



**Evaluation of
precipitation
extremes and floods**

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Evaluation of precipitation extremes and floods and comparison between their temporal distributions

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Abstract

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 compare their inter-annual and seasonal distributions. 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 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 their seasonal distribution and other factors, primarily the antecedent saturation. The differences could be further studied with respect to circulation conditions.

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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. 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 recognize various aspects of the relationship between extreme precipitation and flooding events.

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) 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 extreme precipitation events (EPEs) 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 seems to be the more promising for our purposes. 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

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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).

5 EPEs can then be defined most simply as days with a 1 day precipitation total (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
10 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).

Nevertheless, the duration of events can vary widely, and the precipitation intensity usually fluctuates during the event. Begueria et al. (2009) partly took account of this
15 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. Moreover, precipitation always affects a certain area; thus, precipitation extremes should be considered to be “regional events” (Ren et al., 2012). The latter approach is necessary if the intensity of precipitation and floods is to be compared,
20 because the size of the affected area influences the hydrological response. 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). In our previous paper (Kašpar and Müller, 2008), we used
25 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 only in regions that are prone to them. However, extreme precipitation and floods can occur anywhere on the Earth if a more-inclusive concept of rarity is applied. The concept is frequently used

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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.

To enable this comparison, we propose indices analogous to each other that are based on the estimation of return periods of precipitation totals and peak discharges at individual sites 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 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 analogous extremity indices that enable to compare the temporal distribution of various types of extreme events. The indices are based on the estimated return periods at individual sites, spatial averaging of the values, and optimizing the areal extent and the duration of individual events.

2.1 Evaluation of precipitation extremity

The weather extremity index (WEI) was presented in detail by Müller and Kašpar (2014). The WEI is based on return periods of 1 to 5 day precipitation totals at individual sites. We used data from 711 rain gauges with data series at least 20 years long

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} .

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 during warmer half-years (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.

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 better from this point of view, but we preferred the use of the Gaussian filter in the manner of Kašpar et al. (2013) because of its still better

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performance. 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.

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

$$P_{ms} = \bar{P} \left(\frac{P_d}{\mu_{dG}} \right)^{\frac{\bar{\gamma}}{\gamma_{dG}}}, \quad (2)$$

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 $\bar{P} = E(\mu_{dG})$ and $\bar{\gamma} = E(\gamma_{dG})$. The transformation (Eq. 2) directly standardizes the mean and skewness and indirectly standardizes the standard deviation and kurtosis of the daily data. The correction using \bar{P} and $\bar{\gamma}$ 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.

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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, which can make the results slightly inaccurate. However, 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

$$F_a = \frac{\sum_{j=1}^h (\log(N_{tj}) a_j) \sqrt{a_a}}{a_a \sqrt{\pi}}. \quad (3)$$

The aggregated area a_a consists of $h = 1, \dots, 198$ 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

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of catchments corresponding to gauges with peak flows of $N_j \geq 100$ years exceeded 2000 km², 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.

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:

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

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

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 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.

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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. During the five-year period of 1977–1981, 8 EPEs, 9 EFEs, and 10 APEs occurred. After three unremarkable years, the wet years of 1985–1986 ended a decade of all types of extremes with above-normal frequency and magnitude.

In contrast, the following decade of 1987–1996 was lacking in hydrometeorological extremes. EPEs were generally weaker than APEs during this dry period and produced no flooding. EFEs were completely absent from the warm half-years 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. During the period of 2003–2005, again no EPEs and EFEs occurred during the warmer half-years. Finally, the last five years of the study period were characterized by an abnormally high number of extremes, which were concentrated primarily in 2006 and 2010 (three EPEs and four EFEs in each of these years). If the 2013 flood were considered, four maximum EFEs occurred recently approximately every five 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. In contrast, short events (1–2 days) occurred only from late May through early September. EPEs were as fre-

quent in May as in September, but they were generally less extreme in May (WEI only up to 70).

