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ORIGINAL PAPER

Analysis of the rainfall pattern triggering the Lemešná debris flow, Javorníky Range, the Czech Republic

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Abstract
Two significant rainfall episodes affected the eastern part of the Czech Republic in May 2010 causing dozens of landslides, including a potentially damaging debris flow on Lemešná Mt. in the Javorníky Range on the 2 June 2010. The rainfall data from the rainfall gauges managed by the Czech Hydrometeorological Institute situated 7, 12 and 20 km from the debris flow were analysed and a new rainfall gauge was installed in the immediate vicinity of the debris flow. The following rainfall parameters were calculated as moving values for each day within the period from 1983 to 2018: cumulative rainfall of 2, 3, 5, 10, 20, 30, 60 days and an antecedent precipitation index of 5, 10, 20, 30, 60 days. The rainfall totals, which exceeded the debris flow triggering precipitation by many times, but no slope deformation was recorded during them, were also analysed. The debris flow triggering rainfall values were assessed and they showed a single concordance of all of the tested rainfall parameters on the day of the debris flow. We found that the combination of cumulative rainfall for 30 days together with 1-day and 3-day amounts, overall rainfall pattern and the development of the rainfall situation were more important for triggering the Lemešná debris flow than the individual rainfall extremes. This provides a new perspective to the rainfall thresholds issue. The importance of choosing the calculating method between the cumulative rainfalls and the antecedent precipitation index is illustrated by the significant differences between the values. The significance of the rainfall gauge selection is also emphasised, since the orographic position together with the distance between gauges can significantly influence the differences between on-site and measured rainfall amounts.

Keywords Rainfall thresholds · Antecedent precipitation · Debris flow · Carpathian flysch

1 Introduction

The occurrence and development of slope deformations depend on a great complexity of natural and human conditions (Rączkowski 2007), especially geological, morphometric, hydrometeorological and anthropogenic factors (Pašek 1974; Varnes 1996; Sidle and

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Ochiai 2006). The main trigger of slope deformations worldwide, including debris flow (Rickenmann 1999; Wieczorek and Glade 2005) is extreme or prolonged rainfall (Polemio and Petrucci 2000; Kirschbaum et al. 2012; Segoni et al. 2018a). It increases pore water pressure and decreases soil cohesion, so consequently driving forces exceed resisting forces on a slope and activate a movement (Wieczorek 1996; Iverson 2000; Dhakal and Sidle 2004). The same applies to the Czech Republic, where the majority of slope deformations originate during flood periods (e.g. Gil 1997; Krejčí et al. 2002; Migoń et al. 2002; Kudrna et al. 2003; Bíl and Müller 2008; Pánek et al. 2011a, b; Smolíková et al. 2016).

Rainfall thresholds are the most frequent tool for forecasting the possible occurrence of debris flows; therefore, many case studies of different spatiotemporal scales and using various different analysis methods have been performed (Guzzetti et al. 2007; Kirschbaum et al. 2012; Segoni et al. 2018a). The most common approaches for determining triggering rainfall rely on: (a) rainfall intensity-duration (e.g. Caine 1980; Crosta and Frattini 2001; Cannon et al. 2008; Guzzetti et al. 2008) or (b) antecedent precipitation (e.g. De Vita 2000; Cardinali et al. 2005) with an overwhelming variety of calculation methods (Segoni et al. 2018a). Intensity-duration is usually expressed for sub-hourly intervals, such as 10 or 15 min; hour (e.g. Campbell 1975; Govi et al. 1985); rainfall event (e.g. Sengupta et al. 2010); day (e.g. Šilhán and Pánek 2010; Segoni et al. 2018b). Antecedent or cumulative rainfall is usually calculated for: 1–180 days (e.g. Cascini and Versace 1986; Crozier 1999; Klimeš and Vilímek 2011); 10 days (e.g. Bíl et al. 2016); storm (e.g. Wieczorek 1987; Au 1998); month (e.g. Hutchinson 1970); annual precipitation (e.g. Jibson 1989); 3 years (e.g. Záruba and Mencl 1969). Methods of calculation of antecedent or cumulative rainfall also vary. Some authors include evaporation (e.g. Kohler and Linsley 1951; Pánek et al. 2011a; Ma et al. 2014; Smolíková et al. 2016) whereas the other approach is based on the calculation with total rainfall amounts (e.g. Aristizábal et al. 2011; Engel et al. 2011).

The above-mentioned rainfall parameters are evaluated individually or as a statistical relationship between two parameters, e.g. a combination of daily and 3-day cumulative rainfall (Lee et al. 2015), daily rainfall and 15-day antecedent rainfall (Tien Bui et al. 2013), 3- and 15-day cumulative rainfall (Chleborad 2003), 3- and 30-day antecedent rainfall (Saadatkhah et al. 2015), 24-h total amount before the slope deformation and antecedent rainfall for 3 and 10 days (Engel et al. 2011), the total daily amount for the day of the slope deformation and antecedent rainfall for 1–60 days (Kim et al. 1991; De Vita 2000) or 3–30 days (Dahal and Hasegawa 2008) before slope failure and combinations of 1–7 days with 5–90 days cumulative rainfall (Aristizábal et al. 2011). A different approach was presented by Rebetez et al. (1997), Martelloni et al. (2012) and Segoni et al. (2018b), who used standard deviation. Some authors (e.g. Gil and Starkel 1979; Bíl et al. 2016) adjust the rainfall data before analysis, they eliminated rainfall data higher than 1 mm/min, because they are associated with downpours. Nikolopoulos et al. (2014) discard short rainfall events, since they are very localised and may bring uncertainties.

All of the studies deal with rainfall individual parameters separately for the threshold analysis. In many cases, they calculate several combinations between two rainfall parameters in an attempt to find a unique parameter or unique relationship between them, which represent the threshold best. Few previous studies have taken into account the detailed combination of the entire rainfall pattern (e.g. Smolíková et al. 2016; Drábová 2018), meaning the relationship among all of the calculated rainfall parameters together (short intensities of 10 or 15 min; hourly amounts; daily amounts; cumulative rainfall for different numbers of days; antecedent rainfall including evaporation for different number of days). The study on Smědavská hora Mt., the Czech Republic, in 2010 (Smolíková et al. 2016), demonstrated that a combination of the antecedent precipitation index, daily/hourly total rainfall amounts and short intensities of 10/15 min was much more important for triggering a debris flow than the individual extremes themselves during the 30-year analysed period. Moreover, the calculation of all rainfall parameters could be useful for comparison with events from different region. Most of these studies consider only days with recorded slope deformation. They do not consider the days with no slope deformation when rainfall exceeds the triggering rainfall (Aristizábal et al. 2011).

In terms of the spatial scale of the analysis, the rainfall threshold is defined as either global, national, regional, basin, local or slope (Segoni et al. 2018a). The global rainfall thresholds established worldwide are independent on local morphological, lithological and land use conditions (Guzzetti et al. 2007). They were first proposed by Caine (1980) and followed by many authors (e.g. Crosta and Frattini 2001; Hong et al. 2006; Guzzetti et al. 2007, 2008; Hong and Adler 2008; Kirschbaum et al. 2012). The national threshold refers to a whole country (e.g. Rosi et al. 2016); the regional thresholds for areas from a few to several thousand square kilometres of similar meteorological, climatic and physiographic characteristics (e.g. Martelloni et al. 2012); the basin threshold for a hydrographic catchment area; the local threshold for areas up to hundred square kilometres with a local climatic regime and geomorphological setting (e.g. Guzzetti et al. 2007; Pánek et al. 2011a; Gariano et al. 2015) and the slope threshold is used for studies dealing with a single slope or a single slope deformation (e.g. Bíl et al. 2016; Smolíková et al. 2016; Vallet et al. 2016; Segoni et al. 2018a).

The selection of rainfall gauges is an important step in rainfall threshold analysis, since input data can influence significantly the results (Segoni et al. 2018a). A rainfall gauge may be chosen on the basis of manual selection of expert judgement, automatic selection, the nearest distance, selecting the most extreme/average rainfall totals (Abraham et al. 2020) or is limited by availability to a single station within the study area (Engel et al. 2011). Nevertheless, the nearest rain gauge is usually selected (e.g. Šilhán and Pánek 2010; Tichavský et al. 2017; Segoni et al. 2018a). Considering extreme spatial and temporal precipitation variability (Wieczorek and Glade 2005), rain gauges located at a distance the source area of the slope deformation may reduce the representativeness of the rainfall data, especially in mountainous regions (Vilímek et al. 2006; Smolíková et al. 2016).

The analysed time period also matters considerably to statistical significance of the analysed data. It varies from a short period just before the slope deformation event to periods of less than one month (e.g. Krejčí et al. 2002), one year (e.g. Engel et al. 2011), 5 years (e.g. Kirschbaum et al. 2012), more than 10 years (e.g. Bíl et al. 2016; Smolíková et al. 2016; Froude and Petley 2018).

