Novel indices for the comparison of precipitation extremes and floods; an example from the Czech territory

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Abstract

The paper presents three indices for evaluation of hydrometeorological extremes, considering them as areal precipitation events and trans-basin floods. In contrast to common precipitation indices, the weather extremity index (WEI) reflects not only the highest precipitation amounts at individual gauges but also the rarity of the amounts, the size of the affected area, and the duration of the event. Besides that, the aspect of precipitation seasonality was considered when defining the weather abnormality index (WAI) which enables the detection of precipitation extremes throughout the year. The precipitation indices were complemented with the flood extremity index (FEI) employing peak discharge data. A unified design of the three indices, based on return periods of station data, enables to compare easily inter-annual and seasonal distributions of precipitation extremes and large floods.

The indices were employed in evaluation of 50 extreme precipitation events, seasonally abnormal precipitation events, and large floods 1961-2010 in the Czech Republic. A preliminary study of discrepancies among historic values of the indices indicates that variations in the frequency and/or magnitude of floods can generally be due not only to variations in the magnitude of precipitation events but also to variations in their seasonal distribution and other factors, primarily the antecedent saturation. The events could be further studied with respect to circulation conditions, for example, by the circulation extremity index.

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Odstraněno: We proposed three analogous extremity indices based on the estimated return periods at individual sites and spatial averaging of the values; we optimized both the areal extent and the duration of individual events. The weather extremity index (WEI), the weather abnormality index (WAI), and the flood extremity index (FEI) were applied to the original precipitation data, the seasonally transformed precipitation data, and the runoff data to identify extreme precipitation events (EPEs), abnormal precipitation events (APEs), and extreme flood events (EFEs), respectively. We present 50 events of each type from the period of 1961–2010 in the Czech Republic and

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Odstraněno: Most of EFEs were produced by an EPE in warmer half-years, whereas fewer than half of the EFEs were produced by an APE in the remainders of the years because thawing can substantially enhance the discharge at those times. Most significant EPEs occurred in July and the first half of August, although their hydrological responses were also significantly influenced by the antecedent saturation and other factors. As a result, the accumulation of precipitation extremes during the 1977-1986 period produced less significant flooding than another accumulation after 1996. In general, the primary discrepancies between the magnitudes of EPEs and EFEs occurred in May and September, when consequent floods were usually much larger and smaller in relation to the WEI, respectively. The hydrological response to APEs was usually strong in December, whereas another accumulation of EFEs in March was usually not due to APEs. Neither precipitation nor flood extremes occurred from early April through early May. This

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1 Introduction

Precipitation is extensively studied due to its impacts on the hydrology, geomorphology, and economy of a given region. Precipitation extremes are of special interest because impacts rapidly increase with the precipitation extremity. There are three main concepts of extremity: severity, intensity, and rarity (Stephenson, 2008). Evaluation of the extremity of past events enables to determine return periods of heavy precipitation and to estimate the probable maximum precipitation (Řezáčová, 2005b). Currently, the main challenge in precipitation climatology is understanding past and possible future changes in the frequency and/or magnitude of precipitation extremes (e.g., Alexander et al., 2006). These changes could alter the frequency and/or magnitude of consequent floods. To properly assess this linkage, we need to define quantitative indices to investigate the coupling between precipitation extremes and flood events.

Floods are frequently evaluated by their severity, which can be defined as the amount of socioeconomic loss or number of casualties. For example, Barredo (2007) selected 23 flash floods and 21 river floods during the period of 1950-2005 in Europe based on two criteria: losses exceeding 0.005 % of EU GDP and/or more than 70 casualties. In contrast, severity can hardly be used for evaluation of precipitation events because the damage is usually produced not directly by the precipitation but by subsequent phenomena (floods, landslides, etc.). Moreover, factors of exposure and vulnerability can produce serious discrepancies between causes and consequences.

The concept of intensity better corresponds to physical causes; thus, it is more convenient for comparison between precipitation extremes and floods. Rodier and Roche (1984) and lately Herschy (2003) assessed the world´s maximum floods with respect to their maximum instantaneous discharges. To compare the extremity of floods on various rivers, they used the Francou index, which normalizes the common logarithm of maximum discharge by the common logarithm of the catchment area. Not surprisingly, maximum floods were located in the rainiest regions.

