Responses to reviewer’s comments

First, we want to thank both reviewers for their comments and suggestions. On their basis, we have made several changes in the manuscript. Generally, we adjust our methodology to the method of Uhlemann et al. (2010) and Schröter et al. (2015) for our study area, compare different discharge limits and present a set of extreme floods with their main spatial and temporal characteristics. We add Oder basin into the evaluation of floods and adapt time period to 1951−2013.

Referee 1 comments:

Referee: The paper addresses the topic of identification of flood events in western and central Europe based on multiple series of mean daily discharge for a period of 61 years. Building on the method of Uhlemann et al. (2010) the authors aim to highlight the influence of different parameter choices on the the flood severity index which in turn influences the event identification. Extending the analysis of Uhlemann et al. 2010 to a larger study area, i.e. identifying a true central European event set of large flood events is a valid objective. However, the paper lacks scientifc rigour and presents little novelty on the event severity assessment. I therefore do not recommend the paper for further publication in HESS. In the following, I will outline my key criticism and encourage the authors to commence with their research on the important topic of understanding flood event frequency, severity and causes in central Europe. Uhlemann present a thorough sensitivity analysis of the severity index already and present the impact of different thresholds and input data on the resulting event set. The work presented by Gvoždíková only addresses the sensitivity of two parameters: subcatchment area and flood discharge limit (which is a threshold of flow expressed as the ratio of the peak flow at a gauge against the mean annual maximum flow of the entire time series at that gauge). The selection of the parameters and the chosen range in which they are being tested is not supported by argument. I.e., what is the hypothesis for defining the three variants of the thresholds of what is called the discharge limit (Qs/Qma; Qs/Qma>1.2; Qs/Qma >1.5)? Likewise, choosing either the subcatchment area, its root or logarithm as range for testing the impact of the spatial weight on the severity index is arbitrary.

Authors: Thank you for your comment that our main objective – evaluation of flood extremes without limits of state borders – is valid. Our motivation for modifications of the Uhlemann et al. (2010) index was the future comparison with precipitation extremes where the affected area is a necessary parameter. Nevertheless, we accept your comments regarding the methodology, see our next response. The threshold is set to return levels in the reconstructed paper.

Referee: The event sets identified are limited in a first step to 80 events, and then, for comparing results of the different variants of the index, to 30. Why is that so?

Authors: The first selection was done in order to eliminate less extensive floods. This step is removed. The set of 30 extreme floods is finally presented as we wanted to select one flood per two years on average.

Referee: My strongest criticism is with the principle choice of subcatchment area as spatial weighting factor to account for the relative contribution of a peak recorded at a river gauge to the overall flood severity. This is a classical regionalisation problem in hydrology. Subcatchment area however fails to address this problém and introduces a severe spatial bias into the analysis. Unlike precipitation, for which area indices are well suited, floods are not a space-filling phenomena. In particular, peak flows recorded at downstream gauges of the large streams Rhine, Elbe, to some degree Danube, Weser, and Meuse are in most cases not caused by inflow from their intermittent catchments but are a result of the flood wave propagating from further upstream. Also, when choosing subcatchment area, the density of the gauge network and particularly the uneven distribution of gauges in the river network becomes relatively more important in the severity index calculation and needs sensitivity testing. The original severity index presented by Uhlemann 2010, and also the application of the index in Schröter et al. 2015, provide a method for regionalisation of peak flows to the river network rather than to the subcatchments. I strongly recommend the authors to review their method for computing the spatial extent of the flood events in any further study.

Authors: We fully accept your comment and we recalculated our results with respect to the methodology by Uhlemann et al. (2010).

Referee: In summary, the conclusions reached on the best suited variant of the severity index and resulting event set need thorough reworking. In fact, I think, that the sensitivity study provided in Uhlemann et al 2010 provides all the necessary findings to allow for a fairly straight forward adoption of the severity index to the context of identifying flood events in central Europe. In the final paragraph of the paper the authors highlight that they want to commence with an analysis of the hydro-meteorological causes of large flood events in central Europe. I think, this is where the innovation will come and I highly encourage the authors to proceed on this avenue. The assessment of the severity of events and consequently the identification of the relevant flood events in the region can be natural part of any paper submitted on this.

Authors: Yes, analysis of hydrometeorological causes of central European floods will be the next step of our research. The focus of the reconstructed paper shift from the methodological issue to the analysis of the set of flood events. However, the discussion of the role of threshold remain a part of the paper because the thresholds play an important role in evaluation of floods within the large central European region.

Referee: On the aspect of analyzing severe floods in W/Central Europe in their frequency and severity and also in their spatial-temporal patterns and potential changes of these + attribution of these changes to causes: Reading the title I had expected to see the Odra basin included in the study. This basin forms the eastern boundary of the very wide transitional zone between atlantic and continental influences on flood genesis and at present I expect that in particular some of the summer flood events are insufficiently represented in the event set(s). Also, extending the event analysis to the most recent period, e.g. 2015, would add value to any change detection and finally attribution. In principle, I think Central Europe is the better description for the area under study.

Authors: We agree that Odra river should be studied together with other central European rivers. We extended the study area and partly also the study period according to your comment.

Referee 2 comments:

Referee: The study presented in this paper aims at redefining flood extremity indices over a large region between Western and Central Europe over the period 1950–2010. The approach followed consists of designing flood extremity indices by combining discharge values and the spatial extent of floods. Several versions of such indices were tested, with different weightings of the threshold value of discharge or area parameter for considering a flood event. The topic is suitable for publication in HESS but major revisions would be necessary in my opinion before the paper be published. General: - The paper lacks a discussion on the consistency of the choices to be made for designing the extremity indices (determination of Qs and the threshold Qs/Qma). There is almost no discussion about this point which constitutes the basis of the whole approach. Also, it seems from the discussion/conclusion section that the main difference between this work and previous other ones upon which the present study builds relies on the choice of the threshold selected for discharge: 1) this emphasizes even more the importance of strengthening the discussion on criteria for choosing the best suited Qs/Qma threshold, 2) it questions the value-added of including an area parameter in the approach (the authors themselves state that extremity indices are not very sensitive in changes in the area parameter: if so, then this approach is very similar to previous ones?).

