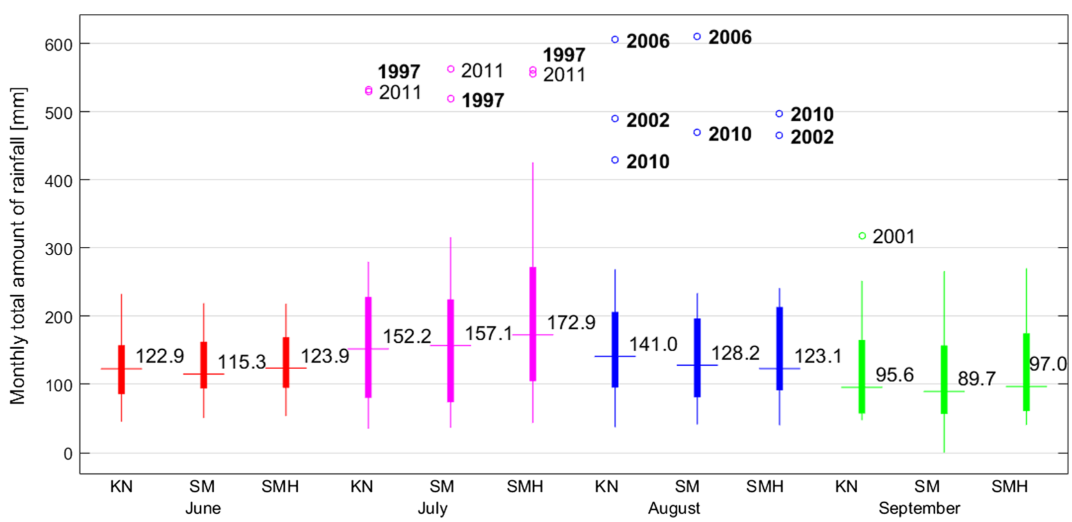

Fig. 6 Long-term monthly rainfall amount during the years 1983–2012 from Knajpa (*KN*), Smedava (*SM*), and Smedavska hora (*SMH*) rain gauges in June (*red box plot*), July (*violet box plot*), August (*blue box plot*), and September (*green box plot*); *horizontal line* corresponds to a median value; *bold vertical line* enhances the lower and upper quartile; the *thin vertical line* represents data range excluding the outliers, which are depicted individually as discharge points; *bold numbers* flood events (source: CHMI)

(2014), 90 % of debris flow events in the Alps occur between June and September, which was also documented by Rebetez et al. (1997) from Valais (Swiss Alps) and Blahut et al. (2012b) from Valtellina (Italian Alps), where debris flows occurred in the wettest period of the year.

Long-term analyses were elaborated from daily amounts from 1983 to 2013, and detailed analyses focused on flood episodes that were identified on the basis of reports and rainfall data obtained from the CHMI.

All of the available daily rainfall amounts from the KN, SM, and SMH rain gauges, and their character are depicted in the form of monthly values for the period 1983–2013 using box plots (Fig. 6). The PC rain gauge has measured since 2011 so it is not depicted. These illustrate the variation in the samples of each rain gauge for each month and allow differences to be visually estimated between median rainfall values (even by 20 mm), the data range, and outliers. The resulting outliers which represent the distance of points from other observations, correspond to the years when floods occurred.

No eminent flood or highly significant rainfall event was recorded during 1983–1996 around the Smědavská hora Mt. according to the CHMI data, but the number of extreme flood events has increased over the last two decades. There was a significant flood in 1997 and the recurrence is less than 5 years (1997, 2002, 2006, 2010, and 2011) (Table 2).

The flood episode with a related debris flow occurrence was during the period 06–08 August 2010. A combination of persistent, convection-type rainfall lasting for 3 h and the occurrence of storm cores enhanced by highly saturated soil after previous rains caused the flood. An interesting fact was that the rainfall was much more intense in the foothills than at higher altitudes than during the other flood episodes. Combination of radar rainfall data projection and measurements of ground rain gauges estimate the daily rainfall to be higher than 160 mm in the area of interest (CHMI 2010).

The basic rainfall characteristics from the selected rain gauges are included in Table 3.

Data analyses

Antecedent precipitation index

One of the examined factors was the antecedent precipitation index (API) which shows the precipitation situation retrospectively and is used to define the antecedent moisture condition (Mishra and Singh 2003); thus, it is used to assess the saturation in the watershed. Soil moisture has a considerable influence on the

Table 2 List of the significant flood periods in the area of interest since 1983 (source: CHMI) (bold and italic - data from debris flow event)

Date of flood	Character of the rain pattern
06–07 Jul 1997	Frontal rainfall
18–21 Jul 1997	
12–14 Aug 2002	Frontal rainfall+short torrential rainfall
05–07 Aug 2006	Frontal rainfall
06–08 Aug 2010 (debris flow)	***Frontal rainfall+torrential convection rainfall***
20–21 Jul 2011	Frontal rainfall

Table 3 Basic rainfall characteristics of the selected rain gauges (KN, SM, and SMH) during the flood episodes (bold and italic - data from debris flow event); long-term monthly/daily average is calculated from data from 1983 to 2013, i.e., 30 years; debris flow occurrence (DF) (source: CHMI)