Rainfall was the principal triggering factor of many debris flows in Central Europe, e.g. in the Tatra Mountains, Slovakia (e.g. Kotarba 2007; Dlabáčková 2015), Babia Góra massif, Poland (Łajczak and Migoń 2007) and as well in the Czech Republic, e.g. the Jizerské hory Mountains (Smolíková et al. 2016), the Krkonoše Mountains (Pilous 1973, 1975, 1977; Migoń et al. 2002; Drábová 2018), the Hrubý Jeseník Mountains (Tichavský et al. 2017), the Moravskoslezské Beskydy Mountains (Šilhán and Pánek 2010) and the Západní Beskydy Mountains (Pánek et al 2011a).

One potentially damaging debris flow originated in the Czech Outer Western Carpathians on Lemešná Mt. in 2010 was chosen for this study for a purpose of a detailed analysis and evaluation of triggering precipitation based on the combination of selected methods and a new approach of the entire rainfall pattern comparison. The main purposes of this paper are: (1) to assess in detail the rainfall pattern preceding the debris flow triggering; especially, to determine dominant triggering rainfall parameters or their combination; (2) to point out that the used methods comparing one or two rainfall parameters could be extended to the calculation of more parameters of the rainfall pattern, which would make the events possible to compare among them; (3) to examine the days when rainfall exceeded the debris flow triggering rainfall in the past, but no slope deformation occurred; (4) to compare two approaches to calculating the antecedent rainfall—cumulative rainfall with the antecedent rainfall index, including evaporation, and lastly (5) to compare differences in measured rainfall data among the rain gauges 7–20 km away in a mountainous area, in order to emphasise the importance of the selection and spatial location of the rain gauge with respect to the studied site.

2 Study area and event background

The area of interest is located in the eastern part of the Czech Republic, in the Javorníky Range, which belongs to the flysch belt of the Outer Western Carpathian System, folded and thrusted during Alpine orogeny. It falls into the Magura nappe group (Chlupáč 2002) characterised by a dense trellis pattern of ridges and valleys (Pánek and Lenart 2016). The Javorníky Range is composed of flysch bedrock, that has very favourable conditions for slope deformations (e.g. Kirchner et al. 2000; Kováčik 1991; Pánek et al. 2009, 2011a; Rączkowski 2007; Klimeš and Blahůt 2012). Its alternating permeable and impermeable rock layers, as well as the easily weathered flysch sediments, make suitable conditions for the development of all the types and sizes of slope deformations (Špůrek 1972; Kirchner et al. 2000; Krejčí et al. 2002; Pánek et al. 2009; Janoška 2013). The elements of geological structure, such as bedding, faults and joint systems in the flysch, give rise to deep-seated slope deformations, while colluvial deposits are associated with shallow mass movements, which are more susceptible to triggering by heavy rainfalls (e.g. Gil 1997; Krejčí et al. 2002). The peaks of the Javorníky Range reach elevations of about 1000 m a.s.l. with differences in the elevation of local relief of about 400 m. The average air temperature is about 6 °C. The annual precipitation is comparably higher than the average of the Czech Republic, the average rainfall varies between 800 and 1100 mm per year. Snow precipitation reaches 3000 mm (Czech Hydrometeorological Institute—CHMI) during the winter season (December–March). The highest snow cover thickness reaches 1000 mm in February.

Two extraordinary rainfall episodes affected the east part of the Czech Republic in 2010. The first between 15 and 18th May and the second between 31st May and 2nd June (Šunka 2011). The episodes generated more than 150 slope deformations of various types, including debris flows, in the eastern part of the Czech Republic, in the flysch of the Outer Western Carpathians (Pánek et al. 2011a; Bíl et al. 2016). Similar landslide activation occurred during floods in 1997 and 2006 (e.g. Krejčí et al. 2002; Bíl and Müller 2008; Klimeš et al. 2009; Pánek et al. 2011a, b). Consequently, one debris flow (sensu Nemčok et al. 1972; Cruden and Varnes 1996) was triggered on Lemešná Mt. (950 m a.s.l.) in the Javorníky Range on 2 June 2010, between 9:30 and 10:00 am (Matyščák, commander of the fire brigade, oral communication).

The studied debris flow originated at 820 m a.s.l. on the south-facing 35° steep slope of Lemešná Mt., whose ridge is oriented WSW-ENE and is bordered by a narrow Lemešná stream valley (Figs. 1, 2a). The presence of two distinct dejection cones (Figs. 1, 2d) developed at the mouth of shallow tributary valleys with small permanent streams give evidence of the ridge slopes being affected by slope deformations in the past. The age of the dejection cones is unknown, but residential houses older than 100 years were built on

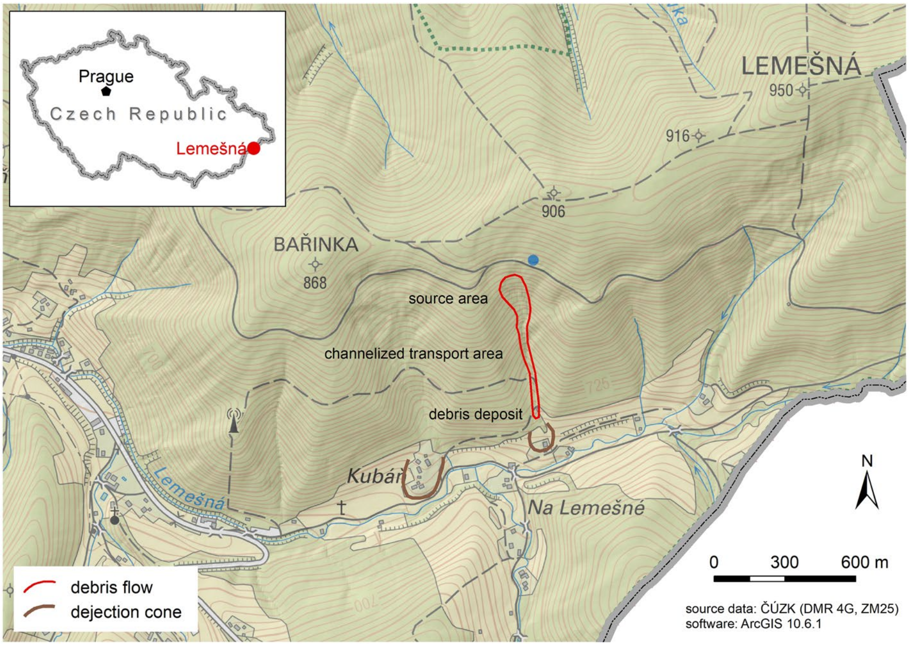

Fig. 1 The area of interest in the Lemešná site with the studied debris flow and old dejection cones

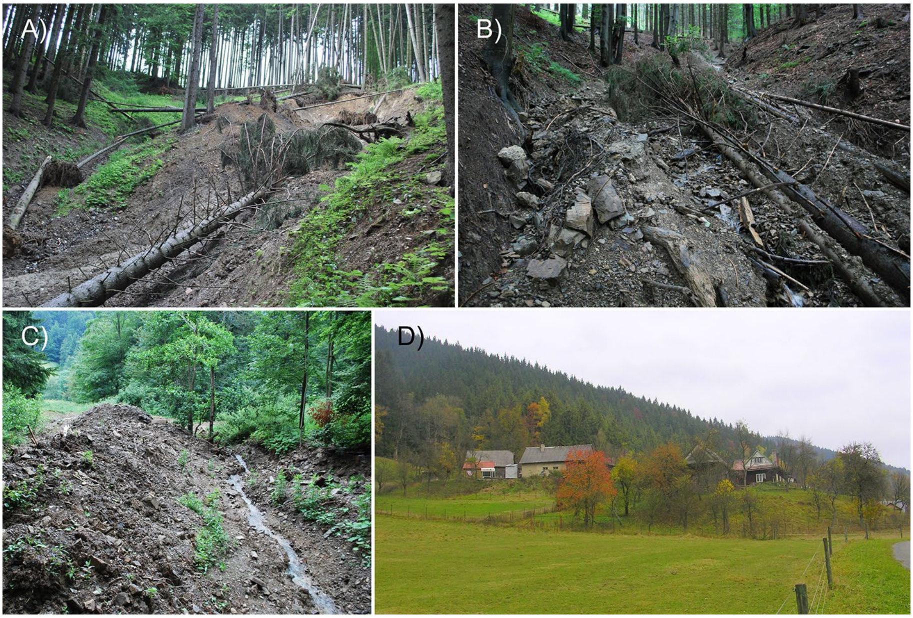

Fig. 2 **a** Source area of the investigated debris flow on Lemešná Mt.; **b** channelized transport area; c debris deposit; d old western dejection cone with residential houses

the western dejection cone (Fig. 2d) and 50-year-old houses on the eastern dejection cone. According to Pánek et al. (2011a), 70% of the May 2010 slope deformations originated inside older (Holocene or older) landslide terrains. No recent slope deformation has been recorded within the study area at least since 1983 (Matyščák, commander of the fire brigade living downhill the debris flow, oral communication; Kaděrka, forest district officer, Forests of the Czech Republic, oral communication).

The 2010 slope deformation initiated as debris slide with the crown width of 14 m and the scarp height of 0.8 m. After 100 m, it channelized into stream and continued as debris flow to a culvert and a forest road downhill, which caught the majority of the transported material (Fig. 2c) and only highly saturated mud reached a house on the dejection cone. The total length of the 2010 event was 340 m and the estimated volume of the source area was 180 m^3. The debris flow caused minor damage to the forest, stream, culvert, forest road and the house.

