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Spatial variability and interdependence of rain event characteristics in the Czech Republic

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Abstract:

Rain event characteristics are assessed in a 10-year (1991–2000) record for 122 stations in the Czech Republic. Individual rain events are identified using the minimum interevent time (*mit*) concept. For each station, the optimal *mit* value is estimated by examining the distribution of interevent times. In addition, various *mit* values are considered to account for the effect of *mit* on rain event characteristics and their interrelationships.

The interdependence between rain event characteristics and altitude, average rainfall depth, and geographic location are explored using simple linear models. Most rain event characteristics can be to some extent explained by average total rainfall or altitude, although models including the former significantly outperformed models using the latter.

Significant correlation was found among several pairs of monthly mean characteristics often including event rain rate (with event duration, depth, maximum intensity, and fraction of intraevent rainless periods). Moreover, strong correlation was revealed between number of events, interevent time, event depth, and duration. In general, correlation decreases in absolute value with *mit*.

Strong spatial correlation was found for the mean monthly interevent time and number of events. Spatial correlation was considerably smaller for other characteristics. In general, spatial dependence was smaller for larger *mit* values.

KEY WORDS rain event characteristics; spatial variability; spatial dependence

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INTRODUCTION

The relevance of individual rain event characteristics for many hydrological processes such as runoff generation, soil erosion, and forest hydrology is well reflected in the published literature. Generally, in addition to total event rainfall depth, characteristics like rain rate, maximum intensity, event duration, or interevent time contribute significantly to the nature of the hydrological response of an event and are also often considered in practical applications.

Based on a comprehensive review, Singh (1997) points to significant effects of rain rate, timing of an event's maximum, and intraevent variability, especially on the overland flow generation and shape of the resulting hydrograph. Soil moisture dynamics (Wang *et al*., 2008; He *et al*., 2012) and infiltration (Ran *et al*., 2012) can also be, to a large extent, explained by event size, rain rate, and interevent times.

The relationships between rain event characteristic (rain rate, maximum intensity, and rainfall depth) and rainfall erosivity are well recognized, and characteristics of rain events are included into methods (e.g. the USLE methodology of Wischmeier and Smith, 1978),which are routinely applied today in soil erosion assessment studies (Angulo-Martínez *et al*., 2009; Huang *et al*., 2012; Meusburger *et al*., 2012).

Important effects of event depth, duration, rain rate, and maximum intensity have been reported for hydrological processes involving vegetation, such as the partitioning of rainfall among interception, throughfall and stemflow (Staelens *et al*., 2008), root extraction (Wang *et al*., 2008), or evaporation (Dunkerley, 2008c).

Rain event characteristics are also very relevant for urban hydrology, determining, for example, the storm sewer flow rates or direct runoff (e.g. Schilling, 1991; Giulianelli *et al*., 2006) or the efficiency of structures for rainfall harvesting or stormwater pollution prevention. For instance, Guo and Baetz (2007) developed a method for optimizing the size of rainwater storage units based on the distribution of interevent times. Todeschini *et al*. (2012) discuss the effect of event rain rate and other

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rainfall characteristics on the ecological benefit and functionality of a wastewater treatment plant. McCarthy *et al.* (2012) examined the correlation of various rain event characteristics with the indexes of intraevent sediment pollution among which the maximum intensity explained most of the variance in pollutant concentrations.

Despite the importance of rain event characteristics, not many studies are explicitly devoted to their systematic exploration. Huff (1967) provides a classic example of a study on interevent variability that analyses the temporal structure of storm rainfall in Illinois using dimensionless hyetographs (i.e. cumulative percentage of rainfall depth, describing the temporal profile of rainfall events), mainly aiming to 'aid the hydrologist in design problems'. The method results in a typology of events based on the quarter in which the maximum rainfall occurred. The distinct rainfall types can be then related to specific synoptic causes. Huff (1967) also analysed various characteristics of rainfall events, such as frequency of bursts or proportion of rainfall depth and duration before the maximum burst or typical duration of each type of storms. This methodology has been applied worldwide, and many studies considering this concept have appeared quite recently (e.g. Samuel and Sivapalan, 2008; Al-Rawas and Valeo, 2009; Terranova and Iaquinta, 2011).

Rain event intensities and durations and their interdependence have been reported by Bidin and Chappell (2006) for Malaysia, while Haile *et al.* (2011) analysed event depth, duration, peak intensity, and interevent times for the source of the Blue Nile River area. A comprehensive review and summary of the published rain event characteristics are given by Dunkerley (2008b), who also studied the characteristics and influence of rain event definition for an Australian dryland site (Dunkerley, 2008a).

Information on dependence between rain event characteristics often can be found also in rainfall modelling studies. For instance, Balistrocchi and Bacchi (2011) developed a statistical model for interdependence between rain event duration, depth, and interevent time and verified it using number of rainfall records in Italy. Similarly, Gyasi-Agyei and Melching (2012) applied their statistical model focused on modelling the interdependence and internal structure of rain events in a network of 25 stations using 21 years of hourly data for Illinois.

The present paper contributes to the systematic exploration of rain event characteristics and their (inter) dependence considering 10 years (May–September) of data for 122 rainfall stations in the Czech Republic. The relationships between rain event characteristics (event depth, duration, rain rate, maximum intensity, interevent time, fraction of intraevent rainless periods, and relative position of peak of an event) and climatological and geographical indexes are examined as well as the dependence of characteristics between stations. The effect of event definition is also considered.

A number of studies have examined precipitation patterns in this area. However, attention has been given mainly to deriving intensity–duration–frequency (IDF) relationships (Trupl, 1958), estimating of probable maximum precipitation (Řezáčová *et al.*, 2005), or, for instance, assessing precipitation extremes and their trends (Kyselý, 2009). Moreover, a number of studies on rainfall erosivity have been published (Kubátová *et al.*, 2009; Janeček *et al.*, 2012) but without any details on rain event characteristics. Recently, attention has been devoted to the analysis of radar data (see e.g. Sokol and Bližňák, 2009; Bek *et al.*, 2010), which yields some relevant information, for instance, on the relationship between rain rate and altitude. The events are usually defined, however, with respect to the space–time characteristics of rainfall fields, and quantities like rainfall duration are often not related to the fixed location (such as rainfall station) but rather to the individual rain cells; thus, the results are then not directly comparable. Heretofore, the characteristics of individual rain events in the Czech Republic had not been systematically analysed. The present study thus provides important information as to the nature of rain event characteristics and their interrelationships, which may also contribute to understanding the consequences of precipitation.

The study area and data used in the analysis are described in the next section, which is followed by a definition of the considered rain event characteristics and the methods applied for their analysis. Thereafter, we present and discuss the main findings, which are finally summarized in the conclusions.

STUDY AREA

Precipitation in the Czech Republic

The Czech Republic (Figure 1) is a small country (79 000 km^2) situated in Central Europe. Precipitation patterns over the country are rather variable, partly due to the relatively complex orography (altitudes up to 1600 m) and partly due to the combination of Atlantic, Mediterranean, and continental effects (Kyselý and Beranová, 2009). In winter, precipitation is mostly due to enhanced westerly flows related to the Atlantic influences. The Mediterranean influences are dominant, however, in the eastern part of the Czech Republic in winter and across the entire area in summer. In the transition seasons, the effects are mixed, with the western part of the area being more affected by the Atlantic and the eastern part by Mediterranean influences (e.g. Brádka, 1972; Brázdil, 1980).

Mean annual total precipitation for the period 1961–1990 for the Czech Republic as a whole was 674 mm, varying from about 400 mm in the western part of the Czech

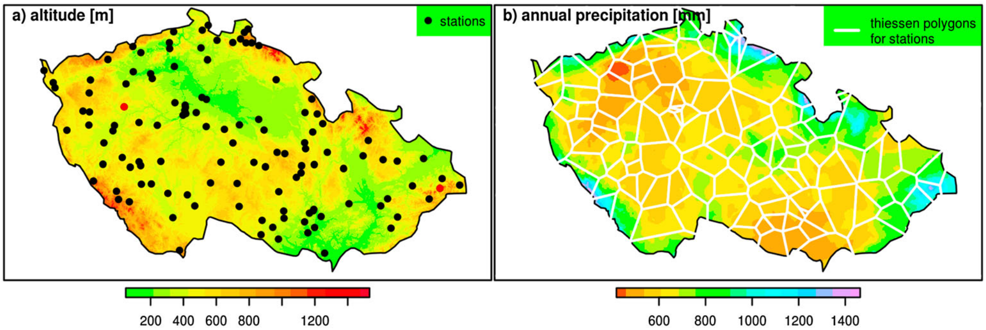

Figure 1. Study area and considered stations. (a) The altitude and locations of considered stations. The red dots indicate the station with the lowest (west) and largest (east) rainfall amount. (b) Mean annual rainfall depth and the Thiessen polygons belonging to the rainfall stations. Note that these polygons are further considered only for visualization purposes, i.e. the stations are not representative of the area in the polygons

Republic up to more than 1400 mm in the mountains to the north. Almost two-thirds of the annual total falls in the summer half of the year (April–September). The maximum precipitation amounts can be quite large at short time scales, thus contributing considerably to the annual total precipitation. Štekl *et al*. (2001) point to historical records of 237 mm in 1 h (25 May 1872), 345 mm in 1 day (29 July 1897), 537 mm in 3 days (6–8 July 1997), and 617 mm in 5 days (4–8 July 1997).