The standard approach to the evaluation of precipitation intensity is to search data series from individual gauges using commonly accepted indices (Zhang et al., 2011), mainly those defined by the Expert Team on Climate Change Detection and Indices (ETCCDI). According to ETCCDI, precipitation extremes can be defined as days with maximum one-day (P_d) or five-day precipitation total in a period. Nevertheless, the duration of events can vary widely,

Odstraněno: we need to recognize various aspects of the relationship between extreme precipitation and flooding events

Odstraněno: There are many ways to evaluate precipitation and flooding depending primarily on the chosen concept of extremity. In general, three main concepts of weather extremes can be distinguished: severity, intensity, and rarity (Stephenson, 2008). ¶
Extreme flood events (EFEs)

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Odstraněno: (P_d) exceeding a threshold at any gauge in the region. This approach was also used in classic hydro-meteorological works in search of EPEs in the Czech Republic. Štekl et al. (2001) studied a set of days with $P_d \geq 150$ mm and their synoptic causes, seasonality, temporal distribution and other aspects. Based on this approach, the maximum Czech EPE occurred on 29 July 1897 when a P_d of 345.1 mm was measured at the Nová Louka gauge in the Jizerské Hory Mts. Indeed, this event was the maximum P_d recorded in Central Europe (Munzar et al., 2011).¶

and the precipitation intensity usually fluctuates during the event. Begueria et al. (2009) partly took account of this fact; they used declustering of daily precipitation totals to distinguish individual precipitation events and characterized them not only by magnitude and duration but also by peak intensity.

Even more important is the spatial aspect of precipitation events. They always affect a certain area; thus, precipitation extremes should be considered to be "regional events" (Ren at al., 2012). The latter approach is necessary if the intensity of precipitation and floods is to be compared, because the size of the affected area influences the hydrological response. In our previous paper (Kašpar and Müller, 2008), we used the concept of areal precipitation intensity and evaluated precipitation events based on the weighted average of daily areal precipitation totals on three consecutive days. Nevertheless, Konrad (2001) demonstrated that the extremity of an event depends on the size of the considered region. As a result, the areal average disadvantages events that were violent but affected only a part of the region over which the mean is taken (e.g., an administrative unit, a catchment).

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Odstraněno: In our previous paper (Kašpar and Müller, 2008), we used the concept of areal precipitation intensity and evaluated EPEs based on the weighted average of daily areal precipitation totals on three consecutive days.

Based on the concept of intensity, extreme events occur mainly in regions that are prone to heavy rains (in the Czech Republic, such regions are along the northern state border because of the orographic precipitation enhancement). In order to reflect regional climatic differences, the concept of rarity is applied; extreme precipitation and floods can thus be detected in the whole studied region. The concept is frequently used with regard to floods, and the intensity (magnitude of the peak flow) is usually compared with return levels. If a set of extreme floods is studied, they are defined as discharges with return periods exceeding a threshold. Nevertheless, Uhlemann et al. (2010) noted that flood events frequently affect several independent catchments and introduced the concept of trans-basin floods. We adopted and adapted this approach to our data because we compared flood extremity with precipitation, which also affects more than one catchment at a given time.

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To enable this comparison, we propose indices analogous to each other that are based on the point estimates of return periods of precipitation totals and peak discharges and on spatial averaging of the values (Sects. 2.1 and 2.3). The method is further enriched by the aspect of precipitation abnormality with respect to the season (Sect. 2.2). We demonstrate the method using data from the Czech Republic and present three sets of events: precipitation extremes regardless and regarding of the season and extreme floods (Sect. 3.1). These sets are further

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compared with regard to their inter-annual (Sect. 3.2) and seasonal (Sect. 3.3) distribution. The results obtained are discussed in Sect. 4.

2 Proposed methods

We proposed three extremity indices that enable to compare the temporal distribution of precipitation extremes and floods. The indices are based on point return period estimates of precipitation totals and peak flows, respectively, spatial averaging of their values, and optimizing the areal extent and the duration of individual events.

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2.1 Evaluation of precipitation extremity

The weather extremity index (WEI) presented in detail by Müller and Kašpar (2014) was employed in searching for extreme precipitation events (EPEs). The WEI is based on return periods of 1-day to several-day precipitation totals at individual sites. We used data from 711 rain gauges with data series at least 20 years long between 1961 and 2010. The return periods were assessed using the generalized extreme value (GEV) distribution (Hosking and Wallis, 1997) because it was confirmed to be a suitable model for precipitation extremes in most regions of the Czech Republic (Kyselý and Picek, 2007). The GEV distribution was applied as the parametric model for annual maxima of the totals. Parameters of the GEV distribution were estimated by means of the L-moment algorithm (Hosking and Wallis, 1997) and the region-of-influence (ROI) method (Burn, 1990). The ROI method is based on 'homogenous regions', in which all regional data, weighted by a dissimilarity measure, are used for estimating parameters of the distribution of extremes at the site of interest. Although the application of the ROI method makes the estimations more robust than local analyses (Kyselý et al., 2011), we did not accept return periods longer than 1000 years. Instead, we set the return period to 1000 years.