3 Data and methods

3.1 Rainfall data

The rainfall data from three rainfall gauges in the wider area (7–20 km) of the debris flow was evaluated. The nearest rainfall gauge was situated 7 km to the west of the debris flow in Velké Karlovice-Pluskovec (VKP) at an elevation of 561 m a.s.l. (Fig. 3). VKP was a manual station recording daily totals every day at 7:00 am with data available between 1

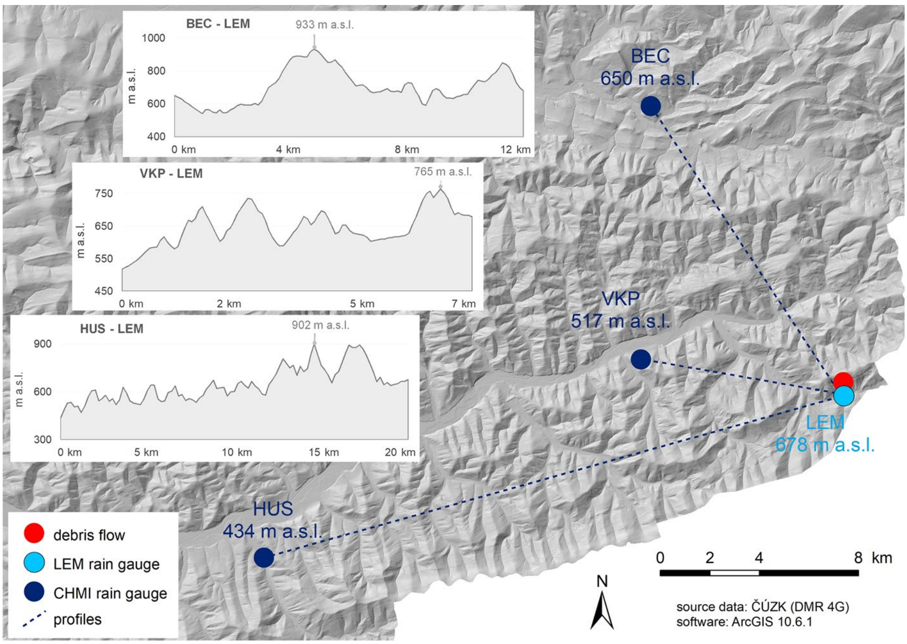

Fig. 3 Location of the rainfall gauges and the terrain profile between the CHMI rain gauges and the newly installed LEM

January 1983 and 31 December 2018. The data provide complete time series except for the period between 1 December 1986 and 31 March 1987, during which time all the data is missing. Two more rainfall gauges were selected to compare the rainfall totals under different orographic conditions, i.e. Horní Bečva (BEC) located 12 km to the NW of the debris flow at 650 m a.s.l. and Huslenky (HUS) 20 km to the SW, at 434 m a.s.l. (Fig. 3). Both rainfall gauges were automated and daily totals were analysed in the period from 1 January 1983 to 31 December 2018. All rainfall gauges were managed by the Czech Hydrometeorological Institute (CHMI) and operate throughout the year, so snow precipitation was included in the rainfall gauge total precipitation as a snow water equivalent.

With regard to the mountainous character of the area, which causes high local variability in rainfall amounts, especially during torrential rainfalls (Smolíková et al. 2016), the new automatic rain gauge in Lemešná (LEM) was installed directly in the area of the debris flow in order to better understand the local variability of the rainfall. The LEM rainfall gauge situated on the foothill of the debris flow slope at 678 m a.s.l. is a tipping bucket rain gauge recording data between 29 June 2012—16 July 2016.

Only the data from VKP rainfall gauge was selected for the rainfall analysis based on expert judgement strengthened by correlation coefficient among the all rainfall gauges (Segoni et al. 2018a). VKP rainfall gauge is the nearest station to the debris flow and it is situated in adjacent valley, while BEC is separated by Vsetínské vrchy highlands and HUS is farther from the debris flow (Fig. 3). Correlation coefficient was calculated among LEM and VKP/BEC/HUS stations within the period of LEM active measurement (29 June 2012—16 July 2016) for LEM daily precipitation higher than 1 mm/2 mm/5 mm/10 mm/20 mm in order to ascertain similarity between the stations. Correlation coefficient resulted very low for all variations (Table 1), but still the highest for VKP station for LEM daily precipitation higher than 5 mm.

3.2 Rainfall data analysis

The analysis of the rainfall pattern triggering the Lemešná debris flow was carried out based on the evaluation of several approaches widely used in landslide studies.

3.2.1 Antecedent precipitations

Two most prevalent methods were used for the calculation of the antecedent precipitation. The first method was the cumulative sum of the rainfall totals of the previews days (CUM_n) expressed as:

Table 1 Correlation coefficient among the rainfall data from the rainfall gauges LEM versus VKP, HUS, BEC during the period from 29 June 2012—16 July 2016

LEM daily precipitation	LEM versus VKP	LEM versus HUS	LEM versus BEC	Number of observations
> 1 mm	0.55	0.51	0.58	472
> 2 mm	0.53	0.52	0.55	383
> 5 mm	0.55	0.46	0.49	241
> 10 mm	0.51	0.44	0.34	126
> 20 mm	0.37	0.25	0.14	39

$$\mathrm{CUM}_n = \sum_{i=1}^{n} P_i \text{ (mm)} \tag{1}$$

where, n—the total number of days prior to the causal rainfall, P_i—the amount of precipitation in i-days prior to the causal rainfall (mm).

The second method was the antecedent precipitation index (API), which is determined by rainfall and evapotranspiration. It shows the precipitation and soil moisture conditions retrospectively (Mishra and Singh 2003), which are naturally influenced by local climate and vary significantly in a spatiotemporal scale (Wieczorek and Glade 2005). The applied API equation (Kohler and Linsley 1951) is defined as follows:

$$\mathrm{API}_n = \sum_{i=1}^{n} c^i \times P_i \text{ (mm)} \tag{2}$$

where, n—the total number of days prior to the causal rainfall, i—the number of days counting backwards from the date on which the API is determined, c—an evaporation constant of $c = 0.93$ determined for the Czech Republic by Hladný (1962) and used by other authors (e.g. Pánek et al. 2011a; Smolíková et al. 2016), P_i—the amount of precipitation in i-days prior to the causal rainfall (mm).

Both CUM and API were calculated from the daily rainfall totals for the whole period from 1983 to 2018 using the data from the VKP rain gauge. The CUM was computed for a floating number of 2, 3, 5, 10, 20, 30 and 60 days and API for 5, 10, 20, 30 and 60 days. These analyses were carried out to find dominant factor of the long-term rainfall preceding the triggering of the debris flow. Consequently, the resulting values of CUM and API were compared to highlight the differences in the utilisation of these methods.

3.2.2 Daily totals

The VKP daily totals were evaluated individually and in pairs together with CUM and API for $n = 2$, 3, or 5, 10, 20, 30 and 60 in order to find the most likely dominant parameter or the combination of two rainfall parameters that triggered the 2010 debris flow. Thereafter, the daily amounts from (a) VKP, HUS and BEC rain gauges from 1983 to 2018 and (b) VKP, HUS, BEC and LEM rain gauges from July 2012 to July 2016 were compared to depict differences in their rainfall amounts in order to indicate the orographic and distance influences.

3.2.3 Rainfall pattern

A new approach was applied to determinate the most significant rainfall parameters of the entire rainfall pattern that influenced the 2010 debris flow triggering. Mutual interaction of all calculated rainfall parameters (daily, CUM_5, CUM_{10}, CUM_{20}, CUM_{30}, CUM_{60}, API_5, API_{10}, API_{20}, API_{30}, API_{60}) was evaluated together simultaneously during the whole rainfall dataset. Consequently, the most significant combination of the rainfall parameters was assessed.

4 Results

The average annual precipitation reached 1032 mm in the period from 1983 to 2018 in VKP (Table 2). The recorded minimum was 730 mm in 2018, whereas the maximum reached 1343 mm in 2010 (the year of the debris flow). The monthly average was 86 mm (Table 2). No rainfall (0 mm) was recorded in November 2011 and the maximum of 354 mm was in July 1997. The daily average was calculated as 2.8 mm (Table 2) and the maximum was 92 mm on 31 August 2010. Days without rain represent 40–60% of the year within the studied period and 90% of the daily rainfall totals were lower than 10 mm (Fig. 4). The monthly and daily long-term rainfall averages are expressed in Table 2.

The debris flow originated on 2 June 2010 between 9:30 and 10:00 am. Due to the fact that the daily rainfall totals were read at 7:00 am every day, the values of the day before the event, 1 June 2010, were set as referential values for the rainfall analyses, hereinafter referred as the "debris flow values". All of the values of the analysed parameters were evaluated but only extraordinary rainfall or flood episodes were expressed in API graphs for better clarity (Table 3).

4.1 Individual rainfall parameters

The "debris flow" daily rainfall totals reached 37.3 mm. This was ten-times higher than the daily long-term average for June (3.6 mm, Table 3), but not the highest within the examined period (Fig. 5a). The value of the "debris flow" daily rainfall was exceeded in 44 cases (Table 4) in the period between 1983 and 2018, and reached only less than half comparing to the value from 7 September 1996 (83.5 mm) or 31 August 2010 (91.5 mm). The course of the cumulative rainfall values for 2 and 3 days corresponded to the daily amounts (Fig. 5b, c), but the number of exceeding days rapidly increased from 97 cases for CUM_2 and 72 cases for CUM_3 up to 348 cases for CUM_{10} (Table 4).