Flood episodes	Knajpa (KN)				Smědava (SM)				Smědavská hora (SMH)			
	Total amount (month)	Long-term monthly average	Max daily amount	Long-term daily average	Total amount (month)	Long-term monthly average	Max daily amount	Long-term daily average	Total amount (month)	Long-term monthly average	Max daily amount	Long-term daily avеage
06–07 Jul 1997	531.9	165.2	125.6	5.5	518.6	172.8	119.2	5.6	561.9	199.3	124.8	6.4
18–21 Jul 1997	531.9	165.2	102.6	5.5	518.6	172.8	113.1	5.6	561.9	199.3	111.6	6.4
12–14 Aug 2002	490.1	175.0	278.0	5.6	–	155.3	–	5.0	465.2	163.4	271.0	5.3
05–07 Aug 2006	606.1	175.0	146.0	5.6	611.1	155.3	146.0	5.0	244.5	163.4	149.0	5.3
05–09 Aug 2010 (DF)	***429.1***	***175.0***	***123.1***	***5.6***	***469.8***	***155.3***	***133.4***	***5.0***	***497.7***	***163.4***	***146.0***	***5.3***
20–21 Jul 2011	530.0	165.2	126.5	5.5	562.2	172.8	137.0	5.6	555.8	199.3	128.3	6.4

physical properties of soil, e.g., pore-water pressure and shear strength (Zhao et al. 2011), which can therefore 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 precipitation is determined by seasonal variations of rainfall and temperature, which affect evapotranspiration. Intense convective storms occur during the summer when evapotranspiration can remove much of the soil moisture within days. Consequently, the significance of antecedent precipitation 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).

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

$$\mathrm{API}_n = \sum_{i=1}^{n} c^i \times P_i[\mathrm{mm}] \tag{1}$$

where:

n The total number of days prior to the causal rainfall, usually n is 5, 10, 20, or 30.

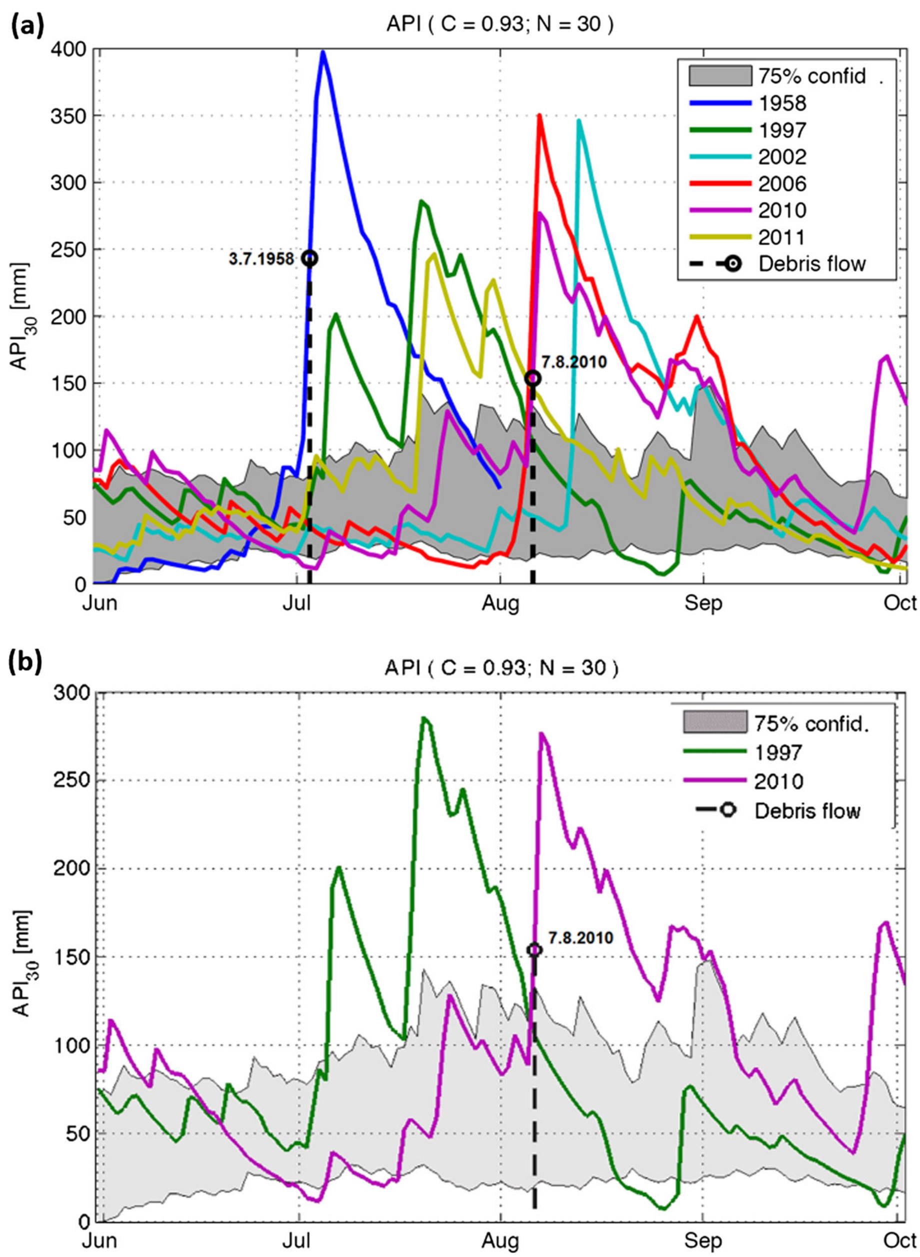

Fig. 7 **a** Antecedent precipitation index for 30 days for the analyzed flood years; **b** comparison of the development of API30 in 1997 and 2010 (calculated from source data: CHMI)

- i The number of days counting backwards from the date on which the API is determined.
- c An evapotranspiration constant (for the Czech Republic c=-0.93 (Steinhart 2010)).
- P_i The amount of precipitation i days prior to the causal r-ainfall (mm).