Authors: Thank you for your comment. We changed discharge limits and use return periods for determining the event sets. Also, the subcatchment area is replaced by the length of river sections of certain order.

Referee: Conducting a more detailed study on the determinism of the occurrence of flood events seems important in order to relate the extremity indices defined to more concrete or practical hydrological/hydrometerological processes (in this sense it is surprising that the role of ground water is never even mentioned), it should be addressed here and would certainly constitute the value-added to other previous studies such as those of Uhlemann et al., etc. As a first step, the authors could try to relate the interannual variability and trends of extremity indices to some climate indices for instance.

Authors: The climatology of extreme flood events is just the first step of the research. The distribution of extreme flood events can be compared e.g. to some drought indices. This comparison and also the role of the antecedent wetness conditions are briefly mentioned within the discussion section.

Referee: Specific comments: - Title: Something like "large spatial extent floods" or "extensive floods" (as used in the introduction) could be included in the title to be more specific as it is an important aspect, and would prevent from using "trans-basin" which indeed could be misleading?

Authors: We included the term “extensive floods” in the title.

Referee: P.4, line 8: I don’t get why only the downstream sub-catchment area is considered when an upstream gauging station is available. The downstream station is still representative of flow occurring over the whole upstream area anyway unless the upstream part of flow is substracted.

Authors: You are right. One possibility would be to substract the upstream part of flow. On the other hand, the actual discharge at certain station cannot be ignored, as it is related to severity of flood in that place. However, on the basis of other comments, we used the length of river sections of certain order instead of subcatchment areas.

Referee: P.4-5, "Methods": I do not recommend using the word "significant" in this context, as this does not refer to any statistical meaning here. I think the rationale for using this method to determine a time series of "significant" discharge values lacks explanation.

Authors: We agree and remove the word from the text. Moreover, when using return periods as discharge limits, the identification of what we called “significant” mean daily discharges is released.

Referee: As well, I am concerned by the approach for determining a significant flood event: the choice of the length of the time window needs a little more explanation. As is, it looks like the method suffers from a lack of either statistical or deterministic basis, and the definition of a flood event seems to be too much data- and operator-dependent and notenough transposable (see for instance "After analyzing all of the data series, we chose a time window [...]"). The fact that the time window had to be extended for one river, or that an additional rule had to be included to prevent merging events that have different atmospheric origins is also problematic: is an automatic split of flood events in two parts when they are separated by 5 days enough to conclude to different atmospheric causes ?

Authors: The time window of 10/12 days was used because of time of propagation of flood waves downstream. For example, during the event of March 1979, it took 11 days from first detected peak to the 10-year discharge value observed at Ketzin station on Havel river. To simplify it, we use single time window of 12 days before and after the observed 10-year discharge. If two or more flood waves occur, it is clearly visible in time series - two peaks greater than 10-year discharge appear at several stations and the distance between these peaks at each station is at least 5 days. E.g. it was the case of August 2002 flood, when two flood waves were detected, which corresponds to other studies about this event.

Referee: P.5, line 19: does the separation date between the cold and warm halves of the year also hold for other regions than the Czech Republic?

Authors: We decided for this separation mainly because of flood in 1998, which started on October 29. This flood clearly belongs to cold half-year floods due to its meteorological causes. Nevertheless, we finally used more classic division when the cold half-year start in November and this particular flood can be listed in cold half-year as the mean day of the event (derived according to Black and Werritty, 1997) occur in November.

Evaluation of extensive floods in Western/Central Europe~~: the role of index design~~

Blanka Gvoždíková[1], Miloslav Müller[1,2]

[1]Faculty of Science, Charles University, Prague, Czech Republic
[2]Institute of Atmospheric Physics AS CR, Prague, Czech Republic

Correspondence to: Blanka Gvoždíková (blanka.gvozdikova@natur.cuni.cz)

Abstract. This paper addresses the identification and evaluation of extreme flood events in the transitional area between Western and Central Europe in the period 1951–2013 ~~1950–2010~~. Floods are evaluated in terms of three ~~several~~ variants on an extremity index that combines discharge values with the spatial extent of flooding. The indices differ in ~~two main aspects: the weight of the area parameter and~~ the threshold of the considered maximum discharges; the flood extent is expressed by a length of affected river network. This study demonstrates that ~~extremity indices are not highly sensitive to the changes in the design of the area parameter. On the contrary,~~ using the index with a higher flood discharge limit changes the floods' rankings significantly. It also highlights the ~~Due to a positive agreement with~~ high severity events.~~, we recommend using the index with a higher discharge limit.~~

In general, we detected an increase in the proportion of warm half-year floods when using a higher discharge limit. Nevertheless, cold half-year floods still predominate in the lists because they generally affect~~ed~~ large areas. ~~is usually large in the case of these floods.~~ This study demonstrates the increasing representation of warm half-year floods from the northwest to the southeast.

1 Introduction

Hydrological events, especially floods, are serious natural hazards in Western and Central Europe (Kundzewicz et al., 2005; Munich Re, 2015). Several extreme floods occurred in Western and Central Europe, e.g., in August 2002, January 2003, March/April 2006, and June 2013. The last was one of the largest in some river basins over the last two centuries (Blöschl et al., 2013).