The month prior to the debris flow, May 2010, was extremely rainy with rainfall totals of 320.6 mm, which was three-times higher than the long-term monthly average for May (Table 2). The only higher monthly rainfall amount of 354.2 mm was recorded in July 1997 (Table 3). Similar extreme was the cumulative rainfall 30 days before the debris flow event (3 May 2010 to 1 June 2010), which reached 350.3 mm (Table 4, Table 5, Fig. 8c). The number of exceeding days for CUM_{30} decreased to 11 cases only (Table 4), and they all occurred during a single rainfall episode in July 1997 (Table 5).

Analysis of the API was carried out using the evaporation index, so naturally the values vary from the cumulative rainfall. The debris flow $API_{5,10,20,30,60}$ were exceeded many times within the examined period (Table 4, Fig. 6) following the trend of the cumulative values, with the highest number for API_5 (150 cases) and API_{10} (184 cases); a high value of API_{30} was observed in 31 cases (Table 4). API_{60} was considered less significant since the calculation does not vary from API_{30} due to subtraction of the evaporation index, so it was not depicted in API graphs.

No single parameter of all calculated (daily, CUM_5, CUM_{10}, CUM_{20}, CUM_{30}, CUM_{60}, API_5, API_{10}, API_{20}, API_{30}, API_{60}) resulted as the highest extreme for the debris flow amounts so none of them was determinative for the debris flow triggering (Table 4).

Table 2 Long-term rainfall averages from the Velké Karlovice-Pluskovec rain gauge within the period from 1983 to 2018

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Av. annual rainfall
Long-term monthly average (mm)	77.2	71.5	73.7	70.7	100.8	108.1	115.8	99.2	84.8	70.8	77.9	81.8	86	1032
Long-term daily average (mm)	2.5	2.5	2.4	2.4	3.3	3.6	3.7	3.2	2.8	2.3	2.6	2.6	2.8	

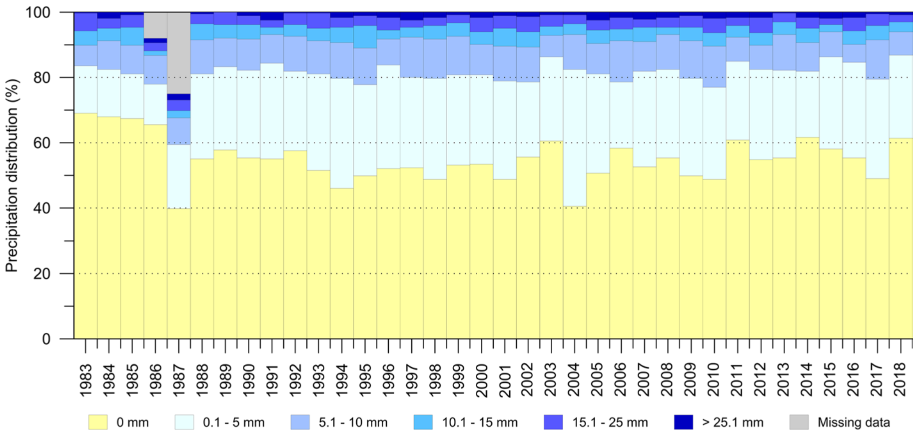

Fig. 4 Distribution of the rainfall daily totals from the VKP rainfall gauge during each year within the studied period from 1983 to 2018

Table 3 Rainfall characteristics of the extraordinary rainfall episodes from the VKP rain gauge

Episode	Max daily total (mm)	Long-term daily average (mm)	Monthly totals (mm)	Long-term monthly average (mm)
08/08/1985	65.5	3.2	249.8	99.2
07/09/1996	83.5	2.8	228.5	84.8
08/07/1997	63.8	3.7	354.2	115.8
02/07/2009	32.8	3.7	144.8	115.8
01/06/2010*	**37.3**	**3.6**	**320.6**	**100.8**
28/07/2014	31.2	3.7	211.1	115.8

The long-term daily/monthly average is calculated from the period from 1983 to 2018; bold text with * is the data from the debris flow event

4.2 Development of the preceding rainfall situation

Two significant consecutive rainfall peaks before the debris flow were evident in 2010 for all of the API analyses, whereas only singular extremes were recorded in the remaining years (Fig. 6). The only similarity appears between the years 1997 and 2010, when extreme floods affected the Czech Republic. Both years show three rainfall peaks in a short period (Fig. 7), with a significantly higher rainfall volume in 1997 than in 2010, but in the half-time in 2010. Despite the fact that almost all of the calculated rainfall parameters for 1997 surpassed the 2010 values (Table 5), no slope deformation was noted in the study area in 1997.

Development of the rainfall situation during 30 days was compared for the period before the debris flow in 2010 with the episodes of extraordinary rainfall amounts in 1985, 1996, 1997, 2009 and 2014 as defined in Table 3. These data were depicted as a 30-day period of daily rainfall totals (Fig. 8a), cumulative rainfall totals (CUM) of

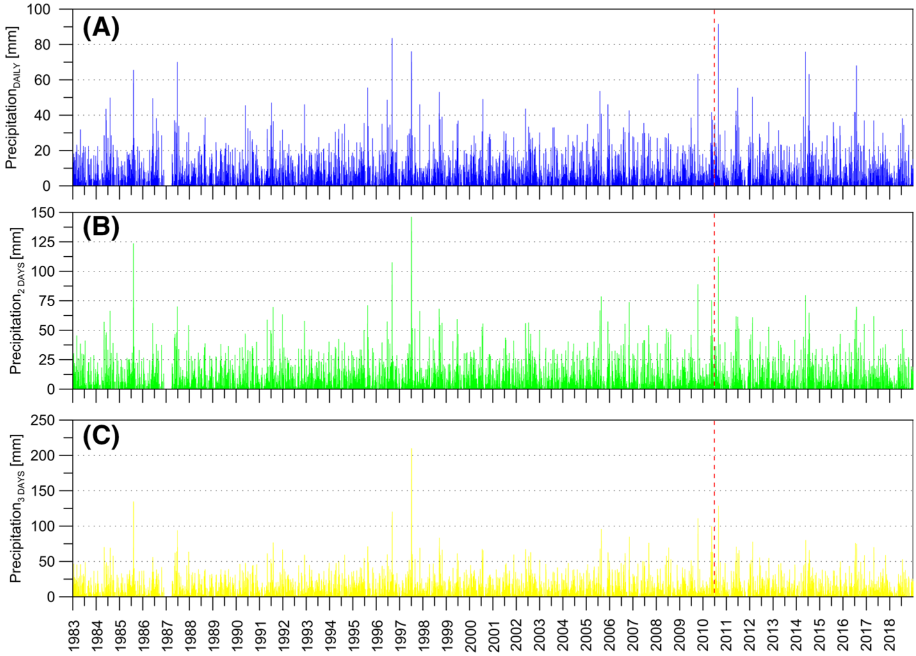

Fig. 5 **a** Daily rainfall totals from the VKP rainfall gauge within the studied period from 1983 to 2018; **b** cumulative rainfall totals of 2 days; **c** cumulative rainfall totals of 3 days (red dashed line—the debris flow day)

the previous 30 days (Fig. 8b), a floating number of cumulative rainfalls for 30 days (CUM_{30}) (Fig. 8c) and API_{30} (Fig. 8d).

The daily rainfall data evince three rainfall episodes with high rainfall amounts, which occurred 29, 16 and 1 day before the debris flow in 2010 (Fig. 8a). Nevertheless, higher daily extremes occurred in other years (e.g. 1985, 1996, 1997, 2009, 2014) than in 2010.

These three rainfall events together with the persistent daily rainfall during the 30-day period resulted in the highest cumulative rainfall totals of 350.3 mm in 2010 compared to the other selected years (Fig. 8b, c). A similar cumulative maximum to the 2010 value was reached in 1997 (342.7 mm). In spite of the similar values, the development of the cumulative maximums in 1997 and 2010 was significantly different (Fig. 8b, c). The cumulative rainfall totals in 2010 increased gradually in accordance with the daily rainfall episodes and were maintained at higher values, whereas the development of the 1997 totals increased sharply before the maximum was reached (Fig. 8b, c). The individual daily extremes in remaining selected years reached even higher values than in 2010 (Fig. 8a); nevertheless, the cumulative rainfalls were considerably lower, from i.e. 177 mm in 2009 to 252 mm in 1985 (Fig. 8b, c). Vice versa, the API_{30} was rather low in 2010 in comparison to the rest of the depicted years. The maximum API_{30} value (155 mm) was detected 12 days before the debris flow and the value on the day of the debris flow (134 mm) was equal to 1996 and even lower than 1985 (165 mm) and 1997 (234 mm) (Fig. 8d).