The API was calculated for a floating number of days (n=5, 10, 20, or 30) from the daily amounts of rainfall for all of the years in the period 1983–2013 using the data from the selected rain gauges (but only years with flood episodes were selected). The data from four rain gauges were used and adjusted using a linear regression. A linear regression was necessary mainly because of occasional measurement outages at the rain gauges because the continuous data series are requisite for API computation. The basic assumption was that the data from the PC rain gauge are the most similar to the rainfall amounts at the site of the debris flow (DF) on the basis of the short distance between DF and PC and orography. Thus, the PC measurements were established as reference data for a further analysis. A linear regression was utilized to supplement data from neighbouring gauges—KN, SM, and SMH.

The estimator has the following form:

$$y = a_1u_1 + a_2u_2 + a_3u_3, \quad (2)$$

where y is an estimate of the amount of rainfall at PC and $u1$, $u2$, and $u3$ are measurements from KN, SM, and SMH, respectively. Linear coefficients $a1$, $a2$, and $a3$ were estimated so that the resulting linear estimator has a minimum sum of squared errors. Note that only rainy days, where data from all stations was available, were used to estimate these parameters. The estimated coefficients were calculated so that their sum was always equal to one. Note also that only missing measurements from the PC gauge were substituted.

Based on the linear regression, we interpolated new values for the whole rainfall data set. When the PC data were available, they were adopted and applied as new values. In cases where data were missing from one or more rain gauges (KN, SM, SMH), a new linear regression was applied and new coefficients whose sum was equal to one were calculated.

Daily rainfall

One-day rainfall data represents the total amount of rainfall measured in the selected CHMI rain gauges (KN, SM, SMH, PC, DS, BD, and MN) during a single day (from 7:01 a.m. 1 day to 7:00 a.m. the next day). These records were provided by CHMI for the period 1983–2013 and the year 1958. Analysis of 1-day rainfall was carried out with the selected maximum values from the rain gauges for each time interval in order to maintain the highest possible rainfall amount. Two–three-day amounts were calculated as moving values from the maximum 1-day amount.

Hourly rainfall

One-, two-, and three-hour rainfall data were calculated from the values of the maximum short rainfall intensities as moving values which ensure the maximum value in the data set. These values are available for flood events from 1997 to 2013.

Short rainfall intensities (10/15 min)

Values of short intensities are available from 1997, when automatic rain gauges of the CHMI were installed, to the present. The data are from the rain gauges KN, SM, SMH, and PC including the flood episodes. The measurement intervals of the data are not unified for all of the rain gauges, the range of precision varies among 10 min/15 min/1 h intensities. Thus, the 1-h intensity (mm/h) was calculated separately in order to make a relevant comparison of the data. The maximum value was elaborated from all of the selected rain gauges for each time record. This provided the maximum possible rainfall value that could occur there.

The rainfall data (API with n=5, 10, 20, and 30, monthly/daily/hourly amounts, 15/10 min intensities) was analyzed. Subsequently, the influence of mutual interactions of all of the analyses was examined, and the likely dominant precipitation factor for initiation of debris flows was determined.

Results

Antecedent precipitation index

The antecedent precipitation index was calculated for all of the years (1958, 1983–2013) for 5, 10, 20, and 30 days in the form of floating values. Only the years of the flood episodes for API_{30} expressed significant values (Fig. 7a).

The highest API_{30} was recorded in 1958 and resulted in a debris flow, whereas the years 2002 and 2006 show a much higher value of API_{30} than 2010 but did not result in a debris flow. The development of the precipitation curves is different. In 1958, 2002, and 2006, the API_{30} values are low but increase very steeply and have only one peak (Figs. 7a and 8). It is assumed that the soil was not saturated prior to the flood episode so the soil condition was favorable for absorbing rainfall. But the debris flow in 1958 does not fit this assumption. When the 2010 debris flow event occurred, two peaks were recorded although not as high as in 1958, 2002, or 2006 and another considerable rainfall episode occurred 1 month before. The soil in this case was saturated, the infiltration capacity of the soil was exceeded, and pore-water pressure was high enough to debris flow occurrence (Záruba and Mencl 1974). A very similar trend of the 2010 API_{30} curve can be seen for 1997 with two high peaks (Fig. 7b). The