A considerable part of the annual precipitation total results from large-scale precipitation. For instance, Brázdil and Štekl (1986) estimated that 53% of winter and 41% of summer total precipitation originate from precipitation events affecting more than 90% of the area of the Czech Republic, although the probability for such large-scale events to occur is, in general, low (~14% in summer and winter).

Data

In the present study, we analysed 10-min precipitation depths derived from pluviograph records for 122 stations, provided by the Czech Hydrometeorological Institute. Since the pluviograph records are unreliable in winter, only those records for May–September have been considered. This period is further referred to as a 'year'.

The 10-min data set was developed by the Czech Hydrometeorological Institute using rainfall data with 1-min resolution obtained from IBA and Hellman float-type self-recording pluviographs (having the interception area of 250 cm^2). These ombrographs operate using the float-siphon device that reads the rainfall amount from the water receiver and records the rainfall data on a clock-operated drum (Kurtyka, 1953). The digitalization process of the raw ombrograph records was complemented with quality control aimed at the identification and reconstruction of unreadable, damaged, or missing pluviograph records. Therefore, many sources of rainfall information have been taken into account (e.g. synoptic situation or monthly, daily, and hourly rainfall depths measured at-site or in the neighbourhood using a standard rain gauge with the interception area 500 cm^2). A minimal volume step to be considered within digitization was 0.1 mm. The methodology of quality control and digitizing of pluviographic measurements is described in detail by Květoň *et al*. (2004) and has been routinely applied on digitalized historical rainfall series in the Czech Republic.

The reconstructed/missing parts of the records are indicated in the data set. Different quality codes have been assigned to the individual 10-min records corresponding to the fraction of daily total being reconstructed (see Květoň *et al*., 2004 for details). For individual stations and years, the fraction of reconstructed records contributing significantly (>50%) to the daily precipitation total is usually less than 10%.

To further assess the quality of the data set, the daily precipitation depths aggregated from 10-min data were compared to the corresponding daily precipitation depths from standard ombrometers. We considered the 10-min data for a day unreliable when this difference exceeded 1.5 mm (for daily precipitation depths below 15 mm) or 10% (for daily precipitation depths above 15 mm). The years for which the fraction of unreliable records was larger than 10% were excluded from the data set.

To analyse the spatial variation in rain event characteristics, a common time period for all stations is generally required since the temporal variation in rain event characteristics is rather strong and could mask possible spatial patterns. In the present study, we identified a common period 1991–2000 for which 122 stations have at least 8 years of reliable data (10 years of data are available for 100 stations, 9 years for 116 stations). The stations more or less uniformly cover the area of the Czech Republic (Figure 1). The altitudes of these stations range from 150 to 1322 m a.s.l. The mean May–September precipitation total varies from 158 mm (31.6 mm/month) in Kralovice (west of the Czech Republic) to 709 mm (141.8 mm/month) at the Lysa Mountain in the north-east (see Figure 1). Note that the average May–September precipitation for the period

1991–2000 (397 mm) was close to that in the standard 1961–1990 period (385 mm).

As a summary of the intensity–duration relationship, we show in Figure 2a the relationship between the observed (1991–2000) maximum rain rate against aggregation time for all stations and aggregation times from 10 min (data resolution) up to 10 h. Clearly, there exists a considerable spread among stations, but the form of the scaling of maximum rain rate with aggregation time is general. The maximum observed rain rates in 10-min data correspond to ~60–200 mm h^{-1}, for hourly data 25–50 mm h^{-1}, and for 10-h aggregation time only ~ 4–10 mm h^{-1}. The low spatial variability of the form of this scaling relationship is visible from Figure 2b, showing relative maximum rain rate scaled by the at-site average maximum across aggregations. Although the spread is considerable for short aggregation times also in the case of relative maximum rain rate, for aggregation times larger than 1 h, the differences between individual stations are small. This suggests that spatial pooling techniques might be potentially useful in summarizing the rain event characteristics.

To explore the nature of the rainfall record further, we examined the contribution of measurement intervals with certain rainfall amount to the total number of intervals and to the precipitation total (see Figure 3). A large part of the record (40–60%) on the wet intervals (being defined as 10-min intervals with nonzero precipitation) is formed by intervals with 0.1 mm of precipitation. Nevertheless, the precipitation at the measurement intervals with 0.1 mm contributes relatively significantly (10–25%) to the overall rainfall total. This is different for 10-min intervals with large amounts of rainfall, e.g. ≥5 mm, which cover less than 1% of the intervals but 4–15% of the total precipitation amount.

METHODS

Many methods can be applied to determine the individual events from rain gauge records. The most commonly used approach is perhaps the minimum interevent time (*mit*) concept, defining events on the basis of a minimum time interval that must be reached or exceeded between the individual events. This criterion is often combined with minimum event depth or minimum event maximal intensity. A classic example is the Universal Soil Loss Equation methodology, which considers only those events separated by at least 6 h and with total depth more than 12.7 mm or with maximum intensity larger than 6.35 mm/15 min (Wischmeier and Smith, 1978). These thresholds are relevant for soil erosion, and different criteria are used in different applications. Based on a comprehensive review of

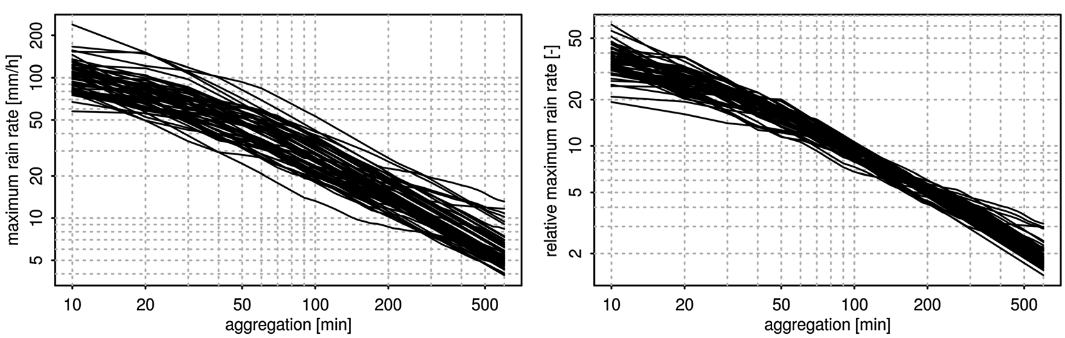

Figure 2. Recorded maximum rain rate in relation to aggregation time for all stations (represented by black lines). (a) Rain rate in mm/h. (b) Rain rate scaled by average maximum rain rate across aggregations for each station

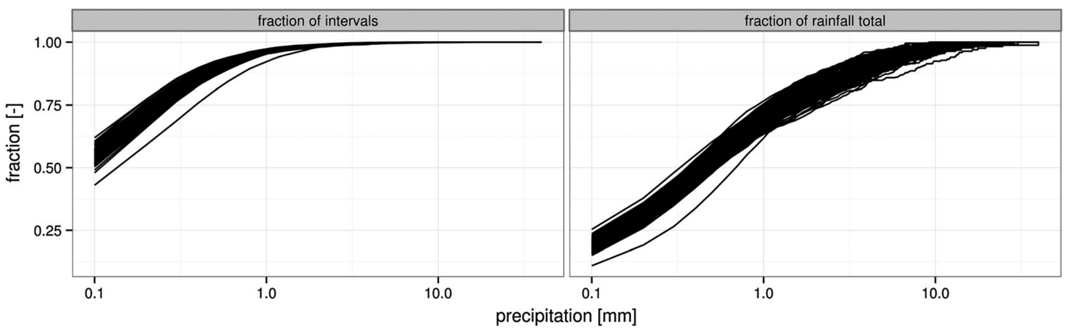

Figure 3. Relation of precipitation amount in the measurement interval (10 min) with (a) the fraction of wet intervals with smaller or equal rainfall amount and (b) the fraction of rainfall total falling in intervals with less or equal precipitation. The lines correspond to the individual stations. All intervals with nonzero precipitation are considered wet

published literature addressing individual rainfall events, Dunkerley (2008a) gives a range of *mit* values varying from 3 min to 24 h in combination with minimum event depths ranging from 0.1 mm to 13 mm, with higher values usually related to soil erosion studies.