The months of greatest activity were clearly July and August, when the four highest values of WEI were noted. 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. 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. 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 (3–5 per month) 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 APE was noted in April. This event and two others in the first half of May lasted only one day each.

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 exceeding 100, 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.

The seasonal distribution of EPEs 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

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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.

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. 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 the warmer half-years (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). 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.

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

This study demonstrates that, compared to the extremity of floods, precipitation extremes should be evaluated considering not only maxima at individual sites but also the spatial extent, duration and temporal concentration of the precipitation. Extreme floods correspond to precipitation extremes; nevertheless, not only the magnitude of precipitation extremes influences the hydrological response. Although most of the EPEs were produced by an EPE in warmer half-years, fewer than half of all EPEs 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 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 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.

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

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in their seasonal distribution and other factors, primarily the antecedent saturation. 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 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.

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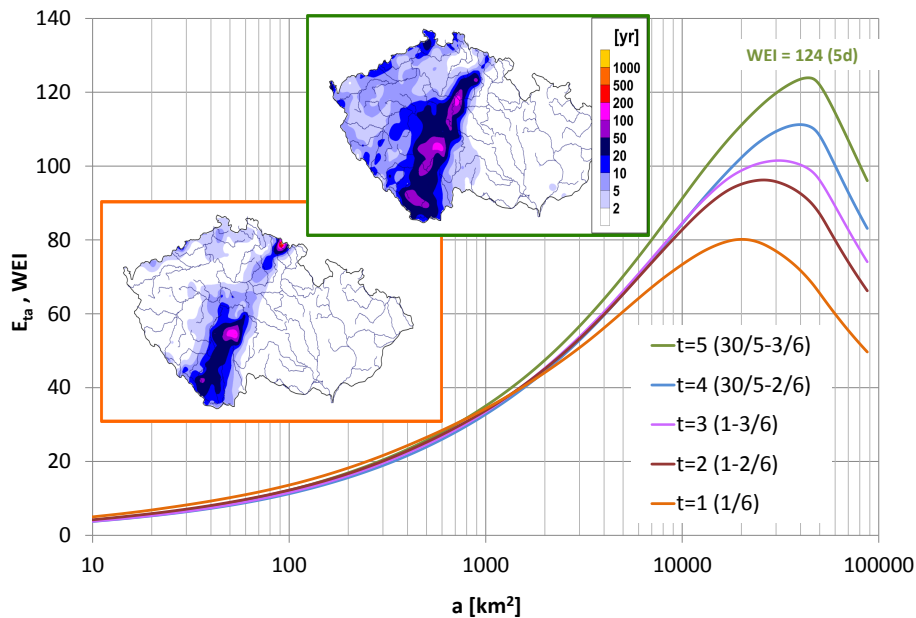


Figure 1. Determination of the WEI of the EPE in May/June 2013 by maximizing E_{t_a} . The inset maps present interpolated return periods of 1 day totals on 1 June (left) and of 5 day totals from 30 May to 3 June (right).

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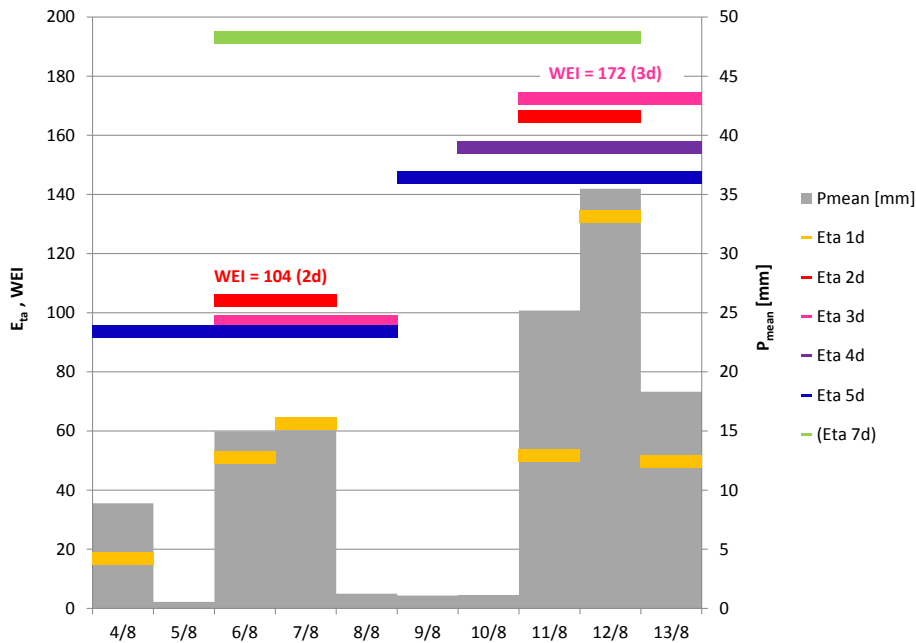