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The next step in the method was the interpolation of return periods from gauges in a regular grid with a horizontal resolution of 2 km. (Experiments have demonstrated that the results are not affected by the resolution if it is constant across all studied events.) Because of the exponential nature of the GEV distribution from which the return periods are derived, we interpolated their common logarithms instead of pure return period values. We chose linear kriging as the interpolation method. Using an inversion transformation, we obtained cell values of N_{ti}, which represents the return period of the precipitation total accumulated during t

days in a cell i. The cells were then sorted in decreasing order with respect to N_{ti} and considered within a stepwise increasing area a of n pixels each representing 4 km^2.

The WEI was calculated by maximizing the variable E_{ta}. This variable is defined as the common logarithm of the spatial geometric mean G_{ta} of the return periods multiplied by the radius R of a circle of the same area as the one over which the geometric mean is taken. This relationship can be expressed as

$$E_{ta} = \log(G_{ta})R = \frac{\sum_{i=1}^{n} \log(N_{ti})}{n} \frac{\sqrt{a}}{\sqrt{\pi}}. \qquad (1)$$

The optimization of a was performed using a step-by-step enlarging of the area under consideration. The variable E_{ta} initially increased as we accumulated cells with lengthy return periods; once the return periods were insufficiently long in the added cells, the value of E_{ta} started to decrease. When we chose a time window for which E_{ta} reached its maximum during the entire event, the respective maximum E_{ta} equaled the WEI. Then, we were also able to determine the affected area a, the duration t, and the respective geometric mean of return periods G_{ta} complying with the relationship E_{ta} = WEI. The method is presented in Fig. 1, which shows the EPE from May/June 2013, which was subsequently added to the study because of catastrophic flooding observed during this time (Šercl et al., 2013). Although the maximum return period at a site belonged to the 1-day total on 1 June (Horní Maršov, 130.3 mm, > 1000 yr), maximum E_{ta} gradually increased with increasing t. The WEI corresponded to the five-day period from 30 May to 3 June 2013.

Nevertheless, the time distribution of maximum E_{ta} values can be more complex. Figure 2 presents such a case from August 2002, when a subsequent EPE followed the previous one after a break of only three days. In this case, two distinct maxima of E_{ta} enabled us to recognize independent EPEs and determine the durations of both events (two and three days, respectively). Adding one or two more days caused the E_{ta} to decrease. However, if we had also considered an E_{ta} spanning a longer time window (7 days), then the two EPEs would have been aggregated. This example induces a question about values of the parameter t because it obviously cannot remain unlimited. We decided to consider precipitation events of the length from 1 to 5 days because the thresholds correspond with two main indices of precipitation extremes by ETCCDI (Zhang et al., 2011).

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Figure 2 also shows that the extremity of precipitation with respect to the maximum E_{ta} can substantially differ from the areal mean of daily precipitation totals throughout the Czech Republic. Although the mean was nearly twice as high on 11 August than on 6 August, the respective E_{ta} maxima were the same. The advantage of the concept of E_{ta} is that the considered area and the time window are "event-adjusted". Although comparably heavy rains were limited to the southwestern Czech Republic on both days, weaker rains occurred only on the latter day throughout the whole country. These non-extreme precipitation totals increased the mean, whereas they were not included in the E_{ta}.

Odstraněno: limit *t* to a value of equal or less than 5 throughout the study. This threshold appears to be appropriate for the Czech Republic but could be slightly higher if the method were applied to a larger area.¶

2.2 Precipitation abnormality with respect to the season

Both precipitation long-term means and extremes are not equally distributed among the seasons in most places on the Earth. In the Czech Republic, higher precipitation totals generally occur in summer (Tolasz et al., 2007). As a result, the WEI maxima are also concentrated in the summer. However, even smaller precipitation totals can be considered to be "extreme" when they occur in a season when they are rare. If precipitation extremes are defined as events significantly different from seasonally normal conditions, then they can occur throughout the year. Precipitation extremes of this type will be referred to as abnormal precipitation events (APEs). They were evaluated using the weather abnormality index (WAI), which has the same design as the WEI, although it is calculated based on seasonally standardized precipitation totals.

Odstraněno: during warmer half-years

The standardization of daily precipitation totals reflects their annual distribution. The mean, variance and skewness fluctuate significantly during the year (Fig. 3), and thus none of these parameters can be avoided in the process of standardization. The same is true for the kurtosis which is very closely correlated with the skewness (not depicted). Furthermore, means and standard deviations are also closely correlated. Therefore, our standardization method consists of removing fluctuations of the mean μ_d and the skewness γ_d from the daily totals on individual calendar days d.