Complementarily to the *mit* concept, Peters and Christensen (2006) defined an event as a sequence of consecutive wet time intervals at a given aggregation level. Ignaccolo and De Michele (2010) have shown, however, that these two concepts are equivalent.

In addition to the arbitrary separation of rain events, more complex objective criteria do also exist. Independent events may be identified by analysis of the serial autocorrelation (Wenzel and Voorhees, 1981; Morris, 1984) or rank (auto) correlation (Grace and Eagleson, 1966), evaluating the autocorrelation coefficients at successive lags until they are no longer statistically significant. Alternatively, since the rainfall occurrence can be represented as a Poisson process, which implies exponential distribution of the interevent times, independence can be checked by examining the distribution of the interevent times as described, for example, by Bonta and Rao (1988). Methods based on statistical physics also have been published. For instance, Ignaccolo and De Michele (2010) suggest the definition of an event based on statistical properties of interdrop time intervals and drop diameters.

Fundamentally different concepts of event definition might be found for radar data. To analyse heavy precipitation, for instance, Sokol and Bližňák (2009) defined an event on a radar pixel such that the sum of two consecutive hourly records exceeds 5 mm (together with several additional conditions). The structure and characteristics of such events are totally different from those defined by *mit*, since by definition, the *mit*-defined events may contain long sequences without rainfall.

In the present paper, we based the definition of the events on the *mit* concept. The optimal *mit* was estimated by examining the distribution of the occurrences. Restrepo-Posada and Eagleson (1982) suggest a simple check based on the coefficient of variation (CV) of the interevent times. Assuming that the distribution of interevent times is approximately exponential, which implies equal mean and standard deviation, the coefficient of variation should be 1. Therefore, *mit* values are systematically altered, and the *mit* leading to CV = 1 is identified as optimal. Although another distribution may also satisfy this condition (e.g. log-normal), many natural rainfall series show exponential or near-exponential distribution of interevent times (Restrepo-Posada and Eagleson, 1982), and exponential distribution for the interevent times is also often employed in rainfall generators (e.g. Waymire and Gupta, 1981; Rodriguez-Iturbe *et al*., 1987). Despite a large fraction of low-intensity rainfall records (see Figure 3), no intensity criteria were considered, since those records concurrently generate a considerable part of total precipitation. Note however, that this decision affects the results, especially the event duration, which is longer, and event rain rate, which is smaller, compared to the characteristics of events being defined with an intensity criteria.

We further systematically analyse the impact of *mit* on spatial variability and (inter)dependence of rain event characteristics by application of *mit* = 30, 60, 120, 180, 360, 720, and 1440 min.

We further consider the following characteristics of rainfall events (see Table I for overview and other symbols used in the paper):

- number of events per year (May–September), n [−],
- event duration, T [h],
- event depth [mm]

$$D = \sum_{i=1}^{6T} I_i, \qquad (1)$$

with I_i being the 10-min intensity for the ith 10-min sequence of an event,
- mean event rain rate [mm h^{-1}]

$$R = \frac{D}{T}, \qquad (2)$$

- maximum event 10-min intensity [mm h^{-1}]

$$Mx = \max_{1<i<6T} \{6I_i\}, \qquad (3)$$

- fraction of event duration until event maximum (time to peak) [−]

Table I. List of symbols

mit	Minimum interevent time	[min]
$\hat{mit}$	Estimated *mit*	[min]
n	Number of events	[−]
D	Total event depth	[mm]
T	Event duration	[h]
R	Event rain rate	[mm h^{-1}]
Mx	Event peak 10-min intensity	[mm h^{-1}]
T^{Mx}	Time to peak	[−]
D^{Mx}	Depth to peak	[−]
EG	Fraction of intraevent rainless periods	[−]
IET	Interevent time	[h]
ALT	Altitude	[m]
TOT	Rainfall depth	[mm]
X	Easting	[km]
Y	Northing	[km]
CDD	Correlation decay distance of rainfall event characteristic	[km]
DST	Interstation distance	[km]

$$T^{Mx} = \frac{t^{Mx}}{T}, \quad (4)$$

with t^{Mx} being the timing of the maximum in the event [h],

- fraction of event depth until event maximum (depth to peak) [−]

$$D^{Mx} = \frac{\sum_{i=1}^{6t^{Mx}} I_i}{D}, \quad (5)$$

- fraction of intraevent rainless periods (event gaps), *EG* [−], and
- interevent time, i.e. length of rainless period between events, *IET* [h].

Such characteristics as *n*, *D*, *T*, *R*, and *IET* are often considered in studies on rain event properties (cf. Guo and Baetz, 2007; Dunkerley, 2008a,2008b; Shamsudin *et al*., 2010; Haile *et al*., 2011). For simple indication of the shape and time structure of a rain event, we also include the characteristics describing the position of the peak in an event (T^{Mx} and D^{Mx}) and fraction of intraevent rainless periods (*EG*), which are relevant for runoff and overland flow generation, infiltration, etc. (cf. Singh, 1997).

In addition, the spatial correlation of rain event characteristics and correlation between characteristics is examined. Since the interdependence between characteristics and also the spatial dependence are often nonlinear (cf. Habib *et al*., 2001), we considered rank correlation coefficient instead of the classical Pearson's formula.

An assessment of intersite correlation on an event basis requires identification of concurrent events. Ideally, this should be based on an analysis of the synoptic situation/areal extent related to each event. A simplified approach has been suggested by Mikkelsen *et al*. (1996) for spatial analysis of extreme precipitation. They considered a time window around a given event at one site. Extremes within this window are considered concurrent. On the other hand, spatial correlation of characteristics such as rainfall maximum is often considered on an annual basis (see e.g. Mailhot *et al*., 2007). Alternatively, Samuel and Sivapalan (2008) analysed monthly mean characteristics of rain events (durations, interevent periods, and rain rates) in their analysis of intra-annual rainfall variability. For the sake of simplicity, monthly mean event characteristics have been considered also in the present paper for the assessment of spatial dependence and interdependence between rain event characteristics.

The interstation correlation of rainfall event characteristics is assessed using the spatial exponential correlation model studied for example by Tabios and Salas (1985), Jones *et al*. (1997); Osborn and Hulme (1997) and Hofstra *et al*. (2010). For a rainfall event characteristics *Z*, the correlation $\mathrm{cor}(Z^i, Z^j)$ between sites *i* and *j* is related to the distance between stations ($DST_{i,j}$) using a one-parameter exponential decay function:

$$\mathrm{cor}\left(Z^i, Z^j\right) = exp\left(-DST_{i,j}/CDD_Z\right) \quad (6)$$

where the correlation decay distance (CDD_Z) is the distance for which the correlation coefficient equals $1/e$. A large value indicates that the rainfall event characteristics are correlated across long distances (Hofstra *et al*., 2010). The model assumes spatial isotropy, i.e. the correlation does not depend on direction (Jones *et al*., 1997; Mandapaka *et al*., 2010). The *CDD* parameter is estimated using an iterative nonlinear least square method as suggested by Jones *et al*. (1997).

The model in Equation (6) can be applied considering all possible pairs of stations, i.e. assuming the *CDD* is constant for a given characteristic. For some rainfall characteristics, however, the CDD_Z may exhibit considerable spatial variability between stations (see e.g. Osborn and Hulme, 1997; Hofstra *et al*., 2010). Therefore, the *CDD* for individual stations has also been analysed.

RESULTS AND DISCUSSION

Identification of individual events

To identify the individual rainfall events, we applied the check of Restrepo-Posada and Eagleson (1982). For each station, the *mit* values were varied from 1 h to 20 h, with an increment of 20 min. For each *mit*, the events were identified, and the CV of interevent times (*IET*) was calculated. Since the optimal value of *mit* can vary during a year, we also estimated the optimal *mit* for individual months. The results for all stations are summarized in Figure 4.

In general, the CV is largest for small *mit* values, for which the standard deviation is considerably larger than the mean. As a result of applying *mit*, the distribution of *IET* is truncated from the left. Increasing the *mit* leads to a larger mean, while the other central moments are almost constant. This results in a decrease in CV of the distribution of *IET* with increasing *mit*. The approximate values of *mit* for which CV = 1 were estimated by interpolation between values for 20-min *mit* increments for each station.