Figure 2. Mean daily precipitation totals P_{mean} in the Czech Republic (right axis) and respective maximum values of E_{ta} on 4–13 August 2002 (color bars, left axis). Selected maximum E_{ta} values for time windows with various lengths of t days are depicted including the hypothetical value of maximum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

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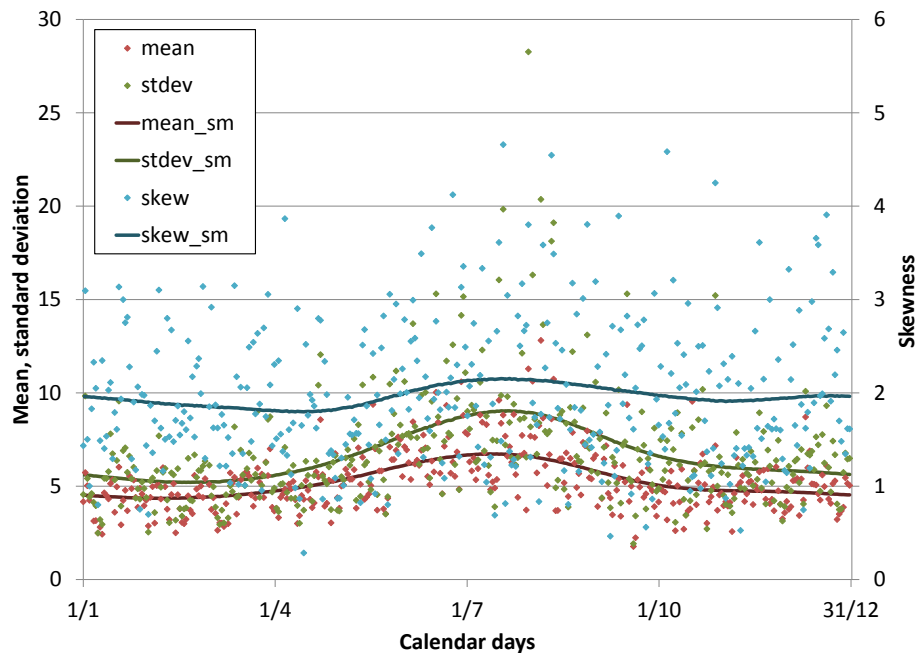


Figure 3. Mean, standard deviation, and skewness of daily precipitation totals on individual calendar days at Churáňov station during the period of 1961–2010; curves depict data smoothed using the Gaussian filter.