Table 4 Number of days exceeding the "debris flow" values and percentage of days below the "debris flow" values for the rainfall parameters of daily totals, cumulative rainfall totals for 2, 3, 4, 5, 10, 20, 30 and 60 days and antecedent precipitation index for 5, 10, 20, 30 and 60 days

Rainfall parameter	1 day	CUM 2	CUM 3	CUM 5	CUM 10	CUM 20	CUM 30	CUM 60	API 5	API 10	API 20	API 30	API 60
01/06/2010 DF value (mm)	37.3	45.9	63.1	63.3	87.5	252.8	350.3	423.2	56.1	70.1	120.9	134.3	137.5
Number of days exceeding DF	44	97	72	222	348	23	11	66	150	184	38	31	33
Percentage of days below DF	99.7	99.2	99.4	98.3	97.3	99.8	99.9	99.5	98.9	98.6	99.7	99.8	99.7

Table 5 All of the calculated rainfall parameters (mm) of the extraordinary rainfall episodes exceeding the rainfall totals of the debris flow day (red highlighted—exceeding value; bold and blue frame—the debris flow values; black frame—the narrowest number of exceeding parameters)

DATE	1 day	CUM 2	CUM 3	CUM 5	CUM 10	CUM 20	CUM 30	CUM 60	API 5	API 10	API 20	API 30	API 60
07/08/1985	58.0	69.1	69.1	84.6	118.5	164.4	186.1	297.2	75.1	95.9	108.5	112.4	116.5
08/08/1985	65.5	123.5	134.6	150.1	184.0	229.9	251.6	354.1	130.8	150.1	161.9	165.4	169.2
09/08/1985	9.5	75.0	133.0	144.1	186.8	219.2	261.1	352.4	120.4	145.4	155.0	162.7	166.1
10/08/1985	5.3	14.8	80.3	149.4	187.9	213.9	266.4	357.7	116.9	138.2	146.7	156.2	159.4
11/08/1985	0.0	5.3	14.8	138.3	187.9	213.9	266.4	353.5	101.6	128.6	136.5	145.3	148.2
12/08/1985	0.0	0.0	5.3	80.3	164.9	198.8	266.4	335.2	56.9	109.2	123.6	135.1	137.6
05/06/1986	49.5	55.9	55.9	78.4	113.4	150.0	168.6	206.0	67.2	86.5	99.0	102.0	103.3
26/06/1987	70.0	70.0	93.8	93.8	103.4	184.9	230.0	386.2	84.2	89.7	120.8	128.7	137.3
07/09/1996	83.5	88.5	108.3	109.3	135.1	180.6	205.4	268.6	98.7	112.4	128.6	132.5	136.1
08/09/1996	24.0	107.5	112.5	133.3	155.3	204.6	229.4	292.0	114.1	125.1	141.9	145.6	148.9
09/09/1996	12.7	36.7	120.2	145.0	151.5	217.3	242.1	303.7	117.2	120.8	143.8	147.2	150.2
10/09/1996	3.3	16.0	40.0	128.5	153.3	199.8	245.4	304.0	99.3	114.7	132.3	140.0	142.8
06/07/1997	76.0	96.5	103.5	107.5	127.8	200.1	209.6	382.7	97.0	109.5	130.0	131.9	139.4
07/07/1997	70.0	146.0	166.5	177.5	196.5	237.9	279.6	424.2	155.3	166.4	179.0	187.8	194.4
08/07/1997	63.8	133.8	209.8	237.3	260.3	301.7	342.7	488.0	201.2	214.0	225.8	233.9	240.2
09/07/1997	0.6	64.4	134.4	230.9	260.9	296.6	343.3	488.6	183.2	199.6	209.3	218.1	223.9
10/07/1997	0.0	0.6	64.4	210.4	250.9	289.6	343.3	488.6	157.1	181.1	193.1	202.8	208.2
11/07/1997	0.0	0.0	0.6	134.4	241.9	289.6	343.3	488.6	96.9	164.4	179.6	188.6	193.7
12/07/1997	1.6	1.6	1.6	66.0	243.5	270.0	344.9	490.2	46.3	154.4	163.9	176.9	181.6
13/07/1997	4.5	6.1	6.1	6.7	244.0	269.0	349.4	494.7	6.0	146.0	155.4	168.7	173.1
14/07/1997	0.0	4.5	6.1	6.1	237.0	268.3	346.3	494.7	5.2	132.6	144.4	156.6	160.9
15/07/1997	0.0	0.0	4.5	6.1	216.5	268.3	346.3	486.7	4.8	114.1	134.3	145.6	149.6
16/07/1997	0.0	0.0	0.0	6.1	140.5	268.3	340.6	469.7	4.5	71.9	124.9	134.8	138.9
19/07/1997	23.2	51.7	56.3	56.3	62.4	323.3	359.0	510.1	49.9	53.5	150.1	154.8	161.5
20/07/1997	8.3	31.5	60.0	64.6	70.7	321.6	360.3	504.4	54.1	57.5	145.2	151.0	157.7
21/07/1997	14.0	22.3	45.5	78.6	84.7	326.6	374.3	512.8	63.4	66.5	146.1	153.4	159.6
22/07/1997	1.9	15.9	24.2	75.9	85.0	328.5	355.0	514.2	57.7	62.9	137.6	142.2	150.2
23/07/1997	4.0	5.9	19.9	51.4	84.5	328.5	353.5	518.0	39.0	60.2	130.8	135.4	143.4
24/07/1997	0.0	4.0	5.9	28.2	84.5	321.5	352.8	518.0	21.2	56.0	120.1	125.9	133.4
25/07/1997	1.8	1.8	5.8	21.7	86.3	302.8	354.6	517.3	16.1	53.7	108.9	118.7	125.7
26/07/1997	4.0	5.8	5.8	11.7	90.3	230.8	358.6	505.3	9.6	53.7	88.5	114.1	120.4
27/07/1997	0.6	4.6	6.4	10.4	86.3	161.4	357.9	492.6	8.2	48.4	67.6	106.6	112.4
28/07/1997	0.0	0.6	4.6	6.4	57.8	97.6	357.9	483.6	5.1	32.2	49.0	99.1	104.4
29/07/1997	0.0	0.0	0.6	6.4	34.6	97.0	357.9	454.1	4.7	19.5	45.4	92.2	96.8
15/09/1998	53.0	56.1	83.2	124.4	131.1	151.2	181.6	251.3	104.6	107.8	115.4	120.5	123.0
24/08/2005	37.8	78.5	95.6	96.2	102.0	136.3	204.5	312.2	84.5	87.4	99.4	113.3	117.5
07/09/2007	22.0	51.6	76.0	107.0	111.7	135.3	166.2	196.8	88.2	90.9	96.8	100.9	102.4
14/10/2009	63.2	85.2	88.5	88.5	93.6	98.5	105.2	157.7	80.5	83.0	84.6	85.5	87.5
16/05/2010	41.6	66.2	70.8	90.6	108.3	201.1	208.0	276.7	78.3	87.6	123.7	124.9	129.3
17/05/2010	33.7	75.3	99.9	120.7	135.5	234.6	241.7	310.4	101.8	109.9	146.3	147.5	151.6
18/05/2010	16.0	49.7	91.3	120.5	145.7	250.6	256.5	326.4	99.1	114.4	151.0	152.0	155.8
19/05/2010	3.2	19.2	52.9	119.1	145.9	253.8	259.7	329.6	92.2	108.1	143.4	144.3	147.9
20/05/2010	23.0	26.2	42.2	117.5	166.5	268.0	281.2	349.1	91.2	120.8	152.8	155.4	158.9
21/05/2010	0.3	23.3	26.5	76.2	166.8	264.9	281.5	349.4	58.2	112.6	141.6	144.8	148.1
22/05/2010	2.1	2.4	25.4	44.6	165.3	262.8	283.6	351.5	34.2	105.1	132.8	136.6	139.6
01/06/2010	**37.3**	**45.9**	**63.1**	**63.3**	**87.5**	**252.8**	**350.3**	**423.2**	**56.1**	**70.1**	**120.9**	**134.3**	**137.5**
03/06/2010	19.2	23.4	60.7	86.5	100.3	255.4	336.3	446.6	69.9	77.3	121.8	133.8	140.4
31/08/2010	91.5	107.5	110.8	120.0	128.8	150.3	179.2	341.1	108.0	113.1	119.6	124.0	131.7
01/09/2010	21.0	112.5	128.5	131.8	149.8	171.3	200.2	362.1	114.0	124.7	130.8	134.8	142.0
02/09/2010	1.9	22.9	114.4	133.7	151.1	167.1	195.8	364.0	107.8	117.5	122.1	126.5	133.8
26/05/2014	75.8	75.8	75.8	75.8	75.8	148.3	158.0	259.7	70.5	70.5	97.0	98.2	105.3
31/07/2016	68.0	69.8	74.6	90.8	93.8	182.5	245.1	292.2	80.1	82.0	104.9	113.9	116.8

4.3 Interaction of 2 parameters and overall rainfall pattern

All possible 2-parameter combinations of the short-term (daily, CUM_2, CUM_3) and the long-term (CUM_5, CUM_{10}, CUM_{20}, CUM_{30}, CUM_{60} and API_5, API_{10}, API_{20}, API_{30}, API_{60}) rainfall data were compared. Only the combinations of CUM_{30} with 1-day and 3-day precipitation resulted as unique with the highest rainfall totals for the 2010 debris flow event (Fig. 9a, b) within the tested period 1983–2018. The rest of the evaluated 2-parameter combinations resulted as less significant, for instance the combination of API_{30} compared to 1-day and 3-day precipitation (Fig. 9c, d).