The estimated values of *mit* for the whole period (further denoted $\widehat{mit}$) vary from 426 min (7.1 h) to 1055 min (17.6 h), with an average of 763 min (12.7 h). Stations with minimal $\widehat{mit}$ values are located in the southwest, and those with maximal values are found in the central part of the Czech Republic (not shown). When the procedure is applied to the individual months instead of the whole period, the optimal *mit* varies (see Figure 4). In

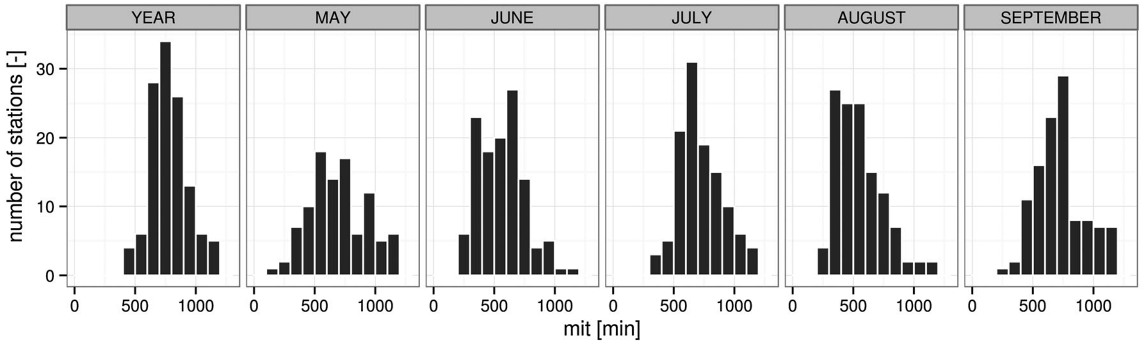

Figure 4. Estimation of *mit* for individual months and the whole period

general, the $\hat{mit}$ is smaller in July and August; however, for individual stations, the temporal pattern of the estimated *mit* is not always clear, which is perhaps due to the natural variability of precipitation in combination with a relatively short record. For instance, the shortest $\hat{mit}$ (190 min) was found for the Dnesice station (central Bohemia) for May. For the same station, the longest $\hat{mit}$ is estimated for June (1070 min), while the estimated *mit* drops again in August to 445 min.

Although it is in principle possible to consider monthly variable *mit* for further analysis, the *mit* estimated considering the whole period was preferred in this paper to provide consistency with other studies and to avoid physically unexplainable variation in the estimated *mit* between months for some stations.

From the review of Dunkerley (2008a), the most commonly used *mit* value is around 6 h, but values close to 12 h or longer are also reported. The values identified in the present study are thus well within the range of presented values. Note, however, that the rationale for the selection of a specific *mit* value is seldom given and can often be arbitrary or ensue from soil erosion assessment methodologies. For the Czech Republic, Trupl (1958) defined events on the basis of maximum total duration of rainless intervals in the rain event, with maximum duration of rainless periods of 5 min for events shorter than 60 min and 10 min for longer events. These values are extremely short. His study was aimed, however, at the derivation of IDF curves, not the assessment of rain event characteristics.

Rain event characteristics

The characteristics of each rainfall event for each station have been estimated using $mit = \hat{mit}$ and $mit = 30$, 60, 120, 180, 360, 720, and 1440 min for event definition. It is clear that in the perspective of the estimated *mit* values (varying from 426 to 1055 min), the *mit* of 30 min would not likely provide independent events. However, the optimal *mit* is not always estimated in the published literature, and thus, the choice of *mit* often follows from different context (as rainfall erosion assessment), subjective judgement, literature review, etc. Therefore, we believe that it is important to study the consequences of such choices for basic statistical assessment in addition to the analysis of the characteristics defined with the estimated *mit*.

The overall mean rainfall event characteristics for all considered *mit* values are given in Table II, and the spatial distribution of the average characteristics for $mit = \hat{mit}$ is shown in Figure 5. Since distribution of rainfall characteristics such as rainfall event depth, duration, and rain rate, and the durations of interevent times are strongly positively skewed (see e.g. Dunkerley, 2008a),

Table II. Overall mean rain event characteristics for different *mit* values

mit	*n*	*D*	*T*	*R*	*Mx*	T^{Mx}	D^{Mx}	*EG*	*IET*
30	168.30	0.46	0.60	0.78	1.26	0.51	0.60	0.20	22.65
60	120.90	0.71	0.93	0.77	1.56	0.42	0.54	0.26	30.61
120	88.24	1.10	1.51	0.74	1.92	0.35	0.49	0.32	40.56
180	72.49	1.48	2.06	0.71	2.28	0.31	0.46	0.36	48.83
360	53.05	2.42	3.58	0.66	2.94	0.26	0.43	0.40	62.71
720	41.20	3.51	5.83	0.61	3.78	0.24	0.42	0.45	77.84
1440	30.37	5.06	10.21	0.50	4.80	0.23	0.41	0.52	96.82
$\hat{mit}$	39.10	3.70	6.13	0.60	3.90	0.24	0.41	0.45	80.95

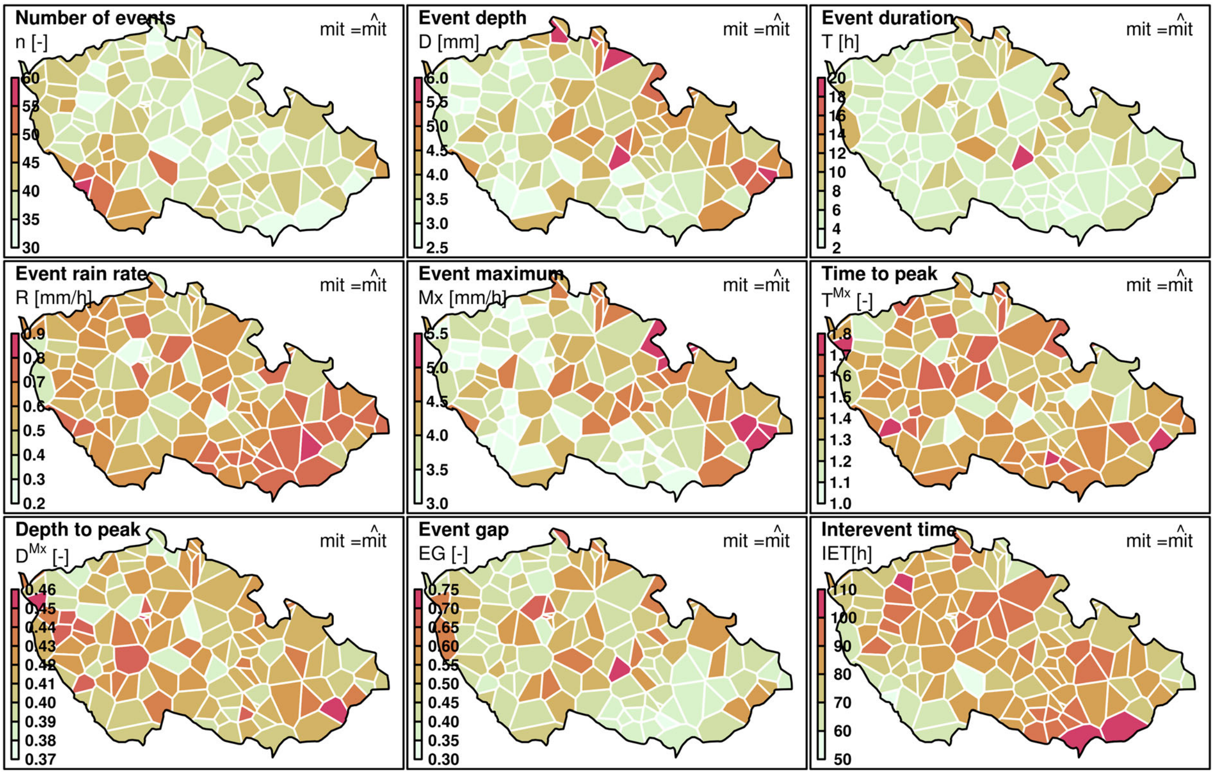

Figure 5. Spatial distribution of selected characteristics

geometric mean was used for summarizing the rainfall event characteristics.

For $mit = \hat{mit}$, the average number of events per year (May–September) is 39 (ranging from 32 in the south-east to 56 in the south-west). The mean event depth is 3.7 mm (2.6–5.8 mm); duration, 6.13 h (3.83–18.3 h); rain rate, 0.6 mm h^{-1} (0.28–0.81 mm h^{-1}); and event peak 10-min intensity, 3.9 mm h^{-1} (3.02–5.28 mm h^{-1}). The peak occurs, on average, at 25% (17–30%) of event duration and 41% (38–46%) of event rainfall amount precipitation before event peak. The average rainfall event contains 45% (35–71%) of rainless records, and the average interevent time is 80.95 h (54–110 h), i.e. 3.4 days (2.25–4.6 days).

Note that the numbers in parentheses above represent the spatial variability of 10-year average characteristics among the stations. The variation for each individual station is much larger. For instance, the (spatial) average range of event depth is 0.12–99 mm; event duration, 10 min to 5.4 days; event rain rate, 0.03–15 mm h^{-1}; and event peak 10-min intensity, 0.1–98 mm h^{-1}.