There are two types of fluctuations in the data. First, μ_d and γ_d change significantly from day to day depending on the presence or absence of heavy precipitation episodes on a given calendar day during the period of 1961–2010. These random fluctuations have to be smoothed using a proper time filter. Monthly means are sometimes used for these purposes, but we have excluded this method as it produces artificial edges in the data. Moving averages are only slightly better from this point of view. We use the Gaussian filter because it is considered the ideal time domain filter (Blinchikoff and Zverev, 2001). We tested several data series to identify the most appropriate length of the filter and chose Gaussian smoothing with a standard deviation σ of 30 days and a time window of 3σ. Time-smoothed values of the mean and skewness are hereinafter referred to as μ_{dG} and γ_{dG}, respectively.

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Even the values of μ_{dG} and γ_{dG} fluctuate through the year because of seasonal changes in precipitation climatology. The actual daily totals P_d were standardized using the relationship

$$P_{ms} = \overline{P}\left(\frac{P_d}{\mu_{dG}}\right)^{\frac{\overline{\gamma}}{\gamma_{dG}}} . \qquad (2)$$

where P_{ms} is the seasonally standardized daily total, μ_{dG} is the time-smoothed mean, γ_{dG} is the time-smoothed skewness of the distribution of daily totals ≥ 0.1 mm for a calendar day d, and $\overline{P} = E(\mu_{dG})$ and $\overline{\gamma} = E(\gamma_{dG})$. The transformation (2) directly standardizes the mean and skewness and indirectly standardizes the standard deviation and kurtosis of the daily data. The correction using $\overline{P}$ and $\overline{\gamma}$ induces an important feature of seasonally standardized daily totals: their mean annual sum equals the actual mean annual total. This process only redistributes precipitation amounts within the data series: seasonally standardized daily totals become higher and lower in seasons that are less and more exposed to high precipitation, respectively.

An example from the mountain station Churáňov is presented in Figs. 3 and 4. The mean and skewness are at a maximum in the summer, whereas the winter is characterized by a minimum of smoothed means but a secondary maximum of the skewness. As a result, extreme totals are substantially reduced (approximately 30 %) by the dual standardization when they occur in the summer. The winter totals are increased (20 %) due to the standardization of means; the increase in the totals due to the standardization of the skewness is present primarily in the spring (15 %). Figure 4 confirms that both moments need to be standardized to obtain a rather even annual distribution of extremes throughout the year.

2.3 Evaluation of flood extremity

To compare the precipitation and flood extremity, we also designed the flood extremity index (FEI), which is analogous to the WEI and enables us to recognize extreme flood events (EFEs). The FEI is based on return periods of peak discharges at individual sites. The Czech

Hydrometeorological Institute provided data from 198 gauges beginning in 1961. However, only the approximate return period values of N = 5, 10, 20, 50 or 100 years were available. Each site represents a catchment with an area exceeding 100 km^2. If there are one or more considered sites upstream, the catchment area does not include the respective sub-catchments.

By analogy to the WEI, we combine the extremity at each site j expressed by the return period N_j with the area of the respective catchment a_j. The area of the basin indirectly represents the magnitude of the river. Return periods were considered without evaluating the possible human impact on peak discharge so the value of the FEI represents the actual course of the flood instead of the theoretical one. Nevertheless, the very high discharges that are crucial for the evaluation of an event are generally less affected by human activities (Langhammer, 2008).

The FEI is defined as the maximum of the variable F_a, which is given by the equation

$$F_a = \frac{\sum_{j=1}^{h} \left(\log(N_{ti}) a_j \right)}{a_a} \frac{\sqrt{a_a}}{\sqrt{\pi}} . \qquad (3)$$

The aggregated area a_a consists of h = 1, .., 198 considered catchments, which are ordered according to N_j in descending order. Return periods shorter than 5 years were assigned a value of N_j = 1 so that $\log(N_j)$ = 0 and the respective catchments do not contribute to the resultant FEI value.

The method is demonstrated in Fig. 5, which compares flooding due to the EPEs in August 1977 and in May/June 2013. The F_a curve representing the 2013 EFE increases more rapidly and starts to decrease later than in 1977; maxima of the curves depict values of the FEI. The reason is that return periods of peak discharges did not reach 50 years during the first event, whereas during the latter event, the total area of catchments corresponding to gauges with peak flows of $N_j \geq 100$ years exceeded 2000 km^2, and the value of a_a corresponding to the FEI was larger. Unlike in Fig. 1, the curves are not fluent because only discrete values of N_j were used (see above). Because of similarities between Eqs. (1) and (3), the WEI and the FEI reach values of the same order. Nevertheless, values of the FEI are usually slightly smaller for several reasons, primarily because all return periods between two values (20 and 50 years, for example) are assigned the lower value. Moreover, the maximum values are 100 and 1000 years when calculating the FEI and the WEI, respectively.