In addition to river floods, flash floods affect this part of Europe, although these are mostly local events that usually produce less damage (Barredo, 2007). Therefore, we are interested in extensive floods affecting several river basins. Uhlemann et al. (2010) call these floods as trans-basin. They are usually triggered by persistent heavy rainfall and/or snowmelt. Differences in the causes of river floods can be detected between the western and central parts of Europe. Western Europe experiences flooding primarily during the cold half of the year due to zonal westerly circulation systems (Caspary, 1995; Jacobeit et al., 2003). Towards the east, warm half-year floods become more frequent. This is largely due to cyclones moving along the Vb pathway described by van Bebber (1891). These cyclones move from the Adriatic in a northeastern direction (e.g., Nissen et al., 2014), and the "overturning" moisture flux brings warm and moist air into the central part of Europe (Müller and Kašpar, 2010). However, it is not possible to delineate the borders of Western and Central Europe precisely with respect to differences in their flood events because of a broad transitional zone where both types of flooding occur.

An extremity index is useful for comparing individual flood events and determining their overall extremity. Various indicators and indices are used for the assessment of extreme events (including floods) and in their quantitative comparison. Different approaches are applied because the definition of event extremity is not uniform (Beniston et al., 2007), so various sets of extreme floods have been compiled in individual papers. The assessment of extreme floods is based on the quantification of human and material losses (severity), high discharge values (intensity), peak discharge return periods (rarity), or a combination of these indicators. The ranking of the largest floods can differ depending on which aspect of extremity was evaluated.

An assessment based on flood severity may be a simple way to evaluate a flood's extremity. Barredo (2007) identified major flood events in the European Union between 1950 and 2005 to create a catalogue and map of the events. He utilized two simple selection criteria: damage amounting to at least 0.005 % of EU GDP and a number of casualties higher than 70.

Other authors prefer evaluations based on the intensity or rarity of flooding because these aspects better reflect causal natural processes. Some authors classified floods into extremity classes based on the observed water levels (Brázdil et al., 1999; Mudelsee et al., 2003), which is most suitable for long-term pre-instrumental flood records. Water level values for individual flood events are at our disposal due to high water marks, chronicle records or other documents. This type of flood extremity evaluation was applied to the long-term flood records of the Basel gauge station on the Rhine river (Brázdil et al., 1999) and in the Elbe and Oder river basins (Mudelsee et al., 2003).

Additionally, Rodda (2005) used maximum discharges to express flood extremity in the Czech Republic. He considered the ratio of the maximum mean daily discharge to the median annual flood. This was completed for each station and flood event to study the spatial correlations among flood intensities in various basins.

Rarity can be used to compare extreme floods at different locations, when extremity is defined not by absolute thresholds (e.g., discharge values) but by relative ones (e.g., n-th quintile of the dataset). Keef et al. (2009) focused on the spatial dependence of extreme rainfall and discharges in the UK and used return periods to define extreme values. Their work confirms that it is possible to compare the event extremities at different locations, even when the actual discharge values vary considerably.

Comprehensive indicators of flood extremity typically combine some aspect of extremity or consider other factors, such as the areal extent or duration of events. When creating these indicators, researchers attempt to add information about flooding from all locations where it was observed. The Francou index k (Francou and Rodier, 1967; Rodier and Roche, 1984; Herschy, 2003) is one of the older indices that assesses flood extremity only at a particular station. In the Francou index, the common logarithm of maximum discharge is divided by the common logarithm of the catchment area (Rodier and Roche, 1984; Herschy, 2003). Among others, it was used to evaluate the largest floods in the World Catalogue of Maximum Observed Floods (Herschy, 2003).

Müller et al. (2015) designed a more complicated extremity index using return periods of peak discharges. They present 50 maximum floods in the Czech Republic for the period 1961–2010, which are identified based on the so-called flood extremity index (FEI) (Müller et al., 2015). In addition to the peak discharge return periods, the size of the relevant basin is considered for each location. The authors also suggested extremity indices other than the FEI that are applicable to precipitation events: the weather extremity index (Müller and Kašpar, 2014) and the weather abnormality index. Comparison of these indices with the FEI may aid in examining the relationship between precipitation and flood extremity (Müller et al., 2015).

To analyze the spatial and temporal distribution of floods in Germany, Uhlemann et al. (2010) developed a comprehensive method for the identification and evaluation of major flooding affecting several river basins. They used a time series of mean daily discharges and searched for simultaneously occurring significant discharge peaks comprising individual flood events. Their index accounts for the spatial extent of flooding (expressed by the length of the affected rivers) and discharge peak values exceeding the 2-year return value. The authors present 80 major flood events in Germany from 1952 to 2002.

Subsequently, Schröter et al. (2015) adopted the approach of Uhlemann et al. (2010) and compared several major floods in Germany. Their modified index compiled only those maximum discharges that exceeded the 5-year return value; the discharges were normalized by the respective 5-year return values and weighted by the portion of the affected river length. The final index equals the sum of these values from affected stations. Thus, the indices by Uhlemann et al. (2010) and Schröter et al. (2015) differ only in the threshold of the discharge values entered into the index calculation (2- and 5-year return values, respectively). However, Schröter et al. (2015) presented only the June 2013 flood extremity in comparison with two other major floods in August 2002 and July 1954. Because other major flood events were not presented for comparison, it is not possible to precisely identify the influence of this methodological change on their results.

The main aim of this paper is to present lists of extreme flood events from the period 1951–2013 and describe their spatial and temporal distribution. The flood events are selected on the basis of extremity indices with different thresholds of the considered maximum discharges. The discussion of the role of discharge thresholds on the floods' rankings is a part of the paper. ~~determine how changes in the flood evaluation methodology influence the results.~~ The presented indices are based primarily upon the approach of Uhlemann et al. (2010).~~, but their design is somewhat modified.~~ Each of the indices combine the flood discharge magnitude with the spatial extent of flooding.~~; differences lay in the discharge thresholds and input area parameters.~~

~~In addition to the sensitivity study, we present lists of extreme flood events from the period 1950–2010 and describe their spatial and temporal distributions.~~ The area of interest might be called "Midwestern" Europe and is basically a transitional area between Western and Central Europe. It has natural boundaries: the Alps to the south, the Carpathian ~~and Sudeten~~ Mountains and Lesser Poland Upland to the east and the coasts of the North and the Baltic Sea to the northwest and the north. The area is defined by six main river basins: Rhine, Elbe, Oder ~~Meuse,~~ Weser, Ems, and Danube up to Bratislava. As mentioned above, this area is interesting because of a noticeable shift in the seasonality of floods in a west to east direction. Due to its heterogeneity and vastness, the area is also convenient for index design assessment when evaluating the extremity of floods affecting several river basins.