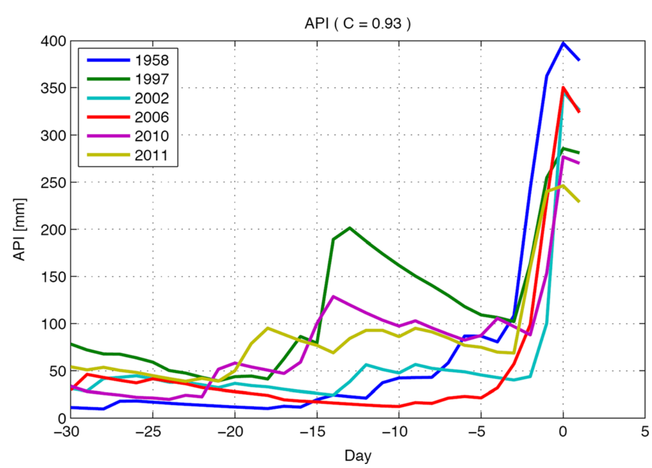

Fig. 8 Antecedent precipitation index for 30 days for the flood years—30 days before the maximum (calculated from source data: CHMI)

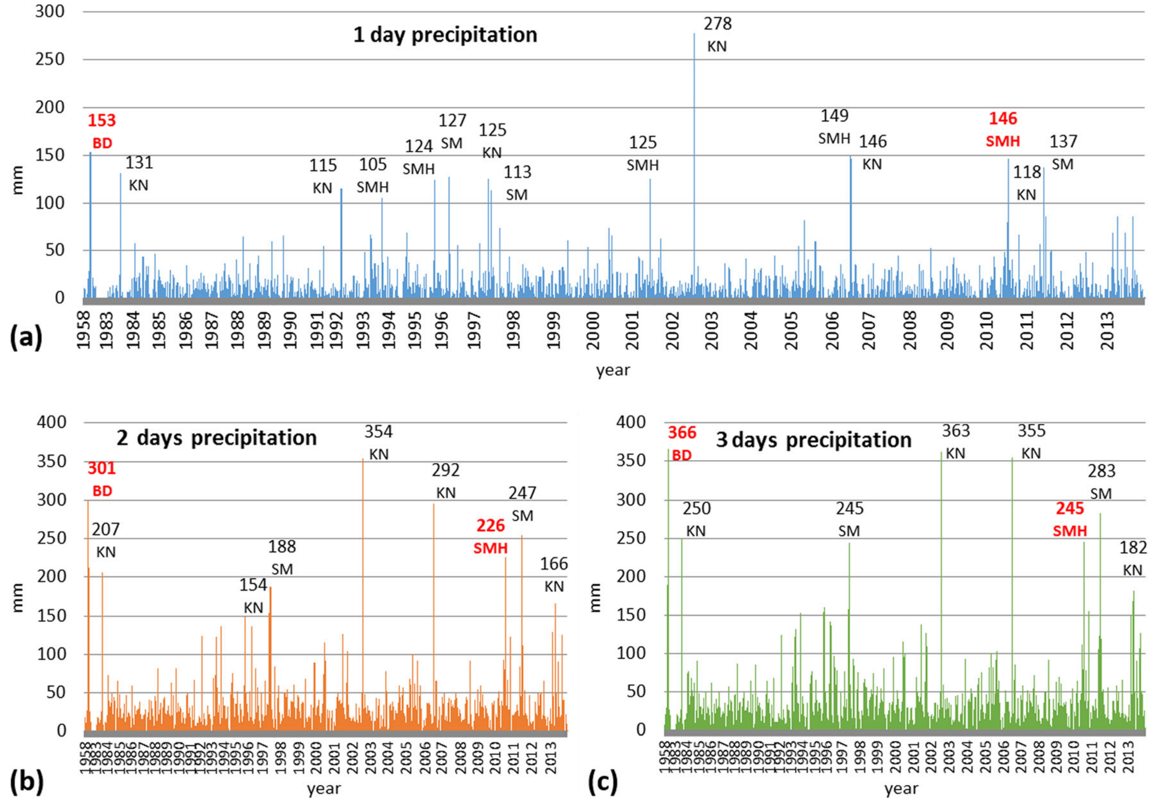

Fig. 9 **a** Daily rainfall amount (1958 from Bedřichov and Mníšek, Fojtka rain gauges; 1983–2012 from Knajpa, Smědava, Smědavská hora, and Pavlova cesta rain gauges); **b** 2-day total rainfall amount; **c** 3-day total rainfall amount; *red numbers* recorded debris flows (source: CHMI)

unique difference is the development of API_{30} curves between the two peaks. In 1997, both of the peaks increase and decrease steeply, whereas in 2010 the increase and decrease of the first peak is gradual with other small peaks and the increase of the second peak is steep so there was new rainfall between the two peaks in 2010. According to the API_{30} analysis (Figs. 7a and 8), the question arises as to why there was no debris flow event in 1997, 2002, or 2006.

The API curve for 2011 has a similar trend but is not as high and it was after the debris flow event in 2010, possibly there was not enough weathered material available to form another debris flow.