Odstraněno: , which can make the results slightly inaccurate. However, There is a question regarding the manner in which the FEI design can affect the results. Therefore, we also calculated a simpler index that only aggregates areas of affected catchments weighted by return period values of peak discharges. An approximate (non-linear) correlation between the two indices was noted, which indicates that the FEI concept is sufficiently robust.

A serious problem is the separation of individual EFEs if additional peaks occur during a short period in the same catchments. We decided to separate EFEs with respect to EPEs. For example, we distinguished two EFEs in August 2002 because they were produced by two independent EPEs (Fig. 2). Naturally, the extremity of the latter EFE was affected not only by the latter EPE but also by the previous one in such a case; this fact can partly explain the discrepancies between the extremity of precipitation and of subsequent flooding.

2.4 Comparison of precipitation extremes and floods

Extremity of precipitation and of subsequent flooding were compared using the normalized ratio of respective extremity indices:

$$C_e = 100\frac{FEI}{WEI}. \quad (4)$$

and

$$C_a = 100\frac{FEI}{WAI}. \quad (5)$$

Values significantly above and below average resulting from Eqs. (4) and (5) indicate that the hydrological response to the precipitation event was most likely affected by factors other than only the extremity of precipitation. One of these factors may be antecedent saturation. This parameter was expressed using the antecedent precipitation index (Köhler and Lindsley, 1951) spanning 30 days (API_{30}) before the first day of the EPE/APE, which is calculated using the relationship

$$API_n = \sum_{i=1}^{n} P_i\, k^{n-i+1}. \quad (6)$$

where P_i is the daily total during the i-th day of the period under consideration spanning n = 30 days, and 0.93 is the generally accepted value of the constant k for the Czech Republic (Brázdil et al., 2005).

One of important climatological aspects of EPEs, APEs, and EFEs is their seasonal distribution. To analyze this distribution, we adopted the directional characteristics method (e.g., Black and Werritty, 1997), which was applied also to selected Czech rivers by Čekal and Hladný (2008). Individual extreme events were depicted by vectors aiming from a point in various directions representing calendar days when they occurred. The mean of the vectors indicates the mean day representing the seasonal centroid of the phenomenon under consideration. Moreover, the length of the resultant vector is proportional to the inequality of the distribution of events throughout the year. In contrast to the above mentioned papers, we modified the method so that vectors representing individual events were not of the same lengths but they were proportional to the WEI, WAI, or FEI. The resultant vectors better represent the seasonality of extremes because strong events are assigned greater weighting.

Odstraněno: In studying the sets of extremes, we considered not only the frequency but also the extremity of the events. Therefore,

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3 Application to the Czech Republic

3.1 Precipitation extremes and floods

Although the WEI, the WAI, and the FEI itself are independent of thresholds, it was necessary to limit their values to constrain the sets of events that would be classified as EPEs, APEs, and EFEs. This step was performed because there are no natural limits dividing extreme from non-extreme events. In fact, the extremity of events gradually decreases with even smaller differences among the events as less-extreme events are considered. We selected the 50 events of each type so that one extreme event occurs per year on average. Sets of EPEs, APEs, and EFEs during the period of 1961–2010 in the Czech Republic are listed in Fig. 6.

The sets of EPEs, APEs, and EFEs partly overlap. We identified 22 precipitation extremes that were classified both as EPEs and APEs. More than a half of the EPEs and nearly 50 % of the APEs produced EFEs. If only the warm half of the year is considered, the number of EFEs produced by EPEs increases to 75 %. Nevertheless, we also identified cases in which the hydrological response to an EPE was too small or too big. These discrepancies will be further discussed in Sect. 4.

Odstraněno: These findings indicate that the proposed indices reasonably reflect the extremity of the studied phenomena.

3.2 Inter-annual variability of extremes

The temporal distribution of extreme events during the period of 1961-2010 is shown in Fig. 7. Regardless of the type of extremes (EPEs, APEs, and EFEs), there are certain common features of their variations in time. One such feature is the below-normal frequency and magnitude of all types of extremes during the first 16 years of this time period. The situation dramatically changed in 1977, when three EPEs occurred in the span of less than one month; two of these were so strong that they also qualified as APEs and produced EFEs (Fig. 6). Similar conditions occurred during the following two years. Moreover, the second and the fourth highest values of the WEI were recorded in July 1981 and 1983, respectively. The wet years of 1985-6 ended a decade of all types of extremes with above-normal frequency and magnitude.