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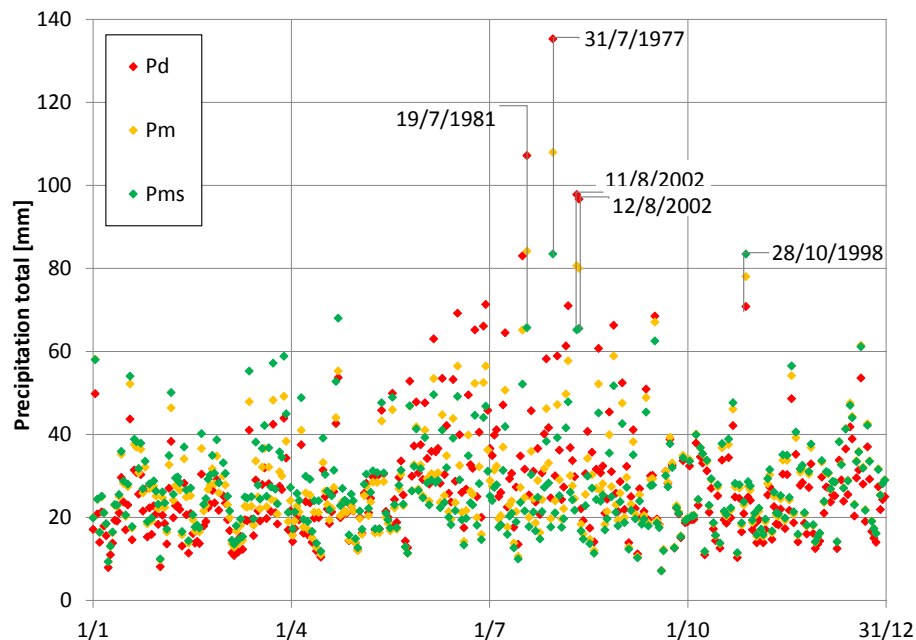


Figure 4. Daily precipitation maxima on individual calendar days at Churáňov station during the 1961–2010 period: non-standardized totals (P_d), totals standardized for the mean and variance only ($P_m = \overline{P_d} / \mu_{dG}$) and fully standardized totals (P_{ms}). Dates of significant totals are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

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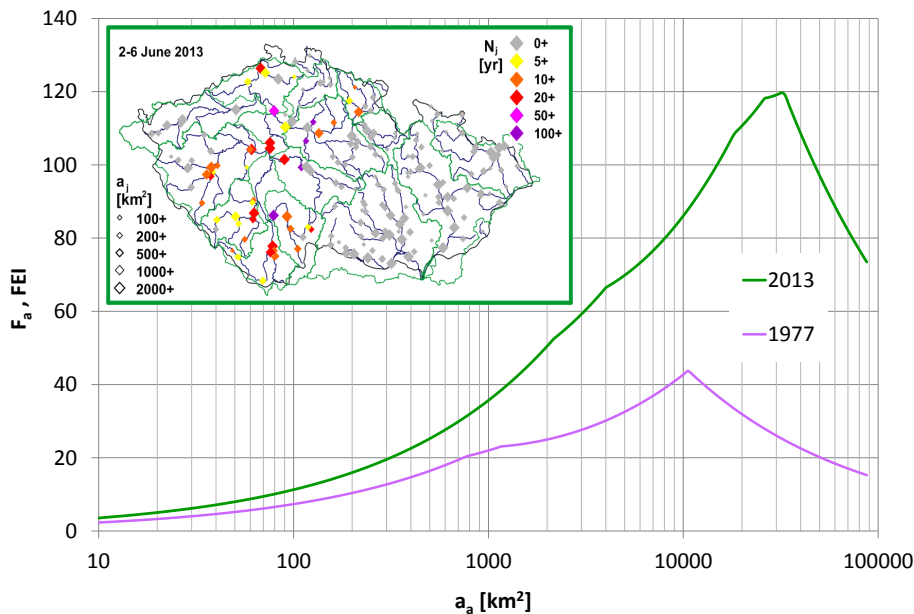


Figure 5. Evaluation of extremity of floods in May/June 2013 and in August 1977 using the FEI. The step-by-step aggregated catchments are ordered in descending order with respect to return periods recorded there. The inset map presents return periods N_j of peak discharges at gauges in 2013; blue and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