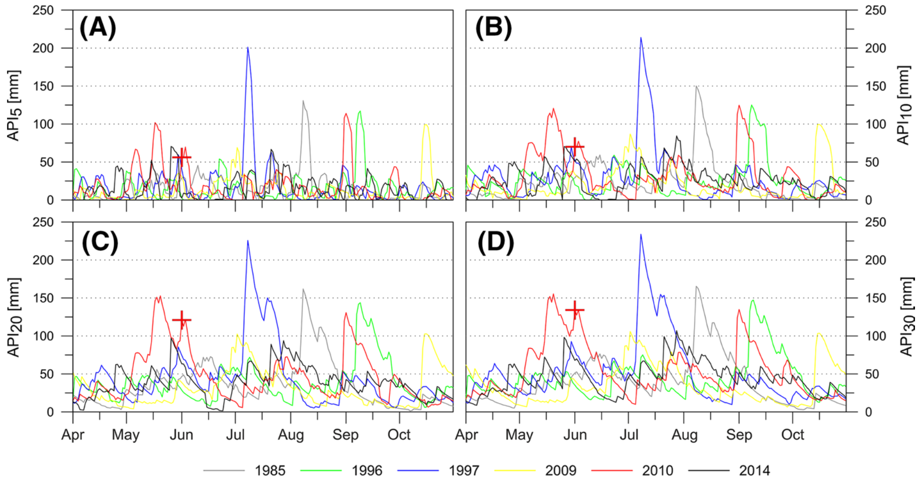

Fig. 6 API for 5 (**a**), 10 (**b**), 20 (**c**) and 30 (**d**) days for the selected years from VKP rainfall gauge (red cross—the debris flow value)

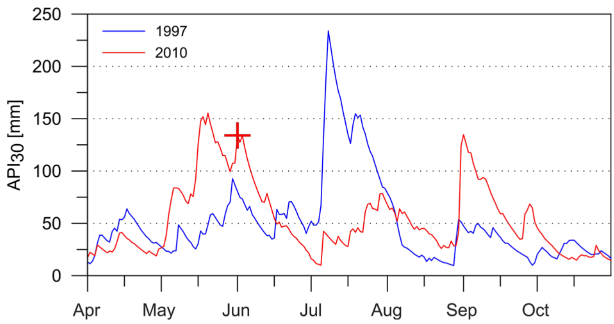

Fig. 7 API 30 for 1997 and 2010 from VKP rainfall gauge (red cross—the debris flow value)

A unique match for the 2010 debris flow rainfall totals also resulted for the comparison of the entire rainfall pattern with all of the calculated rainfall parameters (daily, CUM_5, CUM_{10}, CUM_{20}, CUM_{30}, CUM_{60}, API_5, API_{10}, API_{20}, API_{30}, API_{60}) at the same time (Table 5).

4.4 Comparison of the API and cumulative rainfall methods

The results of the comparison between API and cumulative rainfall for the debris flow day in 2010 are presented in Table 6. The cumulative rainfall values are higher than API, e.g. 63 mm (CUM) compared to 56 mm (API) for 5 days, and the difference between the resulting values increases significantly with an increasing number of antecedent days. The most pronounced difference is observed in the case of CUM_{60} (423 mm) and API_{60} (138 mm) (Table 6). The annual course of API and CUM for 5 and 30 days during 2010 is compared and presented in Fig. 10a, b. Whereas the differences between API_5 and CUM_5 were rather low and did not exceed 20 mm (Fig. 10a), the CUM_{30} were higher, up to 200 mm, on the day of the debris flow (Fig. 10b). API and CUM follow a similar trend in the phase of the increasing rainfall, but API dropped down much rapidly than CUM.

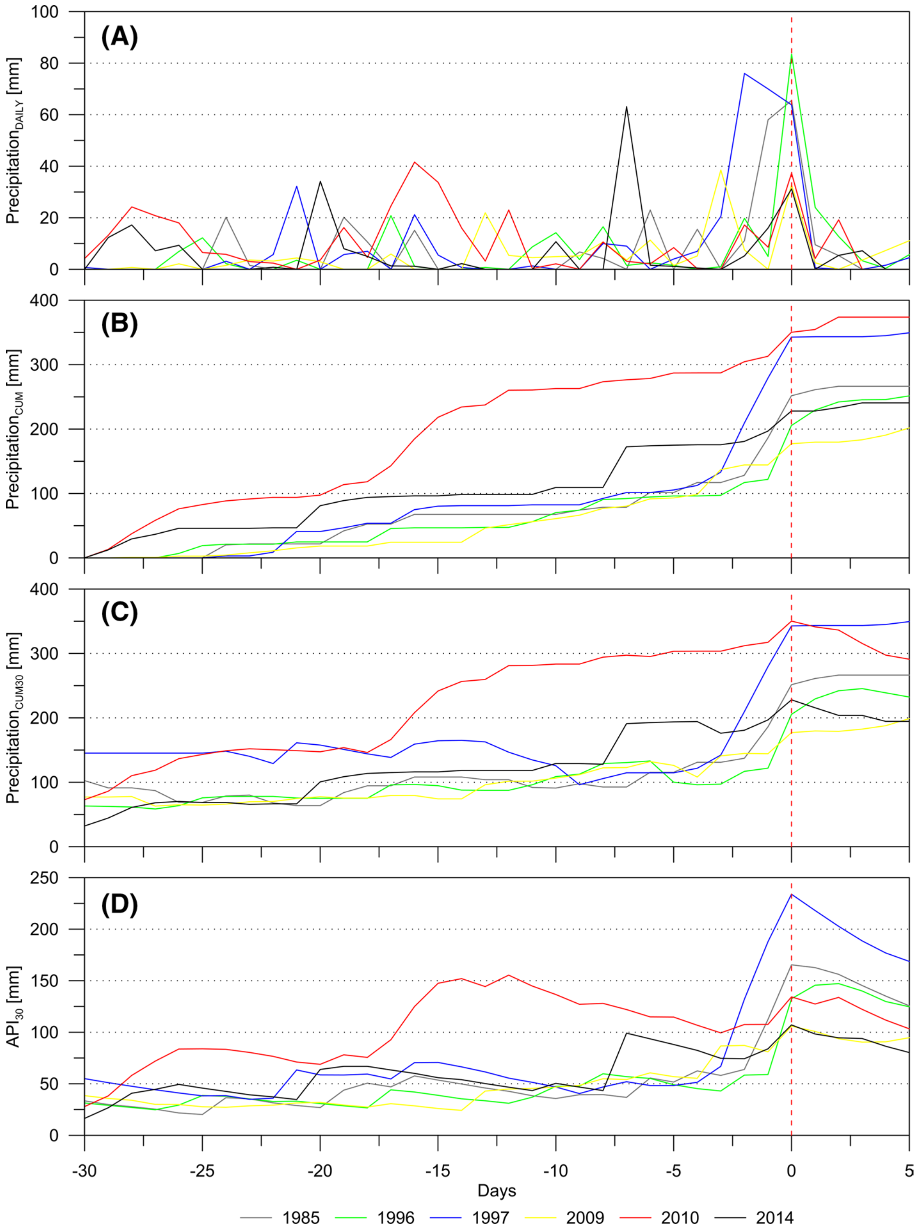

Fig. 8 **a** Daily rainfall totals 30 days before the maximum within the selected episodes from the VKP rainfall gauge; **b** cumulative rainfall totals 30 days before the maximum within the selected episodes; **c** floating values of cumulative rainfall totals for 30 days; **d** API 30 for the selected years expressed 30 days before the maximum (red dashed line—the debris flow day)

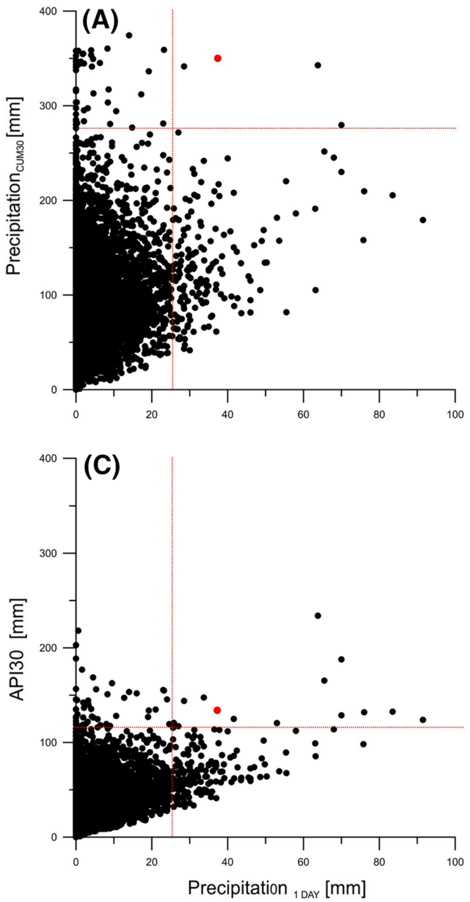

Fig. 9 Comparison of the VKP rainfall totals during the period 1983–2018 of the combination of **a** 1-day precipitation with CUM30; **b** 3-day precipitation with CUM30; **c** 1-day precipitation with API30; **d** 3-day precipitation with API30; red point represents the "debris flow" rainfall data; red lines delimit 99% of days with the amount lower than debris flow amount