The average rain rates are smaller than those reviewed by Dunkerley (2008a). However, most of the studies reported therein used different event selection criteria. In addition, besides applying different *mit* or minimum intensity criteria, the sensitivity of the rain gauge could have an impact especially on the duration of the events and thus also on the event rain rates. This is because the likelihood of reaching the *mit* is lower when the sensitivity of the rain gauge is higher, since the interevent rainless periods are more often terminated by precipitation. Relatively low average rain rates calculated from our data set are related to a large amount of low-rainfall (0.1 mm) records, which often lead to long events with considerable sequences of low rainfall.

Since the spatial variation of the characteristics does not appear to be random, we explore the relationship between average characteristics at each site and altitude (*ALT* [m]), May–September average rainfall depth (*TOT* [mm]), and geographic coordinates (*X*, *Y* [km]) in the Czech S-42 (Pulkovo 1942/Gauss-Krüger zone 3) coordinate system (EPSG:28403) by linear regression.

Since the linear regression assumes independence of residuals, the data set of independent events was developed first using a bootstrap procedure described in the Appendix. A single bootstrap sample is developed by successive elimination of events that could be consequential to a same synoptic event. The procedure is repeated until the required number (here 500) of bootstrap samples is generated. Note that the number of (independent) events in a bootstrap sample is far less than that in the original data set due to the elimination of events. Similarly, the average interevent time becomes much longer. Therefore, these two characteristics have not been considered in the regression analysis. The average rain event characteristics are then reestimated using the resampled data set. For each characteristic, linear models combining the four covariates (without interactions) have been assessed. The best models in terms of the Bayesian information criterion (Schwarz, 1978) are given in Table III. Note that average rainfall depth significantly depends upon altitude, and therefore, using *ALT* instead of *TOT* and vice versa generally leads to similarly appropriate models.

All of the models shown in Table III are significant at the 0.05 significance level, except the model for D^{Mx}. The coefficient of determination for some characteristics is rather small (less than 0.2 for event rain rate, time and depth to maximum, and fraction of intraevent rainless periods). With their coefficients of determination between 0.2 and 0.35, the spatial variation is better described for event depth, duration, and maximum. The average event depth is partly proportional to the rainfall depth and increases with the south–north gradient. Similarly, the event maximum increases with the rainfall depth, and the larger maximums are seen in the north-east. Note that the significance of the relationships is slightly weaker when individual months are considered (not shown); however, only the regression for the time to peak becomes insignificant (at 0.1 significance level) for July, August, and September. Similarly, the coefficient of determination is lower when individual months are considered.

The relationship of rainfall depth, rain rate, and number of events and altitude for the Czech Republic was studied by Sokol and Bližňák (2009)) and by Bek *et al.* (2010). Although the events have been defined differently in their studies, the results on the altitude dependence of these characteristics are consistent with our findings. For instance, the authors found significant positive correlation of rainfall depth to altitude. In addition, Bek *et al.* (2010) found a significant increase in the number of events with altitude. Although the best formulas for event depth and number of events reported in Table III include total rainfall depth, the regressions considering altitude as an explanatory variable are also significant (with coefficients of determination of 0.52 and 0.2 for the relationship between event depth and number of events to altitude, respectively). Sokol and Bližňák (2009) and Bek *et al.* (2010) also mentioned only a weak and insignificant relationship of rain rate to altitude, which is in agreement with our results.

The rain event characteristics are, to a large extent, determined by the *mit* used for the definition of the events. This is demonstrated in Table II and Figure 6. Increasing *mit* leads to a smaller number of events, consequently with larger duration and event depths. For instance, the number of events for $mit = 1440$ min is, on average, only 20% of that for $mit = 30$ min; the events are ~17 times longer, and the event depth is ~11 times greater. On average, the duration of events increases with *mit* more rapidly than does event depth. As a consequence, the average event rain rate decreases, although rain rate for $mit = 1440$ min is still 65% of that for $mit = 30$ min. The interevent time, event maximum intensity, and fraction of event gaps increase ~3–5 times between $mit = 30$ min and $mit = 1440$ min. The position of the event maximum in the event profile is also influenced by *mit*. For $mit = 30$ min, the peak occurs close to the middle of the event, while for $mit = 1440$ min, it is close to a quarter of the event. Similarly, for $mit = 30$ min, an average of 60% of the event rainfall depth falls before peak, while this fraction is only 40% when $mit = 1440$ min.

Table III. Best linear models for rain event characteristics and *mit* together with the coefficient of determination (R^2). All regressions are significant at the 0.05 significance level except for the model for D^{Mx}

	Best model ($mit = \hat{mit}$)	R^2
D	$-11.28 + 0.00376\ TOT + 0.00236\ Y$	0.35
T	$-58.77 + 0.00657\ TOT + 0.0113\ Y$	0.20
R	$4.19 - 0.00066\ Y$	0.1
Mx	$0.534 + 0.0000435\ TOT$	0.23
T^{Mx}	$1.39 - 0.0000681\ ALT + 0.000163\ TOT - 0.000125\ X - 0.000132\ Y$	0.14
D^{Mx}	$0.51 - 0.0000246\ X$	0.02
EG	$-1.98 + 0.0001\ ALT + 0.00044\ Y$	0.13

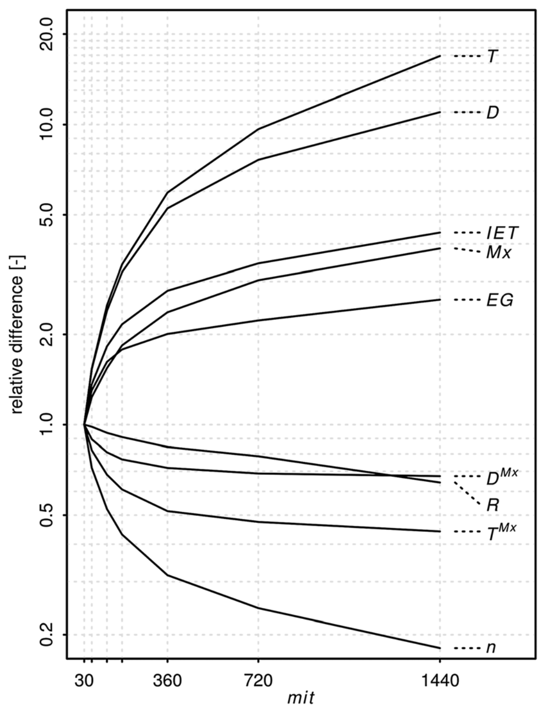

Figure 6. Dependence of rain event characteristics on *mit*. The lines correspond to relative changes with respect to the value of characteristics for $mit = 30$. Note the logarithmic vertical axis

Dunkerley (2008a) used linear and power function models to describe the relationship between rain event characteristics and *mit* at a given site. Since the scaling of rain event characteristics with *mit* at different stations is, in general, similar (not shown), we considered a spatially pooled power model of the form

$$\hat{Z} = a_Z(i)mit^{b_Z} \tag{7}$$

to summarize this scaling. (Note that the linear form of this model was also tested, but the power model was superior for all characteristics.)

For the estimate $\hat{Z}$ of rainfall event characteristics Z in Equation (7), the $a_Z(i)$ is a site-specific regression coefficient for site i, and b_Z is a common scaling factor (constant for all stations) describing the relationship between rain event characteristics and *mit*. We fit the model to all considered characteristics. Since the fit was not satisfactory for R, we applied the model to log-transformed rain rates, which resulted in significant improvement. See Figure 7 for spatial distribution of regression coefficients a_Z and Table IV for the scaling factors b_Z and the coefficient of determination of fitted models.

The coefficients a_Z are strongly correlated to the value of the characteristics Z (not shown). However, the *mit* for which the correlation is largest varies among characteristics and spans the entire range of considered *mit* values. For instance, a_Z is strongly correlated (correlation coefficient, ~0.99) to number of events for $mit = 30$ min and to event duration for $mit = 1440$ min.

The scaling factor b_Z corresponds well to the direction and slope of the curves in Figure 6 (except the log-transformed R), with the largest positive values for event duration (0.638) and total event depth (0.5) and negative values for number of events (−0.388). For all models, the overall coefficient of determination is ≥0.9, and at individual sites, it is usually between 0.8 and 1.0. The fit is not satisfactory for several stations (see blue polygons in Figure 7) in the case of event rainfall rate and depth to peak, suggesting that the relationship of the values for those characteristics to minimum interevent time is complex, and thus, more flexible models might be required.