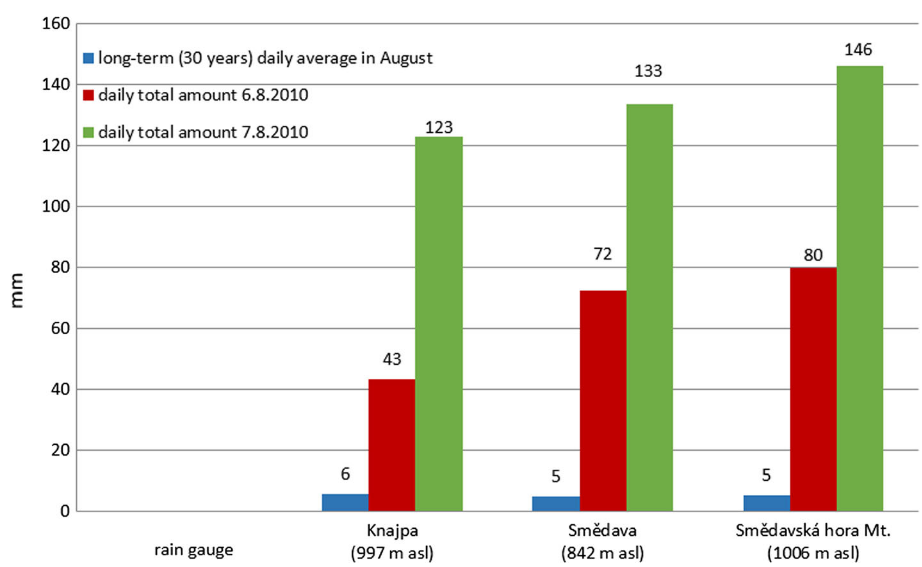

Fig. 10 Daily rainfall during the debris flow episodes (source: CHMI)

Table 4 Moving values of rainfall recorded in rain gauges KN, SM, SMH during the debris flow episodes (Debris flow originated between 10:00–11:00 am—time in CEST) (Source: CHMI 2010)

Rain gauge	Max. measured intensity			Total amount 06–08 Aug 2010
	24 h	1 h	15 min	
Knajpa (997 m a.s.l.)	142.9 mm	32.0 mm	10.9 mm	186 mm
	19:30 6.8.2010	9:30 7.8 2010	10:00 7.8 2010	
Smědava (842 m a.s.l.)	174.9 mm	40.4 mm	13.4 mm	215 mm
	18:00 6.8.2010	11:00 7.8.2010	10:15 7.8.2010	
Smědavská hora (1006 m a.s.l.)		out of operation		240 mm

Daily rainfall

The total daily rainfall on the 7th August 2010 reached 146 mm (Fig. 9a) in the SMH rain gauge, which was almost 30 times more than the 30-year measured daily average for August (Fig. 10). The maximum 24-h total moving amount was 174.9 mm in the SM rain gauge (Table 4) and might be higher in the broken SMH rain gauge because the total amount in SMH was approximately 25 mm higher than in the SM gauge between 6th and 8th August (Table 4). The other noted debris flow formed during the rainfall with a total daily amount of 153 mm in 1958 which is very close to the value from 2010. At the same time, these values are among the five highest daily totals within the period 1983–2013 and 1958 (1958 is the second highest and 2010 is the fourth).

Two-day rainfall data is similar with the value from 1958 being the second highest and 2010 being the fifth highest (Fig. 9b). Analysis of the 3-day data shows that the value from 1958 is the highest and 2010 is the sixth highest (Fig. 9c).

One-, two-, and three-day rainfall seems to be very important for triggering the debris flow in 1958, but this does not apply for 2010. The question arises as to why a debris flow did not form in 2002 when the 1-day total amount reached the record value of 278 mm or in 2006 when two consecutive days had more than 140 mm.

It must be noted that the values may be distorted due to data from different gauges (in 1958 and in 2010; in 2010, the main rain gauge at SMH was out of operation).

Hourly intensities

One-, two-, and three-hour rainfall intensities were analyzed from the detailed data. The 1-h intensity was 40.4 mm in the SM rain gauge during the debris flow event, which was significantly higher than the others in the years of the flood events (Fig. 11). This value was measured at time 10:00–11:00, and the debris flow began at approximately 10:30.