2 Data and methods

2.1 Data

We used mean daily discharge values at selected stations (for each day during the period 1951–2013 ~~1950–2010~~) as a basis when searching for floods that occurred simultaneously within the study area. Only data from stations enclosing at least 2500 km^2 of the relevant river basin were used due to poor data availability for smaller catchments and to exclude minor floods. This work is based primarily on data that were obtained from the database of the Global Runoff Data Centre (GRDC), an international archive of monthly and daily discharges. The time series was incomplete in some cases, so we used additional data from national hydrological yearbooks, ~~and~~ the Czech Hydrometeorological Institute, the Austrian server eHYD and the Polish Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB). When necessary, missing values were obtained using linear regression.~~; only one or two missing years were supplied in this manner.~~

As a result, ~~115~~ 93 gauging stations from ~~six~~ seven countries (the Czech Republic, Slovakia, Poland, Austria, Switzerland, Germany and the Netherlands) were selected to analyze the time series of mean daily discharges between ~~1950~~1951 and ~~2010~~2013. The study area is approximately 579000~~499149~~ km^2, with the length of the river network reaching almost 17700 km. The total river length is given by the summation of river segments of certain Strahler order upstream each station. The selected stations and stream orders are depicted in Fig. 1. The length of river segments ranges from 55 to 522 km, with a mean length of 190 km. ~~the average size of a catchment is 31293 km^2, with the Lobith station enclosing the maximum catchment at 160800 km^2. Only the lower part of a catchment was related to a given station when another station was located upstream. The selected stations and their subcatchments are depicted in Fig. 1. The size of the subcatchments ranges from 248 to 21301 km^2, with a mean area of 4340 km^2. The spatial distribution of gauging stations in the dataset is not entirely uniform: the density of stations is highest in the Weser river basin, and the Meuse river basin has the least coverage.~~

2.2 Methods

The methodology is primarily based upon the approach of Uhlemann et al. (2010). Here, we briefly describe the used methods and we focus mainly on the differences arising from larger size of the study area.

2.2.1 Identification of ~~significant mean daily~~ flood peak discharges

The first step in this study is the selection of flood peaks at individual stations. The local maxima within the time series of mean daily discharges (Q_d) must be identified. Local maxima are Q_d values that are higher than values on both the previous and the following day. If several consecutive days have exactly the same value of Q_d, the first day is used.

For each gauging station, most sets of local maxima are due to minor flow fluctuations. To select real flood peak ~~significant~~ discharges ~~(Q_s)~~, the local maxima are compared with the 2-year return periods of mean daily discharges at a station (Q_2). Peak discharges that are equal to or greater than 2-year return level are denoted as Q_p. Nevertheless, we assume that a serious flood must be characterized by even higher discharges at least in a part of the affected area. Therefore, we also search for peak discharges that are equal to or greater than the 10-year return level of mean daily discharge (Q_{10}). The values of Q_2 and Q_{10} are estimated from the series of annual maxima of Q_d at a station. Each annual maxima series are approximated by the generalized extreme value distribution (GEV) using the maximum likelihood estimation method (Wilks, 2006).mean annual maximum of mean daily discharges (Q_{ma}) calculated from n = 61 annual maxima of mean daily discharges (Q_a) at a station i:

$$Q_{mai} = \frac{1}{n}\sum_{j=1}^{n} Q_{aij}. \quad (1)$$

Discharges exceeding Q_{ma} are considered significant. Nevertheless, we assume that a serious flood must be characterized by even higher discharges at least in a part of the affected area. Therefore, we also search for peak discharges that are equal to or greater than the 10-year return level of mean daily discharge (Q_{10}). The values of Q_{10} were estimated from the series of Q_a values that were approximated by the generalized extreme value distribution (GEV) using the L-moments method.

2.2.2 Determination of significant flood events

A significant flood event is defined here as a group of time-related Q_{sp} at various stations where at least one Q_{sp} value equals or exceeds Q_{10}. However, peak discharges Q_p values often do not occur exactly on the same day due to, e.g., the extent of the study area, the propagation of flood waves downstream, or the movement of the precipitation field. Therefore, a time window when Q_{sp} values seem to belong to the same event is defined. After analyzing all of the data series, we chose a time window that includes ten 12 days before and ten 12 days after the occurrence of the first value of $Q_{dp} \geq Q_{10}$. If there are other values of $Q_{dp} \geq Q_{10}$ within that time span, the time window is further extended with respect to the date of this peak discharge. This time span is slightly longer than that used by Uhlemann et al. (2010), but this difference is reasonable because a larger area is studied here. Moreover, the values of Q_{sp} systematically lag behind at hydrometric profiles on the Havel River and its largest tributary the Spree. This may be due to the lowland character of these basins permitting extensive spilling of water. We therefore decided to extend the time delay at these stations up to 12 days. However, the chosen time window may be too long in some cases because another atmospherically unrelated event may begin.

Therefore, we introduce an additional rule for dividing flood peaks that were identified as time-related but are in fact associated with different atmospheric causes. If more Q_{s10} values are identified in a some time series within an individual flood event and the time span between those peaks is at least five days long, we divide the peaks into two floods; otherwise, only one flood event is considered. Finally, only the highest Q_{sp} in a time series is considered.