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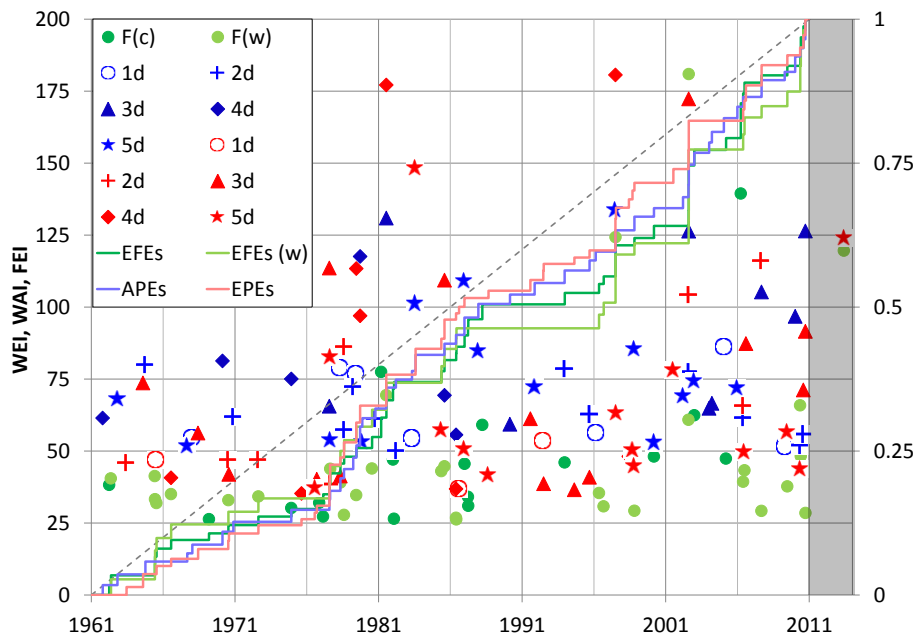


Figure 7. Temporal variability of extreme events, 1961–2010, in the Czech Republic. The red, blue, dark green, and light green symbols denote EPEs, APEs, EFEs during colder half-years (NDJFMA), and EFEs during warmer half-years (MJJASO), respectively. The symbol shapes denote the duration (# of days)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

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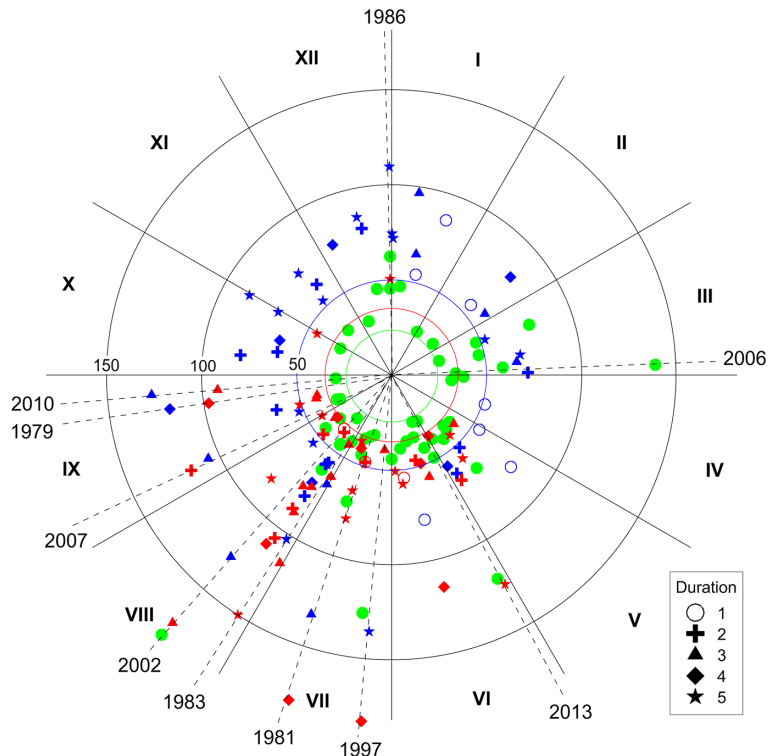


Figure 8. Seasonal distribution of extreme events in the Czech Republic, 1961–2010. EPEs were evaluated using the WEI (red), APEs using the WAI (blue), and EFEs using the FEI (green). Values of the indices are depicted by the distance of symbols from the center of the diagram. The shape of symbols depicts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

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