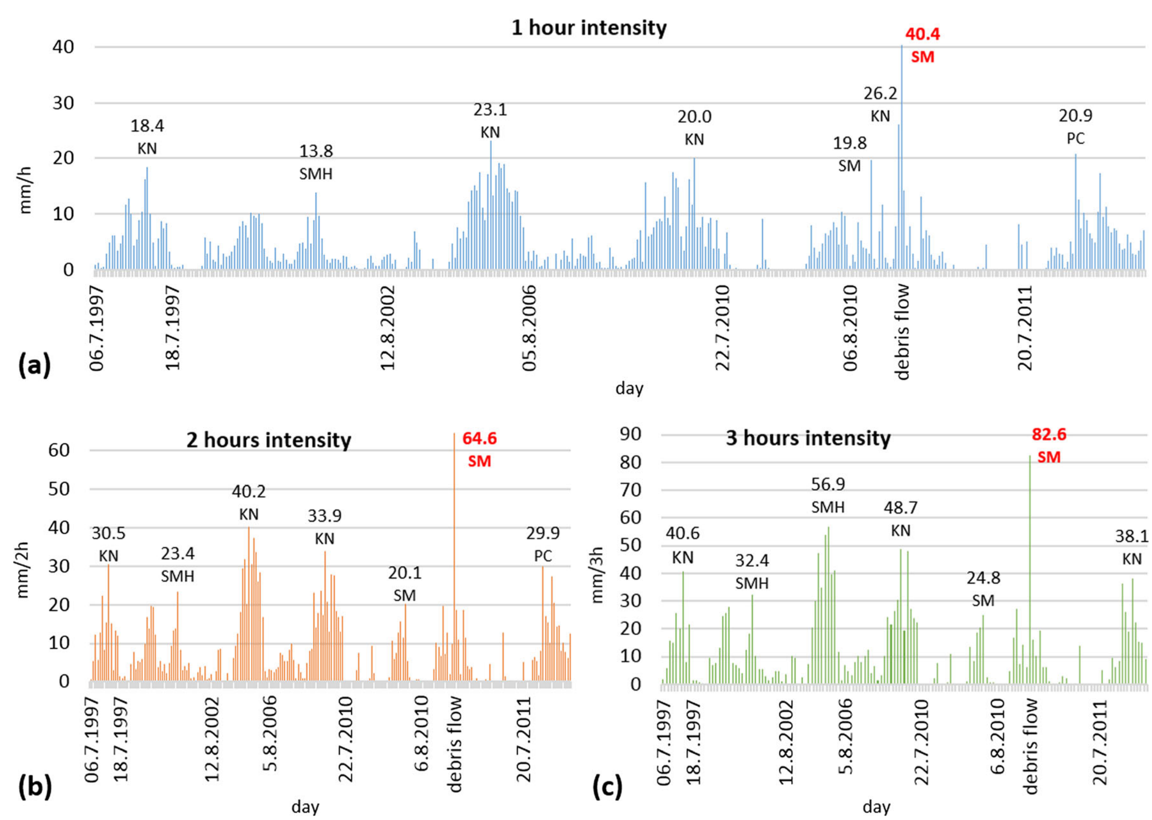

Fig. 11 **a** Hourly rainfall intensity; **b** 2-h intensity (moving values); and **c** 3-h intensity (moving values) (source: CHMI)

Table 5 List of 1-h total rainfall amounts higher than 30 mm (1997–2013) (Source: CHMI) (bold and italic - data from debris flow event)

Date	1 h amount (mm)	Rain gauge
06 Jul 1999	30.30	SMH
07 Aug 2010 (DF)	***40.40***	***SM***
24 Aug 2011	42.60	SMH
24 Aug 2011	41.60	KN
29 Jul 2013	42.90	KN
29 Jul 2013	39.50	SMH
29 Jul 2013	31.40	SM

In addition to the detailed flood event data, 1-h rainfall intensities higher than 30 mm were taken from the whole 1997–2013 data set. There were only four 1-h rainfall intensities higher than 30 mm during this period (Table 5), and one of them occurred during the 2010 debris flow event. Moreover, high values of 42.6 and 42.9 mm were recorded 1 and 3 years after the debris flows, respectively. The analysis of 2- and 3-h intensities shows a similar trend. Based on this analysis, the hourly intensities are crucial for the formation of the debris flows.

Short intensities (10/15 min)

The maximum total rainfall for a 15-min interval during the flood event with the debris flows on the 7th of August 2010 was 13.4 mm at 10:15 (10:00–10:15), and the hourly intensity was calculated to be 53.6 mm/h in the SM rain gauge. The SMH rain gauge had the highest total daily amount but suffered a breakdown and short intensities are not available for the studied period. The hourly intensity was calculated to compare the values obtained from different intervals of 10 or 15 min. Values higher than 10 mm/10 or 15 min (or intensity higher than 40 mm/h) were registered 14 times in the period 1997–2013, where the debris flow event was the only one to occur during the noted flood periods (Fig. 12). At the same time, the debris flow event evinces lower intensities than the rest of the selected records. Note that all of the flood events show lower intensities than no flood periods. Only the record from the 2010 debris flow event shows a flood period and has high intensity at the same time.

Discussion

The debris flows were triggered by very localized heavy rainfall in summer 2010. However, heavier rainfall has been recorded during the last 30 years without any debris flow events. So, the relation between the triggering of the debris flow on the Smědavská hora Mt. in 2010, and the rainfall pattern conditions was determined based on statistics of rain gauge observations.

From this event, we may conclude that for the debris flows initiation on the Smědavská hora Mt., the combination of the antecedent precipitation index, daily/hourly amounts and values of short intensities of 10/15 min is much more important than the individual extreme itself.

The maximum API values were reached in 1958 (after the 1958 debris flow) and in 2006, the daily maximum was in 2002, the hourly maximum was in 2013 (3 years after the 2010 debris flow event) and in 2010, where the hourly maximum was the only maximal value that year, and finally the short intensity rainfall reached maximum in 2011 (after the 2010 debris flow) and in 2003 (before the 2010 debris flow). It is worth noting that when API reached high values, the hourly and short intensities were