2.2.3 Extremity indices design

Over 200 significant150 flood events are identified in the period 1950–20101951–2013. Each event can be described by its extent expressed as a length of affected river network: First, they are evaluated only with respect to the size of the affected area:

$$AL = \sum_{i=1}^{k} la_i \quad (21)$$

where la_i denotes the area length of the river segment belonging to of one of k subcatchments stations where Q_{s2} is detected. The considered part of the river network upstream the station i consists of individual river segments of a certain order. Strahler's stream ordering method is used (Strahler, 1957) when the first order is assigned to a headstream. Stream orders increase when two river segments of the same order meet. This method is dependent on the chosen layer of the river network. In this study, we use European catchments and Rivers network system of the European Environment Agency (EEA). However, only rivers of certain orders are included in the river length l_i. If a station is located on a stream of the fourth order, we consider only this particular river segment upstream the station. In the case of the fifth and sixth orders, also river segments of one lower order are counted. Two lower orders are considered when station is located on the stream of the seventh and eighth order. The 80 largest floods are further examined. First, they are sorted based on whether they occurred during the colder or the warmer half of the year; the decisive day for classification is the first day with Q_s. The colder half-year is set between 16 October and 15 April because there is evidence from the Czech Republic of a relatively sharp interface in terms of flood occurrence in mid-April (Müller et al., 2015).

Both the spatial extent of floods and the aspect of the discharge magnitudes must be incorporated into an extremity index for evaluating extreme flood events. To demonstrate the role of the threshold of the considered maximum dischargesweights of both aspects, we defined nine three index variants with differences in input parameters discharge limits and applied them to the 80 selected floods identified flood events.

Generally, the index is derived from AL by multiplying la_i (or its function) by normalized peak discharges. Three The basic variants considers all of the Q_{sp} values normalized by the respective exact value of the 2-year return period Q_{ma2}:, but they vary in the area parameter. The first variant simply considers subcatchment areas a_i:

$$E_{a2} = \sum_{i=1}^{k} \left(\frac{Q_{spi}}{Q_{ma2i}} al_i \right). \quad (32)$$

whereas two other variants contain the square root of each subcatchment area and their common logarithm, respectively:

$$E_r = \sum_{i=1}^{k} \left(\frac{Q_{si}}{Q_{mai}} \sqrt{a_i} \right), \quad (4)$$

$$E_l = \sum_{i=1}^{k} \left(\frac{Q_{si}}{Q_{mai}} \log a_i \right). \quad (5)$$

~~Using the square root in Eq. (4) reduces the weight of the aspect of the affected area. When applying the logarithm of the area in Eq. (5), the reduction is even more significant because the range of possible parameter values is markedly reduced. As a result, the role of discharge magnitudes in the index increases in Eq. (4) and even more so in Eq. (5).~~

The modification of the extremity index involves changing the threshold~~Another way to modify the extremity index is to set a different threshold~~ of considered discharge values. Although all Q_{sp} values are used in the ~~three~~ basic variant calculation~~s~~, ~~three~~ two other variants labeled ~~$E_{1.2a}$, $E_{1.2r}$, and $E_{1.2l}$~~ E_5 and E_{10} consider ~~discharges~~ Q_p values that are equal to or greater than 5-year (Q_5) or 10-year return periods (Q_{10}). As in the Eq. (2), the new Q_p values are normalized by the respective value of Q_5 or Q_{10}. ~~fulfill the condition Q_s/Q_{ma} >1.2; they are determined by Eqs. (3), (4), and (5). The remaining three variants labeled $E_{1.5a}$, $E_{1.5r}$, and $E_{1.5l}$ are analogous but the threshold is augmented up to 1.5.~~

~~These indices suppress the influence of the size of the flood area in the final extremity index value, and the discharge values of a flood event become more emphasized. When calculating indices with higher discharge thresholds, the total number of flood events may be reduced due to removing some flood events with rather low mean daily discharges.~~

Finally, we select 30 major floods according to each of the ~~nine~~ three extremity index variants. As the total study period covers ~~61~~63 years, we select approximately one flood per two years~~ on average~~. This enables a comparison of the rankings of flood events with respect to the individual index variants. This comparison opens the discussion of the role of extremity index design.

The floods are sorted based on whether they occurred in the colder or the warmer half of the year; the decisive day for classification is the mean point of the event. The mean day is found using the method of directional statistics, which was originally designed for the analysis of flood seasonality (Black and Werritty, 1997). However, it is applicable to the determination of mean day of the flood event. The method transforms the day of Q_p occurrence into directional vectors in a circle representing one year and the mean vector is translated into the mean day of the event. The colder half-year is set from November to April, the events with mean day between May and October are classified as warm half-year floods.

3 Results

The identified floods have various nature; from one or two day flood events caused mainly by localized convective precipitation to long-lasting and extensive cold half-year floods. Although the cold half-year events hit mostly larger areas than warm half-year floods, the flood of June 2013 was the largest one with respect to the affected river network. Flows higher than 2-year return period occurred at about 13700 km of the river network, which is 78 % of the total considered river length. ~~The 80 largest floods affected an area between 81000 and 381000 km^2, which is between 16 % and 76 % of the area of interest (Fig. 2). The dominance of the cold half-year floods is obvious, especially in the first half of the chart in Fig. 2. The largest flood occurred at the turn of March and April 1988. It is clear that the warm half-year floods relate more to the Danube basin or eventually to the Elbe river basin. The Rhine river basin is less represented and in the Meuse, Weser and Ems river basins, warm half-year floods rarely occur.~~

3.1 Comparison of the extremity index variants

As we mainly focus on extensive floods affecting more river basins at the same time, three lists of 30 major floods are created according to values of the index variants (Table 1). The events are listed with respect to the E_2. Floods selected by E_2 are primarily extensive events as small flood discharges are also considered. The flood of June 2013 is the first of the major floods, followed by the March flood of 1988 and the flood of August 2002. Overall, there are ten events in the warm half-year among 30 maxima. On the contrary, the lists of floods according to the E_5 and E_{10} are more balanced from this point of view. They contain several events that are not present among the maxima according to E_2; most of these extra floods belong to the warm half-year. These floods replaced some cold half-year floods with relatively low values of Q_p. More floods with lesser extent are present in the lists according to the E_5 and E_{10}. Mainly the latter list contains relatively shorter and spatially limited May floods, which are associated with spring convection causing higher discharges. Nevertheless, three floods were evaluated as being at the maximum, regardless of the index variant, with only different ranking among them; the June flood of 2013 is the biggest according to each index variant.