Interdependence between characteristics

Correlation between all average monthly characteristics has been calculated for all sites and $mit = \widehat{mit}$ and $mit = 30$, 60, 120, 180, 360, 720, and 1440 min, and the significance of the correlation between the pairs of characteristics has been assessed. Results for $\widehat{mit}$ are summarized in Table V. The table indicates the correlation as well as the proportion and number of

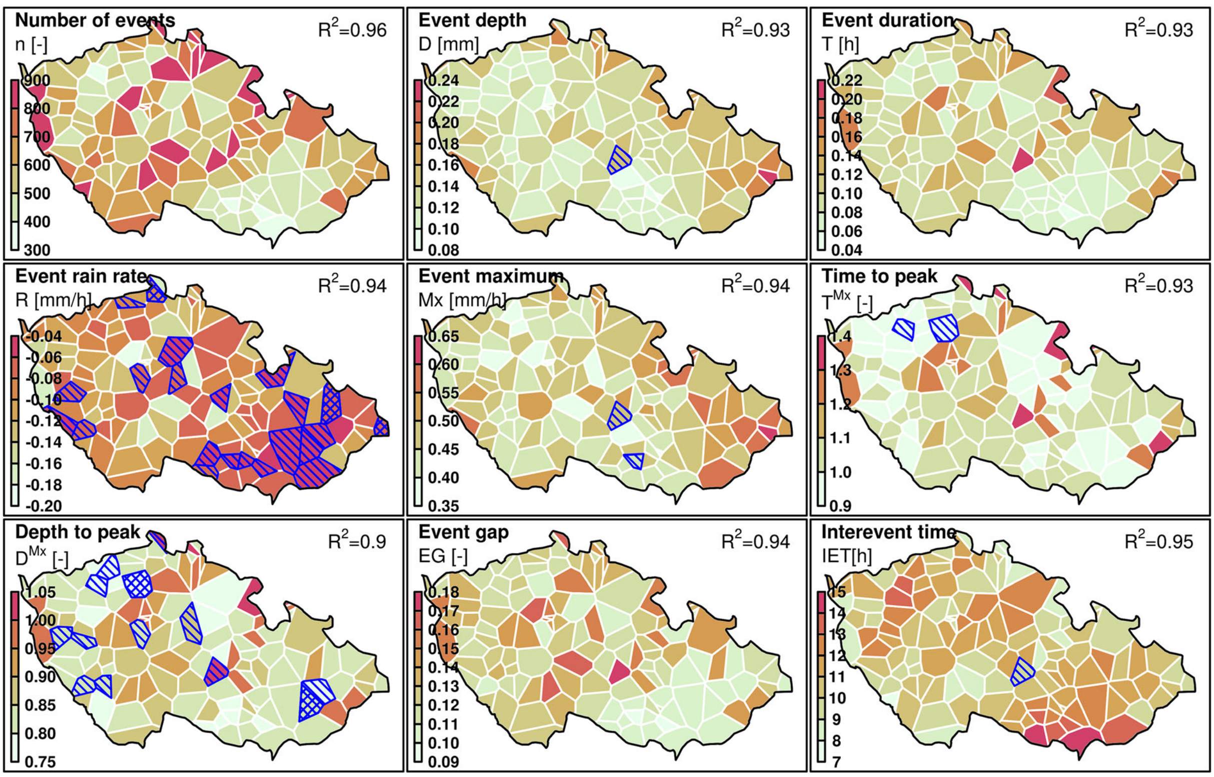

Figure 7. Spatial distribution of regression coefficient a_Z from Equation (7) for all characteristics. Single (double) hatching indicates the stations for which the coefficient of determination was less than 0.8 (0.5)

Table IV. Parameters a_Z and b_Z from Equation (7) summarizing the relationship between rain event characteristics and *mit* together with the overall coefficient of determination. The ranges of regression coefficients a_Z and coefficients of determination (R^2) from all individual sites are given in parentheses

Z	a_Z	b_Z	R^2
n	607 (371, 898)	−0.388	0.96 (0.86, 1)
D	0.132 (0.0887, 0.238)	0.5	0.93 (0.8, 1)
T	0.102 (0.0594, 0.209)	0.638	0.93 (0.85, 1)
log (R)	−0.095 (−0.189, −0.0407)	0.271	0.94 (0.43, 0.99)
Mx	0.0774 (0.0604, 0.106)	0.317	0.94 (0.78, 1)
T^{Mx}	1.07 (0.903, 1.38)	−0.222	0.93 (0.71, 0.99)
D^{Mx}	0.861 (0.773, 1.02)	−0.108	0.90 (0.44, 0.98)
EG	0.125 (0.0976, 0.171)	0.201	0.94 (0.85, 0.99)
IET	10.7 (7.89, 14.4)	0.302	0.95 (0.8, 1)

stations with significant correlation at the 0.01 significance level. From the total number of 36 possible unique pairs of characteristics, given in the table are 10 pairs of characteristics, with the largest proportions of stations having significant correlation.

Strong negative correlation was identified between number of events and interevent time for all stations. Event rain rate significantly relates to intraevent gap (for 97% of the stations), event maximum (for 84% of the stations), duration (for 73% of the stations), and depth (at 44% of the stations) of an event. In addition, event depth strongly correlates with event maximum (for 99% of the stations) and duration (for 98% of the stations). The fraction of intraevent rainless periods is proportional to the duration of an event (at 81% of the stations). Finally, the fraction of event depth before maximum of an event relates to the event maximum (at 46% of the stations) and its relative timing (at 99% of the stations). Note that when ordered according to the fraction of stations with significant correlation, the correlation for the next pair of characteristics (rain rate, depth to peak) is significant only at ~30% of the stations, and the fraction of stations with significant correlation is below 25% thereafter.

The relationship between the correlation between characteristics and *mit* is somewhat complex. Figures 8a–c show (spatial) average correlation between characteristics for different *mit* values. For the sake of clarity, the pairs of characteristics are split into three groups according to the type of relationship to *mit*. For most of the characteristics, the correlation considerably decreases in value with *mit*, which also applies for negative correlations in the case of correlation between number of events and interevent time and between event rain rate and fraction of event gaps in Figure 8a. Figure 8b shows a group of characteristics for which strong correlation in the case of $mit = 30$ min decays relatively steeply until $mit = 360$–720 min and then remains more or less constant (except for correlation between rain rate and event maximum). This is typical for correlation between event depth and event maximum, rain rate, and duration and between event maximum and duration and time to peak and depth to peak. Similar weakening of correlation between rain rate and event maximum was also reported by Dunkerley (2010) for two stations in Southern Australia.

In the case of correlation of event duration to fraction of intraevent rainless periods and correlation between depth to peak and event maximum and rain rate (Figure 8c), the sign of the correlation coefficient changes from negative (in the case of $mit = 30$ min) to positive (for $mit > 360$ min). The opposite applies to the correlation between event duration and rain rate. This means that for large *mit* values, the rain rate is larger for short events and vice versa, while for small *mit* values, the event rain rate increases with increasing duration (see Figure 9), which is somewhat counterintuitive. Since the rain rate is inversely proportional to the fraction of event gaps (EG), a possible explanation follows from the relation of EG to event depth and duration. For small *mit* values, the fraction of event gaps is relatively small (~20%) and decreases with

Table V. Correlation between selected characteristics and the percentage and number of sites for which the correlation is significant at the 0.01 significance level. The last two columns give overall average correlation and average correlation considering only those sites for which the correlation is significant

	Significant [%]	Significant [−]	Mean correlation	Mean significant correlation
cor (n,IET)	100.00	122	−0.96	−0.96
cor (D,Mx)	99.18	121	0.77	0.78
cor (T^{Mx},D^{Mx})	99.18	121	0.66	0.67
cor (D,T)	97.54	119	0.61	0.62
cor (R,EG)	96.72	118	−0.60	−0.61
cor (R,Mx)	84.43	103	0.54	0.60
cor (T,EG)	81.15	99	0.48	0.53
cor (T,R)	72.95	89	−0.44	−0.50
cor (Mx,D^{Mx})	45.90	56	0.35	0.48
cor (D,R)	44.26	54	0.35	0.48