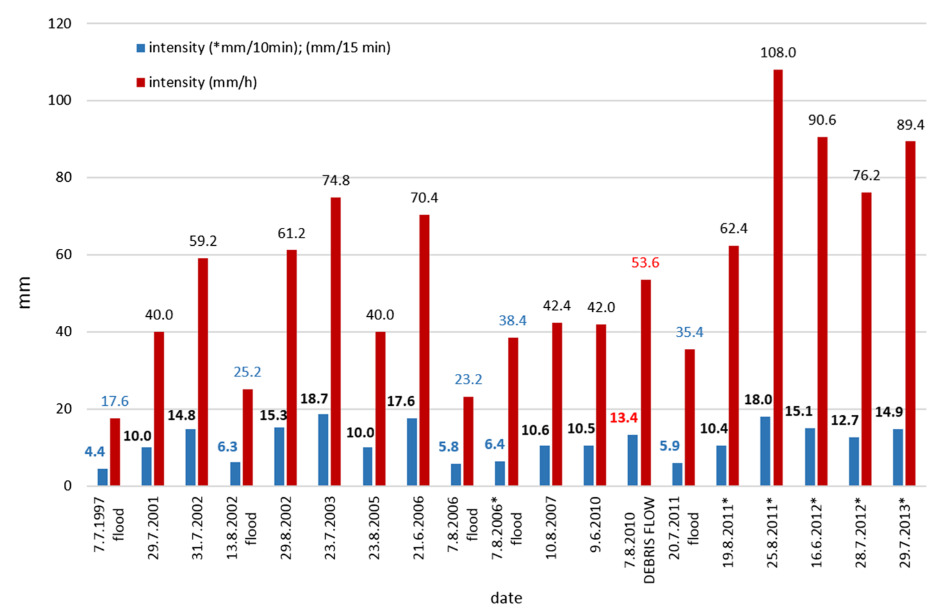

Fig. 12 Short intensities (*blue numbers* flood episodes; *red number* debris flow) (source: CHMI)

Table 6 Detailed rainfall data (*10-minute interval; italics – flood periods; bold – values higher than 10 mm - short intensity 10/15 min, values higher than 30 mm - 1 hour amount, values higher than 100 mm - total daily amount, values higher than 150 mm - API 30; dash – no data; blue frame –2010 debris flow event) (Source: CHMI)

Date	MAX mm/ 15/10* min	Intensity (mm/h)	Rain gauge	1 hour amount (mm)				Total daily amount (mm)			API 30
				KN	SM	SMH	PC	KN	SM	SMH	
03 Jul 1958 (DF)	-	-	-	-	-	-	-	***68.7 (DS)***	***153.2 (BD)***	***141.6 (MN)***	***243.2 (BD)***
07 Jul 1997	*4.4*	*17.6*	*SM*	*18.4*	*15.8*	*17.9*	-	***125.6***	***119.2***	***124.8***	***189.2***
20 Jul 1997	-	-		*10.9*	-	*13.8*	-	*46.7*	*43.7*	*56.7*	***254.5***
29 Jul 2001	**10.0**	**40.0**	KN	18.3	11.3	9.2	-	30.9	22.0	22.5	106.7
31 Jul 2002	**14.8**	**59.2**	KN	24.4	-	16.4	-	24.5	-	16.5	24.4
13 Aug 2002	*6.3*	*25.2*	*SMH*	*23.1*	-	*22.4*	-	***278.0***	-	***271.1***	*100.5*
29 Aug 2002	**15.3**	**61.2**	KN	23.4	-	17.5	-	25.9	-	17.9	129.9
23 Jul 2003	**18.7**	**74.8**	KN	26.2	-	**30.0**	-	30.1	-	30.7	39.2
23 Aug 2005*	**13.4***	**80.4**	SM	20.3	22.5	14.8	-	58.1	60.2	53.2	65.3
21 Jun 2006	**17.6**	**70.4**	KN	20.9	15.1	13.7	-	36.3	30.0	27.3	38.3
07 Aug 2006	*5.8*	*23.2*	*KN*	*20.0*	*12.8*	-	-	***146.4***	***146.1***	-	***230.3***
*07 Aug 2006**	*6.4**	*38.4*	*SM*	-	*15.4*	-	-	***146.4***	***146.1***	-	***230.3***
10 Aug 2007	**10.6**	**42.4**	KN	15.1	1.9	11.6	-	32.4	27.5	31.1	29.6
09 Jun 2010	**15.1**	**60.4**	SMH	22.2	19.3	25.1	-	32.4	29.7	30.8	75.1
07 Aug 2010 (DF)	***13.4***	***53.6***	***SM***	***32.0***	***40.4***	-	-	***123.1***	***133.4***	***146.0***	***153.5***
*20 Jul 2011**	*5.9**	*35.4*	*PC*	*17.3*	-	*18.2*	*20.9*	***118.0***	***110.0***	***116.0***	*68.7*
*21 Jul 2011**	*3.7**	*22.2*	*SMH*	*17.8*	-	*16.8*	*14.6*	***126.5***	***137.0***	***128.3***	***159.6***
19 Aug 2011*	**15.6***	**93.6**	SM	19.3	25.2	26.2	24.1	45.7	49.2	49.4	77.2
25 Aug 2011*	**18.0***	**108.0**	KN	**41.6**	**35.9**	**42.6**	29.7	49.5	44.6	50.3	94.7
16 Jun 2012*	**15.1***	**90.6**	KN	19.0	15.2	14.4	21.1	21.8	18.0	18.0	40.8
28 Jul 2012*	**12.7***	**76.2**	KN	27.8	17.5	28.0	28.3	46.9	39.3	48.5	33.7
29 Jul 2013*	**14.9***	**89.4**	KN	**42.9**	**31.4**	**39.5**	**50.1**	62.7	54.4	66.1	32.6