Figure ~~3~~2 depicts differences among the extremity index variants in terms of their dependence on the ~~size of the~~ proportion of the affected river length A/L ~~area A~~. Each chart in Fig. ~~3~~2 represents one variant of the extremity index. The correlation between A/L and the index values is much higher when the discharge threshold ~~Q_s/Q_{ma}~~ is set to 10-year return period. If we only consider such high discharges, the summation of the affected river length will approach the index values. The correlation is not so close in the case of Fig. 2a. The placement of cold and warm half-year events has a specific character in Fig. 2. The cold half-year floods are more extensive and have lower index values compared to the floods of the warm half-year, which applies to each chart. ~~Surprisingly, this close correlation persists, even when the common logarithm of the catchment areas is applied (Fig. 3a at the right). There are similarities among rankings of the events with respect to both A and the index values. The only exception is the August 2002 flood with a relatively small value of A.~~ The rankings of the three highlighted flood events remain close, regardless of the variant. However, relatively smaller discharges of March 1988 flood cause the decrease of its E_5 and E_{10} values. On the contrary, the extremity of June 2013 flood is even more highlighted in Fig. 2c as it significantly departs from other events. This is also shown in Fig. 3 representing the differences between E_2 and E_{10} values for 30 individual events. In the case of E_{10} both June 2013 and August 2002 floods reach much higher index values than the rest of the events. Floods are ranked as in Table 1.~~This is also shown in Fig. 3b representing index variants with the threshold $Q_s/Q_{ma} = 1.2$. Nevertheless, the correlation between A and the index values is lower, which is even more obvious when the threshold $Q_s/Q_{ma} = 1.5$. Still, we can see only minor differences among the indices with the same discharge threshold but a different area parameter shape.~~

~~In summary, the dependence of flood extremity on the size of the affected area does not change significantly with changes in the area parameter. This indicates that the index is not highly sensitive to changes in the area parameter but is instead related to the discharge threshold. If the threshold of Q_s/Q_{ma} rises to 1.2 or even 1.5, only stations with greater flood discharges are included in the calculation. The influence of the affected area of flooding is suppressed in these indices, and the flood extremity should relate in particular to the flood discharges reached.~~

3.2 Major floods characteristics

Figure 3 indicates large spatial differences among the flood events. It is clear that the warm half-year floods relate more to the Oder, Danube and Elbe river basins. The Rhine river basin is less represented and in the Weser and Ems river basins, the warm half-year floods rarely occur. A more comprehensive insight into this issue is provided in Fig. 4. The occurrence of flood discharges in the basins is demonstrated on 30 maximum floods according to E_2. The differences are evident within the individual basins. There is a shift from warm to cold half-year floods when we move from the upper Rhine or Oder downstream. The Warta, a main tributary of the Oder, is affected mainly by cold half-year events. However, the last displayed station is located on the Oder river. Within the Danube basin, a gap in the occurrence of cold half-year floods is visible in the middle part of the basin. Some consecutive flood events are similar to each other, which is due to the fact that they both occur in a relatively short time. The first event has an effect on the initiation of the second one, which is the case of a pair of floods in June 1965 and July 1997. The flood of June 2013 is unique as it is the only event, which largely affected Weser and Rhine basins.

~~Two variants of the index (E_r a $E_{1.5r}$) were chosen to create the final lists of 30 major floods in the transitional area between Western and Central Europe in the period 1950–2010 (Tables 1 and 2, respectively). They both employ the middle variant of the area parameter, i.e., the square root of A, which makes them similar to the variants using either the actual area or its logarithm. Nevertheless, the chosen variants differ significantly in the discharge threshold.~~

~~Floods selected by E_r are primarily extensive events as small flood discharges are also considered. The flood of March/April 1988 is the first of the major floods, followed by the January flood of 2003 and the flood of August 2002. Overall, there are only four events in the warm half-year among 30 maxima. On the contrary, the list of floods according to the $E_{1.5r}$ is more balanced from this point of view. It contains seven events that are not present among the maxima according to E_r; five of these extra floods belong to the warm half-year. These floods replaced some cold half-year floods with relatively low values of Q_d. More floods with lesser extents are present in the list in Table 2. Nevertheless, four floods were evaluated as being at the maximum, regardless of the index variant, with only different ranking among them; the August flood of 2002 is the biggest according to the $E_{1.5r}$ due to its extremely high discharge values.~~

3.2.1 Seasonal distribution

Floods of the cold half-year are generally better represented among the major flood events. The seasonal distribution is quite similar for E_{r2} and $E_{1.5r10}$, with a frequency maximum in winter and a secondary maximum in summer (Fig. ~~4~~5). According to E_{r2}, major events are concentrated ~~from~~ in January ~~to~~and March, but the March floods are not so pronounced ~~they are spread more equally from December to April according to~~ in the case of $E_{1.5r10}$. ~~This indicates that the first half of April is characterized by floods with rather small spatial extents.~~ The secondary frequency maximum occurs in July ~~and August~~ and for both indices has a similar character. Surprisingly, a great difference arise in the number of extreme floods in May. These are spatially limited events, which moved up in a ranking due to higher discharges. ~~is much more pronounced according to $E_{1.5r}$.~~ The rest of the year is characterized by a low frequency of major floods. Although one event per calendar month was recorded in both May and June, onlyOnly a single major flood occurred from late August to the beginning of December. It began at the end of October 1998, but the mean day of the event lies in November.and its Its extremeness was surprisingly high, mainly according to both variants E_2 variant of the extremity index.