Table 6 Comparison of the cumulative rainfalls and antecedent precipitation index for 5, 10, 20, 30 and 60 days for the debris flow values on 1 June 2010

Antecedent precipitation	5 days	10 days	20 days	30 days	60 days
CUM (mm)	63.3	87.5	252.8	350.3	423.2
API (mm)	56.1	70.1	120.9	134.3	137.5
CUM–API (mm)	7.2	17.4	131.9	216.0	285.7

4.5 Comparison of the rainfall gauge data

Character of the rainfall data variability from VKP, HUS, BEC and LEM rainfall gauges is depicted in the form of monthly values for May, June, July and August for the period

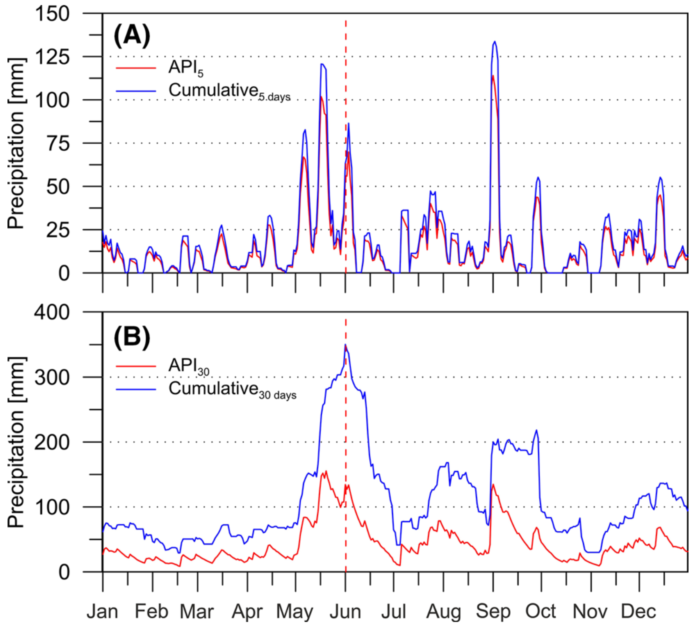

Fig. 10 Comparison of two methods, Pcum and API, for 5 (**a**) and 30 days (**b**) in 2010 with data from the VKP rainfall gauge

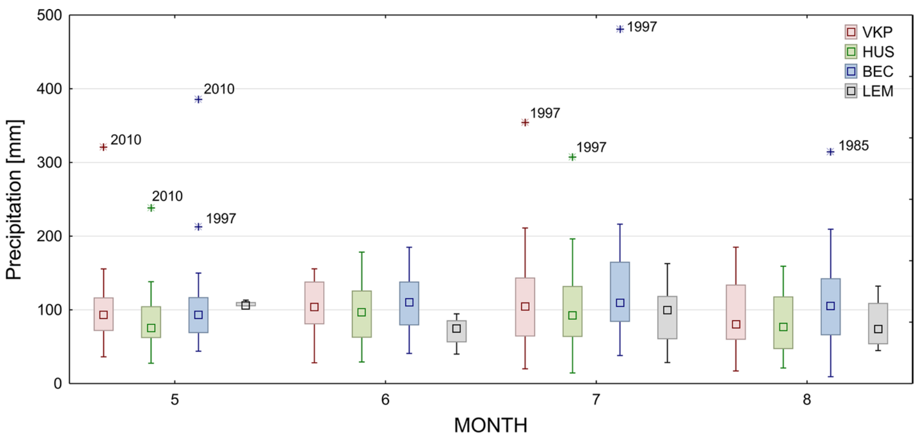

Fig. 11 Long-term monthly rainfall amount during the years 1983–2018 for VKP, HUS, BEC and Jul 2012-Jul 2016 for LEM rainfall gauges in May, June, July and August; box plot rectangle enhances the lower (25%) and upper (75%) quartile; thin vertical line represents data range excluding outliers; square in the box plot corresponds to a median value; cross are outliers

1983–2018 for VKP, HUS, BEC and July 2012—July 2016 for LEM station using box plots (Fig. 11).

The rainfall data from all four rainfall gauges (VKP, HUS, BEC, LEM) were available at the same time within the period between July 2012 and July 2016. The rainfall sums for

Table 7 Comparison of the daily rainfall totals at the rain gauges and their differences higher than 35 mm during the period 1983–2018; bold text with * in a blue frame marks the data from the debris flow day

Date (dd/mm/yyyy)	VKP [mm]	HUS [mm]	BEC [mm]	LEM [mm]	VKP-HUS [mm]	VKP-BEC [mm]	VKP-LEM [mm]
24/081983	0.0	35.5	4	-	-35.5	-4	-
04/06/1984	43.5	2.7	22.6	-	40.8	20.9	-
14/05/1985	1.7	42.2	20	-	-40.5	-18.3	-
09/07/1991	47.0	45.3	11.8	-	1.7	35.2	-
17/07/1994	29.5	67.3	24.4	-	-37.8	5.1	-
02/07/1995	4.0	2.1	64.5	-	1.9	-60.5	-
21/08/1995	55.5	3.5	11.5	-	52	44	-
07/09/1996	83.5	75.2	131.1	-	8.3	-47.6	-
06/07/1997	76.0	86.9	125.5	-	-10.9	-49.5	-
08/07/1997	63.8	38.6	106.8	-	25.2	-43.0	-
30/08/1997	23.8	27.5	67.8	-	-3.7	-44.0	-
12/06/1998	24.8	83.6	25.4	-	-58.8	-0.6	-
07/08/1999	7.8	9.8	91.5	-	-2.0	-83.7	-
14/06/2000	15.8	2.3	18.6	-	13.5	-2.8	-
17/07/2000	14.5	19.7	56.6	-	-5.2	-42.1	-
20/02/2002	4.5	46.2	26.3	-	-41.7	-21.8	-
27/05/2002	43.6	5.2	34.0	-	38.4	9.6	-
08/08/2006	33.0	48.4	91.0	-	-15.4	-58.0	-
05/11/2006	31.0	32.2	66.1	-	-1.2	-35.1	-
02/08/2008	9.4	41.5	55.7	-	-32.1	-46.3	-
15/08/2008	23.5	47.8	62.1	-	-24.3	-38.6	-
16/05/2010	41.6	53.5	97.2	-	-11.9	-55.6	-
01/06/2010*	**37.3**	**42.4**	**40.3**	**-**	**-5.1**	**-3.0**	**-**
31/08/2010	91.5	72.0	130.2	-	19.5	-38.7	-
04/06/2011	42.4	1.9	14.7	-	40.5	27.7	-
21/07/2011	7.0	48.9	43.8	-	-41.9	-36.8	-
15/08/2011	16.4	28.3	61.5	-	-11.9	-45.1	-
24/02/2013	2.1	2.2	0.8	40.0	-0.1	1.3	-37.9
04/04/2014	0	51	0	0	-51	0	0
15/05/2014	27.8	13	88.3	27.6	14.8	-60.5	0.2
26/05/2014	75.8	9.2	15.3	4.8	66.6	60.5	71.0
21/07/2014	63.1	25.3	35.8	41.2	37.8	27.3	21.9
17/09/2014	0	47.2	14.5	0	-47.2	-14.5	0
04/08/2015	35.9	0	0	0	35.9	35.9	35.9
10/06/2018	4.4	46.3	1	-	-41.9	3.4	-
Rainfall sums (Jul 2012-Jul 2016)	3 939.1	3 307.2	3 922.6	3 805.6	-	-	-
Average daily rainfall totals (Jul 2012-Jul 2016)	2.7	2.2	2.7	2.6	-	-	-

this period are very similar at the individual rainfall gauges. The lowest rainfall total was measured in HUS (3307 mm), then LEM (3805 mm), BEC (3922 mm) and the highest was in VKP (3936 mm) (Table 7). The average daily rainfall totals differ by a maximum of 0.5 mm (Table 7). The differences in the daily rainfall totals among the rainfall gauges show regular variability, when a difference of less than 10 mm occurred in 95% of cases.

Nevertheless, some extreme differences were noted in the remaining 5%. Differences in the daily amounts among the all rainfall gauges were registered on 24 February 2013 with maximum amounts in LEM and a difference of 37.9 mm. On the contrary, minimum rainfall in LEM and higher rainfall amounts in VKP, HUS and BEC were noted on 26th May 2014 (Table 7). The highest differences in daily totals reached 84 mm between VKP and BEC on 7 August 1999 (Table 7).

5 Discussion

More than 150 landslides originated in the Czech Republic in 2010 due to intensive and long-lasting rainfall (Pánek et al. 2011a; Bíl et al. 2016; Smolíková et al. 2016; Tichavský et al. 2017). Most of them developed in the region of the Flysch Outer Western Carpathians during May and June, as well as the Lemešná debris flow. A particularly wet season with a strong increase in rainfall-triggered landslides was also observed in other regions around the world in 2010, especially in Latin America, Asia and Central Europe (e.g. Pecho et al. 2010; Kirschbaum et al. 2012; Sepúlveda and Petley 2015; Froude and Petley 2018).