Odstraněno: The accumulated values of all three indices reached only approximately 15 % of their values for the entire period, whereas this 16-year time interval (1961–1976) spans 32 % of the studied period.¶

Odstraněno: During the five-year period of 1977-1981, 8 EPEs, 9 EFEs, and 10 APEs occurred. After three unremarkable years, t

In contrast, the following decade of 1987-1996 was lacking in hydrometeorological extremes. EFEs were completely absent from the warm half-years (MJJASO) and did not occur again until 1996. The rest of the 1990s would also be considered to be below normal if July 1997 were not included. The first of two EPEs in this month exhibited maximum values of both the WEI and WAI. Similar values were also observed five years later, in August 2002. Compared to similarly strong precipitation events in the early 1980s, these two events produced much greater flooding. Last five years of the study period were characterized by an abnormally high number of extremes, which were concentrated primarily in 2006 and 2010. If the 2013 flood were considered, four maximum EFEs occurred recently approximately every five years.

Odstraněno: EPEs were generally weaker than APEs during this dry period and produced no flooding.

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Odstraněno: During the period of 2003-5, again no EPEs and EFEs occurred during the warmer half-years. Finally, the l

Odstraněno: (three EPEs and four EFEs in each of these years)

3.3 Seasonal distribution of extremes

The seasonal distribution of EPEs was significantly unequal during the period of 1961–2010 (Fig. 8). Based on the selected threshold, these events occurred from May through December of any given year. Nevertheless, only two such events occurred since October, both being rather weak and lasting five days. The months of greatest activity were clearly July and August, when the four highest values of WEI were noted. The level of activity during the first half of August was particularly pronounced: this time period was the seasonal peak in EPEs during the period of 1961–2010.

Odstraněno: In contrast, short events (1–2 days) occurred only from late May through early September. EPEs were as frequent in May as in September, but they were generally less extreme in May (WEI only up to 70). ¶

Odstraněno: Nevertheless, there was a difference in the frequency of EPEs between July (9 events) and August, when they occurred twice as often. If another threshold were considered (e.g., WEI = 50), the dominance of August would be even more pronounced.

Odstraněno: As a result, the mean day of the seasonal distribution of EPEs is 27 July.

Naturally, APEs were distributed more equally from season to season during the 1961–2010 period than were the EPEs (Fig. 8). We noted at least one event in every calendar month. From October to March, the distribution of APEs was very uniform in terms of both the number of events and the magnitude. The values of the WAI were less than 100 with only one exception, which occurred during the 5 days from 28 December 1986 to 1 January 1987. This event was so exceptional that it also qualified as an EPE (see above). In contrast, only one

Odstraněno: (3–5 per month)

APE was noted in April. This event and two others in the first half of May lasted only one day each.

The seasonal distribution of EFEs partly correlates with the seasonality of precipitation extremes, but it is also significantly affected by snow accumulation during the winter and by changes in the saturation of basins. As a result, we identified three main periods when the frequency of EFEs is increased: (i) the period from May to August, when most of the EPEs occur; (ii) the second half of December and early January, when the values of the WAI are slightly increased in comparison with the months before and after; (iii) March and very early April, when the values of the WAI are not very high. Mainly the last period is affected by thawing. The rest of April is characterized by a distinct break both in precipitation and flood events. As in the winter apart from December, only weak EFEs occurred during the fall, when, in contrast, APEs were frequently noted. September appears to be the month with maximum differences between precipitation and flood extremity because; although several high EPEs were noted then, the EFEs remained small.

Odstraněno: Another significant feature of the seasonal distribution of APEs during the 1961–2010 period was the lower number of such events in June and July. Apart from 3 EPEs with values of the WEI exceeding100, which also qualified as the largest APEs, less significant EPEs dropped below the threshold of the WAI. However, August remained the most represented month, with 8 APEs. Even greater values of the WAI in excess of 100 were noted in September. This finding is most likely due to the significant decrease in mean precipitation in September, which results in such events being abnormal during this month. As a result, the mean day of the seasonal distribution of APEs is 5 October, although the length of the resulting vector is very small.¶

4 Discussion of results

The presented evaluation of precipitation extremity can be compared with the standard approach based on maximum daily totals recorded at individual gauges because Štekl et al. (2001) analyzed days during the period of 1876–2000 when a daily total reached at least 150 mm anywhere in the Czech Republic. Based on this approach, the maximum Czech EPE occurred on 29 July 1897 when a P_d of 345.1 mm was measured at the Nová Louka gauge in the Jizerské Hory Mts. Indeed, this event was the maximum P_d ever recorded in Central Europe (Munzar et al., 2011).