3.2.2 Interannual variability

Major floods do not occur regularly over time. Some clusters of flood events are apparent in Fig. 56, which presents the distribution of major floods between 19501951 and 20102013. The July flood of 1954 is the first recorded flood in the period examined. A significant accumulation of flooding is apparent in the 1980s and from 1993 to 2006. On the contrary, a long period without major floods occurred at the beginning of the 1960s. The first 15 years have only one flood of the cold-half year.

Generally, there are more major floods in the second half of the period, which applies to both index variants. It seems that the number of events is increasing mainly from 1980s, as is their extremity. However, the extremity according to $E_{1.5,2}$ is increasing more rapidly, which may be due to a higher number of warm half-year floods towards the end of the study period.

3.2.3 Spatial distribution

Regarding the spatial distribution of floods, Fig. 23 demonstrates that floods during the warm half-year relate more to the Oder, Danube and the Elbe river basins. Warm half-year floods are less frequent in the Rhine river basin, and they occur very rarely in the Meuse, Weser and Ems river basins, where cold half-year floods dominate. This is confirmed by Fig. 67, which depicts the frequency of 30 major floods in both half-years within individual subcatchments gauge stations.

In general, the number of cold half-year floods decreases towards the southeast, whereas the number of warm half-year floods increases in the same direction. Regardless the variant of the extremity index, there are regions affected by extreme floods only in one part of the year. This is true for the Meuse, Weser, Ems, and the lower part of the Rhine river basin including Main (cold half-year) and most of the Alpine rivers (warm half-year). On the contrary, other regions are prone to extreme floods both in the cold and the warm halves of the year: the Oder, Elbe and Danube river basins, apart from the Alpine tributaries. However, low number of identified floods does not exclude their occurrence at individual station. It means that floods in a given location are not part of large-scale cold or warm half-year floods, which were evaluated in this study.Differences among the variants of the index exist only in the numbers of flood events in individual subcatchments.

4 Discussion and conclusions

This paper addresses the evaluation of major flood events in the transitional area between Western and Central Europe in the period 1950–20101951–2013. Major floods are defined according to the value of a flood extremity index. We created nine three variants of the index with differences in terms of design, specifically regarding discharge thresholds. and area parameters.

We were motivated by Uhlemann et al. (2010) and Schröter et al. (2015), who used similar flood extremity indices, with only a difference in the threshold of the discharge values entered into the calculation. Uhlemann et al. (2010) used a 2-year flow threshold~~, which corresponds approximately to the value of Q_{ma}, or is slightly lower.~~, while Schröter et al. (2015) chose a higher limit of a 5-year flow, thus making these studies incomparable. In this paper, we introduce the differences that arise in the resulting lists of major floods when we use indices with different discharge thresholds.~~ and area parameters.~~ We selected the value of Q_{ma2} as a basic threshold and two additional threshold values: ~~designed as multiples of~~ Q_{ma5} and Q_{10}. We found that the value of this threshold is crucial for the ranking of major floods. The number of warm half-year floods slightly increases in the lists of major floods when using the higher discharge thresholds. ~~On the contrary, the index variants are not highly sensitive to changes in the area parameter.~~ Two sets of 30 major floods are presented according to ~~their~~ E_{r2} and $E_{1.5r10}$ indices, and the respective lists are compared in terms of seasonality, interannual variability and spatial distribution.

Generally, the lists of major floods are quite similar to the list of German trans-basin floods presented by Uhlemann et al. (2010) because Germany covers more than half of the area studied in this work. The duration of "identical" floods is slightly different, as is their ranking. This is mainly due to the different size of the area of interest. Schröter et al. (2015) used an index similar to Uhlemann et al. (2010), but the authors only offered a comparison of the extremity of three summer flood events: the floods of 1954, 2002 and 2013. The flood event of 2013 is reported as the largest, followed by the flood of 1954. In this paper, the flood of August 2002 is always more extreme than the flood of 1954, regardless of the index variant used, because of the differences in the extent of the area of interest. Nevertheless, the flood of June 2013 remains on top of the lists.

We can also compare our results with those of Barredo (2007), who provided a set of 21 large European river floods compiled according to the amount of damage caused. Six of these floods affected our area of interest; all are included in the set of major floods according to E_{10}, but only four belong to the 30 major events with respect to E_2. Obviously, floods that caused major damage are better represented by the variant of the extremity index with a higher threshold of considered discharge values. From this point of view, the E_{10} index might be better able to identify major floods, which however noticeably depart from other events.

Regarding the seasonal distribution of major flood events, the predominance of cold half-year floods is apparent in both lists. Uhlemann et al. (2010) showed the same result. In contrast, floods during the warm half of the year dominate the list of the 30 major floods in the Czech Republic by Müller et al. (2015). This may be due to the fact that the occurrence of warm half-year floods is increasing from the northwest to the southeast in the studied area. ~~The list of major floods for the Czech Republic is closer to the list based on $E_{1.5r}$ because warm half-year floods are better covered by the index variant that has the higher discharge threshold.~~