There is a considerable difference in the threshold precipitation that triggers landslides in the Carpathian region due to the geology of the substratum and the related relief energy (Gil and Długosz 2006). According to the example from the Polish Carpathians, the landslide processes usually begin after precipitation exceeding 200 mm, lasting for a few days, and providing medium moisture of the bedrock. Shallow landslides in colluvium needed 200–250 mm of precipitation on sandstone in one or a few days to develop (Gil and Długosz 2006). Debris flows in the Czech Carpathians, the Moravskoslezské Beskydy Mts., originated with the daily rainfall amounts of 111–234 mm (Šilhán and Pánek 2010). Bíl and Müller (2008) proposed thresholds of water infiltrated into soil of between 100 and 155 mm within 10 days. These figures were later specified to 67 mm (lower boundary) and 163.3 mm (upper boundary) within 10 days (Bíl et al. 2016). On the other side, debris flows in the Krkonoše Mts. originated due to rainfall values of 60–300 mm within 1–4 days (Migoń et al. 2002) and 0.2–266 mm per day (Drábová 2018) and in the Hrubý Jeseník Mts. with daily rainfall totals higher than 100 mm (Tichavský et al. 2017).

According to Pánek et al. (2011a), 70% of the studied slope deformations in the Czech part of the Outer Western Carpathians from May 2010 were triggered by CUM_3 totals higher than 81 mm and 50% of them by API_{30} between 80 to 100 mm. Nevertheless, 69% of these landslides were situated on slopes that were undercut by stream erosion.

The surroundings of the Lemešná study area have been affected by landslide activity in the distant past, but the 2010 debris flow was the only known landslide occurred there within the last 36 studied years. However, the daily rainfall totals as well as all of the calculated rainfall parameters reached higher values many times during the period from 1983 to 2018 than those of the 2010 debris flow.

Nevertheless, some combinations of the rainfall parameters turned out to be crucial for 2010 debris flow origin. The decisive combinations were CUM_{30} with 1-day and 3-day precipitation and surprisingly the combination of the entire rainfall pattern with all of the calculated rainfall parameters (daily, CUM5, CUM10, CUM20, CUM30, CUM60, API5, API10, API20, API30, API60). There was no single day exceeding 2010 debris flow rainfall amounts for all calculated parameters at the same time within the 36-year dataset of measurement, which makes the pattern combination unique as well. This concordance of the “debris flow” values occurred only in the debris flow day. This finding may explain why the debris flow did not occur during previous significant events, when some or several of the precipitation characteristics matched or exceeded those of the 2010 debris flow.

The most similar concordance to the debris flow day was noted on 8th July 1997. Most of the values were two or three times higher on this day, with only the CUM_{30} value being lower than the debris flow value. CUM_{30} in 2010 increased due to three significant rainfall episodes and remained high thanks to the persistent rainfall, which very probably led to soil saturation, unlike the low CUM_{30} in 1997 with a sharp increase.

The results show that the overall rainfall pattern (all rainfall parameters as daily totals, cumulative totals for 2, 3, 5, 10, 20, 30, 60 days and API for 5, 10, 20, 30 and 60 days) and the development of the rainfall situation were more important for the Lemešná debris flow than the individual rainfall extremes themselves, as stated by most authors (e.g. De Vita 2000; Crosta and Frattini 2001; Guzzetti et al. 2007; Cannon et al. 2008; Gariano et al. 2015; Bíl et al. 2016). The same rainfall pattern scenario was recognised for the Smědava debris flow, which originated in the Jizerské hory Mts. Concordance among all of the rainfall parameters and antecedent rainfall totals was also crucial for triggering the Smědava debris flow; however, it occurred in thin colluvial deposits of up to 0.5 m in medium-grained porphyric biotitic granite (Smolíková et al. 2016).

The rainfall data and resulting analyses are generally accompanied by many uncertainties. One of them is the real value of the rainfall that triggered the debris flow (Aristizábal et al. 2011). The real in-situ value can differ significantly from the data from nearby rain gauges due to very localised torrential rainfall, which can vary within a radius of 5 km (Panziera et al. 2011) or less, especially in mountainous areas (Smolíková et al. 2016). A comparison of the daily totals from the adjacent rainfall gauges VKP, BEC, HUS and LEM confirmed this assumption. The maximum daily totals did not prevail at a single rainfall gauge, since they alternated between all of the gauges. The high differences represent only 10% of the data, but they are potentially crucial for triggering the debris flow. The remaining 90% of the daily rainfall regime is similar in the VKP, BEC, HUS and LEM rainfall gauges, with differences in daily totals being below 10 mm. The rainfall situation during the 2010 Lemešná debris flow could have been similar, i.e. the real values of the triggering rainfall in 2010 could vary greatly, whether they were underestimated or overestimated. A comparison of the data from the rainfall gauges supports the claim that the choice of rainfall gauge is essential for a better determination of the rainfall thresholds of the landslides (Wieczorek and Glade 2005; Tichavský et al. 2017; Segoni et al. 2018a).

More uncertainties in the rainfall data can arise owing to the accuracy of the data measured once per day instead of moving hourly values, as well as lack of data and selection of the statistical method (Aristizábal et al. 2011). For example, antecedent rainfall can be calculated by API or cumulative sum, but each numerical method produces significantly different results. Likewise, the number of antecedent days used for the calculation can influence the results, if a period of 5, 7 or 10 days is chosen. A period longer than 30 days is disputable for shallow landslides, since the evaporation and runoff significantly reduce the amount of water present in the ground.

Last but not least, it is necessary to take into account the influence of geological, geomorphological, soil, vegetation and water circulation conditions as well as slope instability due to erosion and human intervention, which also play a significant role in the occurrence of a landslide (Gil and Długosz 2006; Sidle and Ochiai 2006).

6 Conclusions

The debris flow on Lemešná Mt. in the Javorníky Range in the Czech Republic occurred after two significant rainfall episodes on 2 June 2010. The analysis of the rainfall data from the permanent rainfall gauges at Velké Karlovice-Pluskovec, Huslenky and Horní Bečva in the vicinity of the debris flow was performed. The new Lemešná rainfall gauge was installed in the area of interest and the rainfall data were compared to the permanent gauges.

VKP rainfall gauge was chosen as a principal rainfall station for calculation of the following rainfall parameters: daily totals, cumulative rainfall of 2, 3, 5, 10, 20, 30 and 60 days and antecedent precipitation index of 5, 10, 20, 30 and 60 days. Cumulative and antecedent precipitation were calculated as moving values for each day within the period from 1983 to 2018 and were evaluated both separately and combined. This study evaluates all measured days throughout the period 1983–2018, so it considers the debris flow day as well as the days with no slope deformation.

Based on the processed analyses the following conclusions were found:

(1) No single parameter of all these calculated resulted as the highest extreme for the debris flow amounts. All of them were exceeded during the 36-year-long period many times, even the amounts were two or three times higher. So, none of these factors was determinative individually for the debris flow triggering.

(2) The combinations of CUM_{30} with 1-day and 3-day precipitation resulted as decisive for the 2010 debris flow triggering with the highest rainfall totals simultaneously.

(3) Unexpected result was the entire rainfall pattern evaluation with all of the calculated rainfall parameters (daily, CUM_5, CUM_{10}, CUM_{20}, CUM_{30}, CUM_{60}, API_5, API_{10}, API_{20}, API_{30}, API_{60}) at the same time. There was no single day exceeding 2010 debris flow rainfall amounts for all calculated parameters at the same time within the 36-year dataset of measurement, which makes the pattern combination unique and decisive for the 2010 debris flow origin as well.

It can be concluded that the combination of CUM_{30} with 1-day, CUM_{30} with 3-day precipitation, overall rainfall pattern and the development of the rainfall situation were decisive for the Lemešná debris flow triggering and more important than the individual rainfall extremes themselves. Analysis of the whole rainfall pattern and an assessment of the rainfall extremes with no landslides provides a innovative perspective to the rainfall thresholds studies.

(4) Importance of the method choice for the antecedent rainfall analyses between API and cumulative amounts was emphasized and supported by analyses. Considerable differences in values between API and cumulative analyses for the same number of counted days prove that it highly depends on the choice of these methods for the rainfall thresholds determination. Likewise, the number of previous counted days for the antecedent rainfall analyses is important.

(5) In the case of the API analyses with the evaporation constant of 0.93 determined for the Czech Republic, the number of evaluated days higher than 30 is questionable, because the 31st day counts the value of the 1st day with very low weight or none at all. The number of days greater than 30, for both API analysis and cumulative precipitation and especially the CUM greater than 60 or 90 is questionable as well, because it does not correspond to the real water volume present in the ground.

(6) Rain gauge selection is also very important and plays a major role in the determination of the rainfall thresholds triggering a slope deformation, especially in the mountains. The enormous differences in the daily rainfall totals between two rainfall gauges only 7 km apart reached 71 mm/day and 9 km apart reached 84 mm/day. These variances are influenced by the orographic position together with the distance of rainfall gauges, which indicates a distortion in the real rainfall totals. Nevertheless, these local torrential rainfalls are crucial for the slope deformation triggering.

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