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Table 7 Comparison of the total daily amount and 24 h moving values of rainfall during the flood episodes (source: CHMI) (bold and italic - data from debris flow event)

Flood episodes	Knajpa (KN)		Smědava (SM)		Smědavská hora (SMH)	
	Daily amount	Max 24 h amount	Daily amount	Max 24 h amount	Daily amount	Max 24 h amount
06–07 Jul 1997	125.6	144.8	119.2	139.6	124.8	136.6
18–21 Jul 1997	102.6	107.2	113.1	–	111.6	127.5
12–14 Aug 2002	278.0	315.4	–	–	271.0	307.2
05–07 Aug 2006	146.0	237.7	146.0	227.6	149.0	–
05–09 Aug 2010 (DF)	***123.1***	***142.0***	***133.4***	***174.9***	***146.0***	–
20–21 Jul 2011	126.5	177.0	137.0	–	128.3	179.2

negligible and conversely events with high hourly and short intensities evinced low API values. Only in 2010 during the flood event with debris flows events were all of the values of these analyses highly above average (Table 6). Unfortunately, the short rainfall intensities are not available from the 1958 debris flow, but the daily amounts and API correspond to the 2010 situation.

Rainfall data analysis is usually connected with many uncertainties. The real values of the rainfall data that result in debris flows can be significantly different from values estimated based on measurements from nearby rain gauges. Although the spacing between rain gauges is exceptionally dense in the area of interest (less than 2 km) compared with the Alps, which is between 4 and 15 km (Nikolopoulos et al. 2014), the daily rainfall amounts at the individual rainfall gauges vary by as much as 30 mm. More uncertainties in the rainfall data may arise from the rainfall duration and intensity, when the error decreases with an increase in rainfall duration and short rainfall with high intensity shows higher uncertainty (Nikolopoulos et al. 2014). Technical possibilities of the measurements influence accuracy of the measurements as well, for example, the manner of recording, when the total daily amounts and maximum 24-h moving values differ by as much as 40 mm (Table 7). Rain gauge breakdown, lack of detailed data, and statistical methods used to process the data may lead to an undervalued rainfall threshold assessment and influencing of the data set size as well.

The results are also influenced by the following circumstances: the data from 1958 were measured at different rain gauges thus they might be less significant for determining the thresholds; the detailed data from 2010 were from a rain gauge which had a total daily amount lower than the broken rain gauge. The fact that only one debris flow event was analyzed in detail may distort the conclusions, and it would be good to compare it with another debris flow event in this locality. Incomplete series of data and their subsequent processing could also lead to more inaccuracies in the results. Finally, rainfall is not the only causative factor for debris flow initiation (Aleotti and Chowdhury 1999), the geologic, geomorphologic, soil, and vegetation conditions also have to be taken into consideration. The source area of the debris flow could have formed prior to the debris flow being activated in 2010. However, there were four source sites on the Smědavská hora Mt. in 2010, so the probability that so many triggering fissures could be formed at the same time is relatively low.

Conclusions

This study shows that for the debris flow initiation, the combination of the antecedent precipitation index, daily/hourly amounts, and values of short intensities of 10/15 min is much more important than the individual extreme itself. This area has been affected several times by long-term rainfall which created flooding or was hit by shorter and more intense torrential rainfall (CHMI). None of these situations created debris flows in the past (with two exceptions in 1958 and 2010). The short intensities during the cyclone flood periods did not reach high values, but the total daily amounts are significantly higher than during periods of torrential rainfall. Conversely, the short intensities during periods of torrential rainfall are very high but the total daily amounts are low. The 2010 debris flow event is a combination of specific situation when short-intensity rain (15 min) reached more than 10 mm, hourly amounts more than 30 mm, total daily amounts more than 100 mm, and API30 was more than 150 mm (Table 6). All of these values were highly above average, but none of them were really an outstanding exception. Nevertheless, their combination and joint influence resulted in triggering debris flows.

The first recorded debris flow in that area in 1958 happened under similar meteorological conditions—total daily amounts more than 100 mm and API30 of more than 150 mm, which corresponds to 2010. Unfortunately, short intensity (15 min) and hourly amount are not available from this period.

We also analyzed the exceptional precipitation values from the period 1983–2013, and we found higher 10/15 intensities compared with 2010: during 23 August 2005 or in 2011 (Table 6) when the intensities were almost two times higher and no debris flow occurred. It could be explained by rather lower level of 1-day rainfall amount and API30 which did not reach values recorded during 2010 debris flow event and the 2011 was 1 year after debris flow occurrence.

From the complete precipitation record of 2010 debris flow and incomplete data of 1958 debris flow, we cannot set up seriously exact precipitation thresholds for the studied area. Nevertheless, the analysis of the rainfall pattern elucidated the role of combination of different factors (short-term intensity, hourly and daily amounts, and API) with respect to single extremes. First preliminary local thresholds were set up during the 2010 event and partly confirmed by the 1958 debris flow. These data could be compared during the next possible debris flow in the area of interest.

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