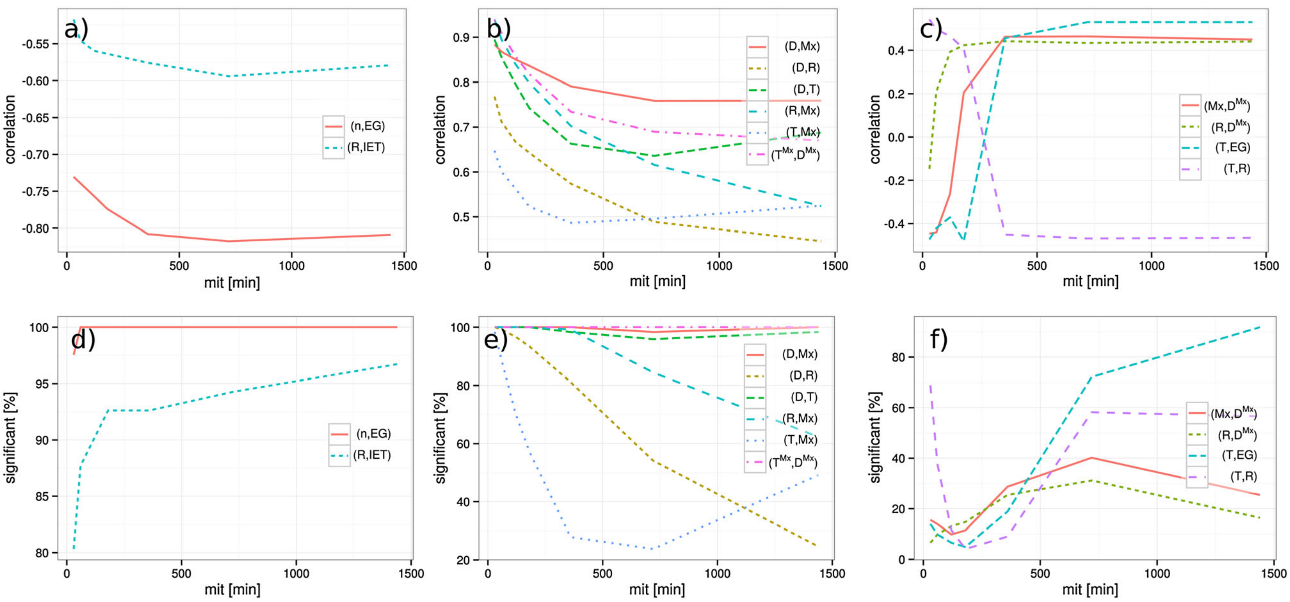

Figure 8. (a–c) Spatial average correlation coefficient for selected pairs of characteristics for different *mit* values. (d–f) Percentages of stations with significant correlation at 0.01 significance level for different *mit* values

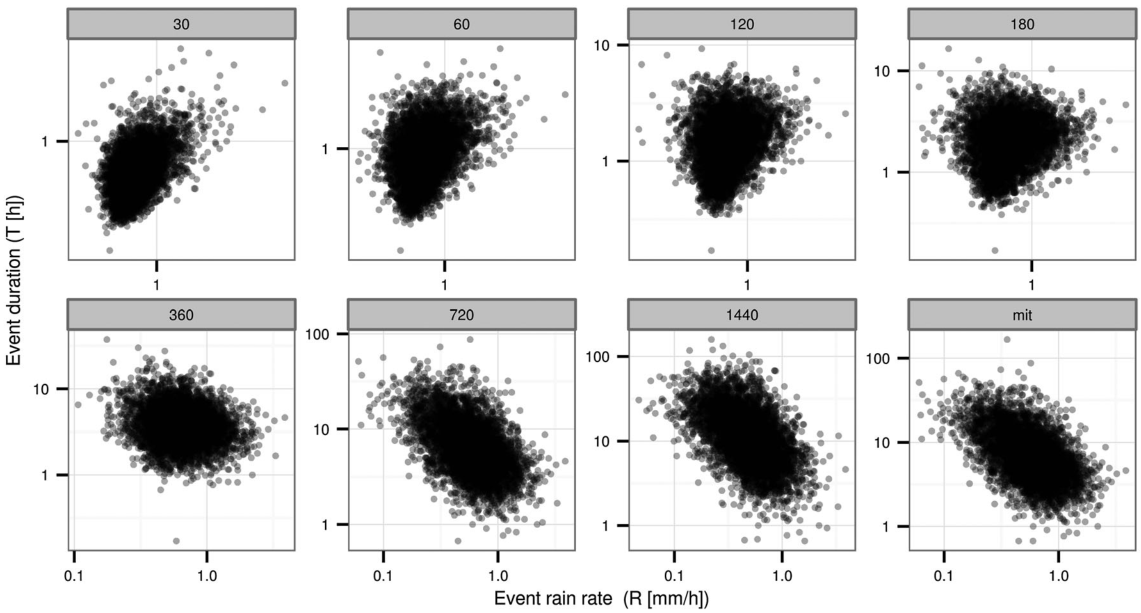

Figure 9. Correlation of event rain rate and event duration for all stations and months for $mit = 30$, 60, 120, 180, 360, 720, and 1440 min and $\hat{mit}$. The characteristics for each station have been scaled by the geometric mean. Note the logarithmic scales

event depth, and the event duration is slightly larger for events with small *EG*. For instance, the average event depth for events with $EG < 0.1$ is twice that for events with $EG > 0.1$. This implies that (for small *mit* values) the event rain rate is, to a large extent, determined by wet intervals, and especially for larger events. As a consequence, the event rain rate increases with increasing event duration.

For large *mit* values, the fraction of event gaps is larger than for small *mit* values (*EG* is more than 50% in the case of $mit = 1440$ min). Moreover, the fraction of event gaps increases with event duration. For events with $EG < 0.25$, for example, the average event duration is ~30% of that for events with $EG > 0.25$. In addition, the average event depth is also larger for events with larger *EG*. The event rain rate is thus greatly influenced by the presence of dry intervals, especially for long events.

Figures 8d and 8e show the percentage of stations with significant correlation at the 0.01 significance level for different *mit* values. The significance of correlation does not depend on *mit* for the relationships between number of events and interevent time, event depth and event maxima, event depth and duration, and time to peak and depth to peak. The percentage of stations with significant correlation does not vary much also for the correlation between rain rate and fraction of interevent rainless periods. The number of stations with significant correlation decreases with *mit* for event rain rate and event maximum, event rain rate and event duration, and event duration and event maximum. For the characteristics from Figure 8f, the correlation is significant at more than half of the area only for correlation between event duration and rain rate and fraction of intraevent rainless periods in the case of *mit* values larger than 600 min, for event duration and rain rate, the correlations are significant for more than half of the stations also for *mit* = 30 and 60 min.

Table VI. The linear dependencies of correlation decay distance (*CDD*) on *mit*; R^2 is the coefficient of determination

Characteristics	Model	R^2	*p*-value
n	−0.072 *mit* + 250.61	0.93	<0.01
D	0.053 *mit* + 31.00	0.96	<0.01
T	0.049 *mit* + 16.97	0.94	<0.01
R	−0.040 *mit* + 100.93	0.88	<0.01
Mx	0.017 *mit* + 81.51	0.81	<0.01
T^{Mx}	−0.0004 *mit* + 6.40	0.04	0.67
D^{Mx}	−0.0031 *mit* + 12.40	0.42	0.12
EG	−0.001 *mit* + 26.30	0.01	0.82
IET	−0.01 *mit* + 273.27	0.13	0.41

Interstation dependence

We estimated the interstation correlation of all rainfall event characteristics for all pairs of stations considering $mit = \hat{mit}$ and 30, 60, 120, 180, 360, 720, and 1440 min. The *CDD* values have been estimated using the exponential model from Equation (6) for the relationship between correlation and distance between the stations.

In the data set, the interstation distances range from ~1.7 to 477 km, and the mean distance between stations is 157.30 km. The average station has 11 neighbours within a distance shorter than 50 km, 35 neighbours closer than 100 km, and 87 neighbours closer than 200 km.

For $mit = \hat{mit}$, the correlation decay length is largest for interevent time (~272 km) and number of events (~187 km). For event duration, depth, rain rate, and maximum, the *CDD* is between 62 and 95 km. For the rest of the characteristics (time and depth to peak and fraction of event gaps), the spatial correlation is rather low, with *CDD* smaller than 22 km.