During the 40 years that overlap with our study, the authors identified 18 such days, 13 of which were days when EPEs occurred. Because of the high autocorrelation of the daily precipitation time series, on several occasions, this threshold was exceeded on two or even three consecutive days with an EPE. In contrast, there were many significant EPEs without daily totals exceeding 150 mm. These included the second largest EPE, in July 1981, which was characterized by a daily maximum of only 122.0 mm but produced the third largest EFE during MJJASO (Fig. 6). A still lower daily maximum (only 97.6 mm) was recorded on 2 September 1890. However, the 3-day areal precipitation totals were nearly as high in 1890 as in August 2002, and flooding was only slightly less catastrophic (Řezáčová et al., 2005a).

Odstraněno: the warmer half-years

These two examples demonstrate that it is necessary to take into account both the spatial extent and duration of precipitation events to make valid comparisons with consequent floods.

Nevertheless, there are still discrepancies between the WEI and the FEI and even greater discrepancies between the WAI and the FEI values. For example, the fourth largest EPE did not produce an EFE in August 1983; in fact, this EPE resulted in very limited flooding (C_e = 8 %, see Fig. 6). Several factors affected the hydrological response of this event. These include unusually low antecedent saturation (mean API_{30} only 9.3 mm!) and a moderately even distribution of rainfall over five days, whose maximum occurred on the second day of the event. Regulation processes by the dams could also play a role; nevertheless, Brázdil et al. (2005) confirm that no even unaffected peak flow with the return period of two or more years occurred at Vltava River in Prague even though the catchment belonged to the most affected by heavy rains.

All these factors will be studied in the future together with spatial patterns of precipitation to elucidate the discrepancies between individual precipitation and flood events. One of the factors to be considered should be the season when an EPE occurred, as discussed in Sect. 3.3. The important role of this factor is confirmed by Fig. 9. It is clear that the hydrological effect of an EPE is typically strong in May, more ambiguous in summer, and considerably weaker in September. The very last event from the turn of May and June 2013 also supports this conclusion (C_e = 96 %, see Fig. 6). If an EPE occurs in the last month of the year, it also appears to produce flooding, although such events are very rare.

Odstraněno: T

The hydrological effect of APEs (Fig. 9) is substantially reduced in the winter, early spring (most likely due to precipitation in the form of snow) and autumn. In contrast, if precipitation events are sufficiently high to qualify as APEs in the late spring and summer, they are usually flood producing; surprisingly, this is also the case with most APEs in December. A subsequent detailed study of intra-annual variations in precipitation patterns is necessary to explain these findings.

However, seasonality can hardly explain the difference in flood activity between two periods with unusually high EPEs (1977–1986 and 1997–2010). The FEI exceeded 50 in association with only two EFEs during the first period, whereas this occurred six times since 1997 (Fig. 7). Several factors most likely explain the difference: (i) if two or more EPEs appeared during one year in the first period, they were separated by a much longer interval than in the latter period (the shortest interval between two EPEs was 8 days in 1977 but only 3 days in 2002);

(ii) in cases of EPEs following one after another, the magnitude decreased in the first period (WEI decreasing from 113.5 to 38.3 in July/August 1977) but increased in the second period (WEI increasing from 104.2 to 172.3 in August 2002); (iii) just before the main EPEs, the mean antecedent saturation was much lower on 17 July 1981 (24.6 mm) and on 1 August 1983 (9.3 mm) than on 4 July 1997 (34.5 mm) and on 11 August 2002 (50.1 mm because of the above-mentioned preceding EPE); (iv) the EPEs in 1981 and 1983 lasted one day longer than those in 1997 and 2002. It demonstrates that changes in a flood regime can also occur without significant changes in only the magnitude of precipitation events.

5 Conclusions

The paper presents three indices for evaluation of hydrometeorological extremes. In contrast to common indices, the presented indices reflect not only maxima of precipitation amounts and peak discharges at individual gauges but also the rarity of values, the size of the affected area, and the duration of precipitation. Besides that, the aspect of precipitation seasonality was considered which enables the detection of precipitation extremes throughout the year. A unified design of the presented indices enables to compare easily inter-annual and seasonal distributions of precipitation extremes and large floods.

The application of the indices to the Czech territory demonstrates that this approach enables to compare the extremity of precipitation and consequent floods rather than if precipitation events are evaluated only by the maximum precipitation total at one station. Extreme floods correspond to precipitation extremes; nevertheless, not only the magnitude of precipitation extremes influences the hydrological response but also the season, the antecedent saturation and other factors. The study confirms that variations in the frequency and/or magnitude of floods can be due not only to variations in the magnitude of precipitation events but also to variations in these factors.

Additional detailed studies are necessary for elucidating the way in which seasonality influences the hydrological effect of precipitation extremes. This effect could be due to seasonal differences in evapotranspiration or to possible seasonal variations in the attributes of the precipitation itself. The events can differ, e.g., in the spatial distribution of precipitation within the affected area or in the temporal concentration of precipitation during the event (intensity can increase, remain the same or decrease). In addition, various circulation conditions could explain the differences among the extremes (Kašpar and Müller, 2010). In a

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Odstraněno: , precipitation extremes should be evaluated considering not only maxima at individual sites but also the spatial extent, duration and temporal concentration of the precipitation.

Odstraněno: . Although most of the EFEs were produced by an EPE in warmer half-years, fewer than half of all EFEs were produced by an APE because thawing can substantially enhance the discharge. Most significant EPEs occurred in July and the first half of August, but their hydrological responses were also significantly influenced by

Odstraněno: As a result, the accumulation of precipitation extremes during the 1977-1986 period produced less significant flooding than another accumulation after 1996. In general, the primary discrepancies between the magnitude of EPEs and EFEs were noted in May and September, when consequent floods were usually much larger and smaller in relation to the WEI, respectively. The hydrological response to APEs was usually strong in December, whereas another accumulation of EFEs in March was usually not due to APEs. Neither precipitation nor flood extremes occurred from early April through early May. ¶

Odstraněno: ir seasonal distribution and other factors, primarily the antecedent saturation next step, we plan to explore the dependences on the circulation extremity index (Kašpar and Müller, 2014), which completes the set of tools for studying the pathway of causation from circulation to precipitation and runoff.

Acknowledgements

The research presented in this study is supported by the Czech Science Foundation under the GACR P209/11/1990 project. Precipitation data were provided by the Czech Hydrometeorological Institute. We would also like to thank J. Kyselý and L. Gaál from the Institute of Atmospheric Physics in Prague for implementing the ROI method.

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Figure captions

Figure 1. Determination of the WEI of the EPE in May/June 2013 by maximizing E_{ta}. The inset maps present interpolated return periods of 1-day totals on 1 June (left) and of 5-day totals from 30 May to 3 June (right).

Figure 2. Mean daily precipitation totals P_{mean} in the Czech Republic (right axis) and respective maximum values of E_{ta} on 4–13 August 2002 (color bars, left axis). Selected maximum E_{ta} values for time windows with various lengths of t days are depicted including the hypothetical value of maximum E_{ta} for the 7-day period of 6–12 August.

Figure 3. Annual cycle of the mean, standard deviation, and skewness of daily precipitation totals at Churáňov station. Individual points represent the values of the mean, standard deviation, and skewness, calculated for each calendar day taking into account the period of 1961–2010; curves depict data smoothed using the Gaussian filter.

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Figure 4. Daily precipitation maxima on individual calendar days at Churáňov station during the 1961-2010 period: non-standardized totals (P_d), totals standardized for the mean and variance only ($P_m = \overline{P} P_d / \mu_{dG}$) and fully standardized totals (P_{ms}). Dates of significant totals are indicated (day/month/yr).

Figure 5. Evaluation of extremity of floods in May/June 2013 and in August 1977 using the FEI. The step-by-step aggregated catchments are ordered in descending order with respect to return periods recorded there. The inset map presents return periods N_j of peak discharges at gauges in 2013; blue and green curves correspond to the main rivers and watersheds, respectively.

Figure 6. EPEs, APEs and EFEs in the Czech Republic, 1961–2010. Colors denote the assignment of events to one or more types of extremes; the ratios of the FEI to the WEI and to the WAI are designated the C_e and C_a, respectively. For comparison, an extra event from May/June 2013 is represented by values of the WEI and the FEI.

Figure 7. Temporal variability of extreme events, 1961–2010, in the Czech Republic. The red, blue, dark green, and light green symbols denote EPEs, APEs, EFEs during colder half-years (NDJFMA), and EFEs during warmer half-years (MJJASO), respectively. The symbol shapes denote the duration (# of days) of EPEs and APEs. The curves express relative cumulative

values (right axis) of the WEI, the WAI, and the FEI (dark green denotes all seasons, light green denotes warmer half-years only).

Figure 8. Seasonal distribution of extreme events in the Czech Republic, 1961–2010. EPEs were evaluated using the WEI (red), APEs using the WAI (blue), and EFEs using the FEI (green). Values of the indices are depicted by the distance of symbols from the center of the diagram. The shape of symbols depicts how many days the precipitation event lasted.

Figure 9. Relative magnitude of the hydrological response to individual EPEs (left) and APEs (right) with respect to their magnitude in different months (distinguished by colors).