The relationship between *CDD* and *mit* was analysed for all characteristics using a simple linear model. The resulting formulas are given in Table VI. *CDD* decreases

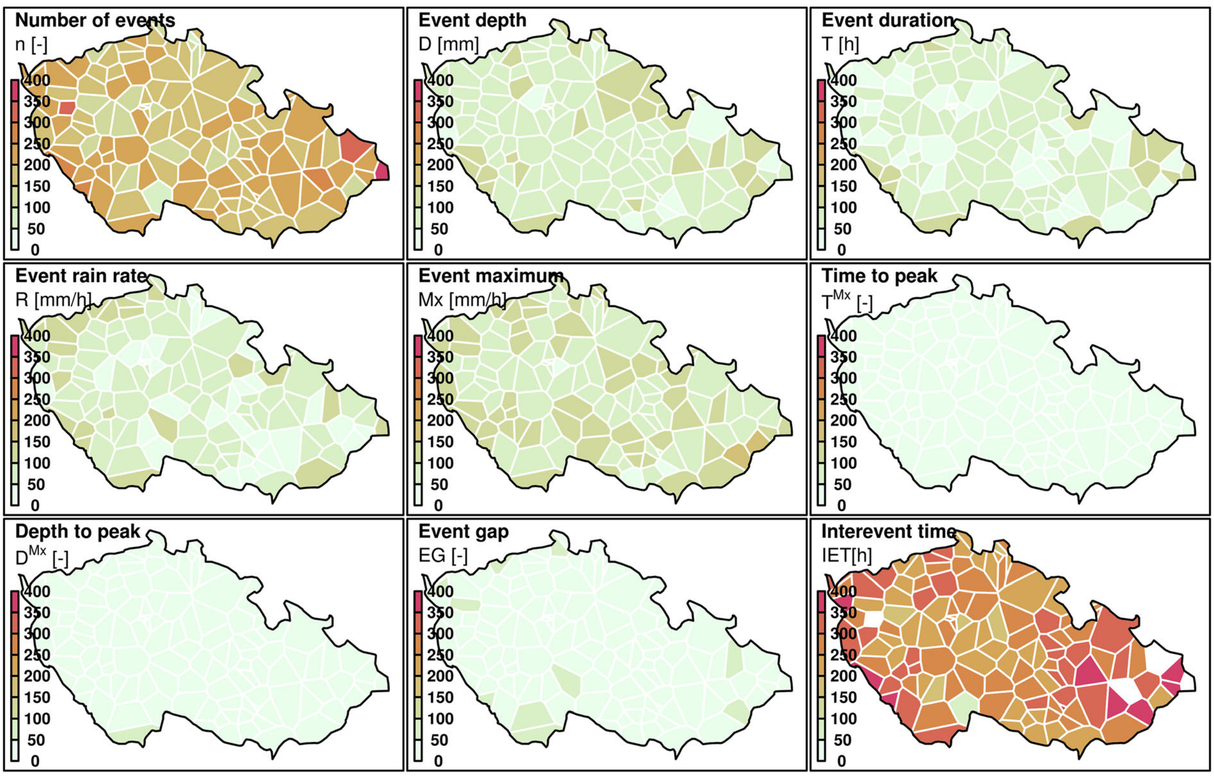

Figure 10. The spatial distribution of correlation decay distance (*CDD*) of all monthly mean rainfall event characteristics estimated for $mit = \hat{mit}$

significantly with *mit* for rain rate and number of events. For instance, considering *mit* = 30 min, the *CDD* for number of events is ~256 km, while for *mit* = 1440, it drops to ~144 km. Similarly, the *CDD* for event rain rate decreases from ~109 km for *mit* = 30 min to ~48 km for *mit* = 1440. Note that the spatial correlation for event rain rate is already rather small.

Although event duration, depth, and maximum intensity show significant increase of spatial correlation with increasing *mit*, the absolute differences in *CDD* values are relatively small across *mit* values also for those characteristics, with *CDD* usually less than 67 km. For instance, the range of *CDD* across *mit* values is 37–104 km for event depth, 48–109 km for event duration, and 90–108 km for event maximum. For time to peak, depth to peak, interevent time, and fraction of intraevent rainless period, the regression is not significant.

Finally, we estimated the *CDD* for all rain event characteristics (defined by $\widehat{mit}$) for all individual stations. For a station *i*, the *CDD* was calculated considering the correlation and distance between site *i* and all other sites. The spatial variability of *CDD* is given in Figure 10. The largest spatial variability is seen for interevent time (with mean *CDD* = 277 km and standard deviation = 60 km) followed by number of events (with mean *CDD* = 193 km and standard deviation = 45 km). For event depth, duration rain rate, and peak intensity, the absolute values of *CDD* for individual stations range from 20 km to 167 km. The spatial variability is rather small for depth to peak, time to peak, and fraction of event gaps.

SUMMARY AND CONCLUSIONS

In the present paper, we analysed the characteristics of rain events (number of events, event depth, duration, rain rate, maximum, time to peak, depth to peak, fraction of intraevent rainless periods [event gaps], and interevent time) in 10-year pluviograph records (1991–2000) for 122 stations in the Czech Republic from the warm part of the year (May–September). The events have been defined on the basis of *mit*. The impact of the choice of *mit* (in the interval of 30–1440 min) on various rainfall event characteristics, their at-site correlation, and (spatial) *CDD* was assessed.

As expected, the considered rain event characteristics depend significantly on *mit*. In particular, a decrease in number of events accompanied by an increase in event duration and depth with *mit* is clearly pronounced. The fraction of rainless periods within the events and between the events also increases with *mit*. The increase of the fraction of event gaps is, to a large extent, related to a decrease in event rain rate. However, the changes of event rain rate with *mit* are, on average, relatively small. The scaling of rain event characteristics with *mit* is not very different over the whole study area for most of the characteristics, i.e. the relation of characteristics to *mit* can be summarized by a single (station-independent) parameter. More complex relationships to *mit* have been found for rain rate and depth to peak.

In addition, the *mit* providing, on average, independent arrivals of rain events has been estimated ($\widehat{mit}$) for each station, with the estimated values varying between 426 and 1055 min. These estimated values have been further used for the assessment of the relations between the average rain event characteristics and altitude, rainfall total, and easting and northing. While the spatial variation of most of the characteristics can be described by the average rainfall total and altitude, the models considering average rainfall depth consistently outperformed the altitude-based models. In addition, considerable dependence of some of the characteristics on the geographic location was revealed. This is most likely related to the combination of continental, Atlantic, and Mediterranean influences on climate in the Czech Republic. Except for the average event depth, event maximum intensity, and interevent time, the spatial relations are, however, weak and especially so for rain rate, fraction of event gaps, and depth to peak.

The spatial correlation was described using the exponential correlation decay model with *CDD* as a parameter. The spatial correlation is large for number of events and interevent time, and considerable spatial dependence was also revealed for event duration, rain rate, and maximum intensity. *CDD* varies with *mit* for all characteristics except interevent time, depth and time to peak intensity, and event gaps. The spatial distribution of *CDD* for $\widehat{mit}$ shows the highest absolute values for interevent time and number of events.

Also assessed were correlations between rain event characteristics. The correlation coefficients were significant among rain event depth, duration, rain rate, and event gaps, as well as between number of events and interevent time. A surprising relationship was found between rain rate and event duration, with a different sign of correlation for different *mit* values. For *mit* = 30 min, the rain rate increases with duration. This is related to the intermittency of rainfall, since the fraction of event gaps is, in general, small for short events and the rain rates for short events are then defined mainly by wet intervals, which is not the case for large *mit* values. The importance of rainfall intermittency on characteristics such as event rain rate has been stressed by Dunkerley (2010), and its relevance for soil erosion studies is also reflected in the classical Universal Soil Loss Equation methodology, since the rainfall erosivity is related to the event maximum and event rain rate (which, in turn, accounts for fraction of rainless periods).

The rain event characteristics and their spatial distribution and (inter)dependence are important for many rainfall impact assessment studies, such as on the soil erosion and runoff generation. Although the area under study is not very large, we believe that the findings can contribute to, for example, developing more sophisticated spatial models for rain event characteristics or their application to rainfall erosivity mapping or regionalization. We also confirm a strong dependence of the rain event characteristics and their interdependence and spatial dependence on the methodology used in defining the events.

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APPENDIX A

Bootstrap procedure for elimination of spatially dependent events

The procedure work on a data set of the event characteristics. The record of an event consists of the station name, unique identification of the event (*id*), the beginning and end of the event, and the considered event characteristics: event depth (D), event duration (T), event rain rate (R), event maximum intensity (Mx), time to peak (T^{Mx}), depth to peak (D^{Mx}), and fraction of intraevent rainless periods (EG). This is further denoted in the original data set. The procedure consists of successive elimination of the events that could belong to a same synoptic event from the original data set. Two events are considered to belong to the same storm when they occur within a time window w at a distance less than or equal to r km.

The procedure can be summarized as follows:

1. Create a sample data set as a copy of the original data set and move it to the first time window.
2. In the sample data set, identify all rainfall stations recording events within this time window.
3. Randomly select one of these stations.
4. In the sample data set, exclude all stations within an r-km neighbourhood of the selected station belonging to the same time window. Note that the events are eliminated by their *id*, i.e. events that have been once eliminated cannot appear in the following time window.
5. Repeat steps 2–4 until there are remaining stations recording events within the actual time window (that have not been excluded in previous step).
6. Move to the next time window and go to step 2.
7. Repeat steps 1–6 until the required number of bootstrap samples is generated.

In our application, the time window w was set to 1 day, which is four times larger than the average duration of an event. Since Brázdil and Štekl (1986) note that most of the precipitation events cover areas smaller than half of the Czech Republic, the radius of the neighbourhood r was set to 100 km, i.e. 31 416 km^2.