The temporal distribution of major flood events during the period between 195~~0~~1 and 201~~0~~3 is rather uneven. There are certain clusters in terms of the occurrence of major floods. Some periods of reduced or increased frequencies of major flooding are identical to the results of other papers (Uhlemann et al., 2010; Müller et al., 2015). For example, we found these identical trends: a higher frequency of major floods in the 1980s and a decline in the number of identified floods in the 1990s. The ~~last~~ five-year period between 2006 and –2010 is different, however, because it is a period with a higher frequency of major flooding in Müller et al. (2015). The increase in major flooding in the second half of the period is again consistent with the findings of Uhlemann et al. (2010). However, it remains unclear whether this is a trend or just a part of a cycle. In the last years, there is a discussion about increasing flood risk due to ongoing climate change and anthropogenical modifications of the landscape and especially floodplains. On a local level, the runoff is influenced by the changes in landuse, riverbeds or the surface drainage, which often lead to runoff acceleration and steeper flood waves (Langhammer and Vilímek, 2008). On the contrary, the construction of water reservoirs can reduce a flood. The Slapy dam at the Vltava river was only partially filled before the flood of July 1954. Unaffected discharge of 2920 $m^3 \cdot s^{-1}$ would be the second largest in Prague in the 20th century after the flood of March 1940, the actual discharge was only 2240 $m^3 \cdot s^{-1}$ (Brázdil et al., 2005). However, the effect of local landscape changes can be less significant for extensive events as it depends on the flood extremity (Langhammer and Vilímek, 2008).

The temporal characteristics of major flood events are also connected with the opposite extreme. The historical records show, that an extreme flood was followed by a great drought in same cases (Brázdil et al., 2005). Lloyd-Hughes and Saunders (2002) conclude that the greater pan-European droughts occurred in the early 1950s and the 1990s; lesser drought incidence is apparent in 1980s. For the analysis, they used Palmer drought severity index and standardized precipitation indices calculated at different time scales.

At a shorter time scale, the wetness conditions are crucial for flood initiation; antecedent soil moisture can highly influence the flood extremity. The June 2013 flood was the case, when great precipitation amounts coincided with high antecedent soil moisture and produced an exceptional flood (Blöschl et al., 2013). The effect of antecedent wetness conditions depends on the season and a type or an extremity of flood. High antecedent soil moisture relates in particular to cold half-year floods, while the signal varies in warm half-year cases (Nied et al., 2013).

Generally, the lists of major floods are quite similar to the list of German trans-basin floods presented by Uhlemann et al. (2010) because Germany covers more than half of the area studied in this work. The consensus is greater in the case of the E_r index. The duration of “identical” floods is slightly different, as is their ranking. This is due to the different size of the area of interest and the flood identification methodology. Schröter et al. (2015) used an index similar to Uhlemann et al. (2010), but the authors only offered a comparison of the extremity of three summer flood events: the floods of 1954, 2002 and 2013. The flood event of 2013 is reported as the largest, followed by the flood of 1954. In this paper, the flood of August 2002 is always more extreme than the flood of 1954, regardless of the index variant used, because of the differences in the extent of the area of interest.

We can also compare our results with those of Barredo (2007), who provided a set of 21 large European river floods compiled according to the amount of damage caused. Six of these floods affected our area of interest; all are included in the set of major floods according to $E_{1.5r}$, but only three belong to the 30 major events with respect to E_r. Obviously, floods that caused major damage are better represented by the variant of the extremity index with a higher threshold of considered discharge values. Therefore, we recommend using $E_{1.5r}$ for the evaluation of extensive floods. The $E_{1.5r}$ index is apparently better able to identify major floods.

Further research on ~~this~~ the topic of extreme floods will examine the related ~~atmospheric~~ meteorological conditions. A comprehensive evaluation of antecedent wetness conditions, causal atmospheric circulation ~~conditions~~, the consequent precipitation and the flow response is needed. A comparison of major floods with precipitation and circulation extremes would be useful for a better understanding of the causes of extensive floods, which affect several river basins.

Acknowledgements. ~~The presented research is supported by the Charles University (project GA UK 276816). We thank the Global Runoff Data Centre and the Czech Hydrometeorological Institute for providing runoff data.~~We thank all the institutions, which provided runoff data, mainly the Global Runoff Data Centre, the Czech Hydrometeorological Institute and the Polish Institute of Meteorology and Water Management.

References

Barredo, J. I.: Major flood disasters in Europe: 1950–2005, Nat. Hazards, 42, 125–148, doi:10.1007/s11069-006-9065-2, 2007.

Bebber van, W. J.: Die Zugstrassen der barometrischen Minima nach den Bahnenkarten der Deutschen Seewarte für den Zeitraum 1875–1890, Meteorol. Z., 8, 361–366, 1891.

Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A. T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikof, J., Schöll, R., Semmler, T., and Woth, K.: Future extreme events in European climate: an exploration of regional climate model projections, Climatic Change, 81, 71–95, doi:10.1007/s10584-006-9226-z, 2007.

Black, A. R. and Werritty, A.: Seasonality of flooding: a case study of North Britain, J. Hydrol., 195, 1–25, 1997.

Blöschl, G., Nester, T., Komma, J., Parajka, J., and Perdigão, R. A. P.: The June 2013 flood in the Upper Danube basin, and comparisons with the 2002, 1954 and 1899 floods, Hydrol. Earth Syst. Sci., 17, 5197–5212, doi:10.5194/hess-17-5197-2013, 2013.

Brázdil, R., Dobrovolný, P., Elleder, L., Kakos, V., Kotyza, O., Květoň, V., Macková, J., Müller, M., Štekl, J., Tolasz, R., and Valášek, H.: Historical and Recent Floods in the Czech Republic, Masaryk University and Czech Hydrometeorological Institute, Brno, Prague, Czech Republic, 2005.

Brázdil, R., Glaser, R., Pfister, C., Dobrovolný, P., Antoine, J.-M., Barriendos, M., Camuffo, D., Deutsch, M., Enzi, S., Guidoboni, E., Kotyza, O., and Rodrigo, F. S.: Floods events of selected European rivers in the sixteenth century, Climatic Change, 43, 239–285, 1999.

Caspary, H. J.: Recent winter floods in Germany caused by changes in the atmospheric circulation across Europe, Phys. Chem. Earth, 20, 459–462, 1995.

Francou, J. and Rodier, J.-A.: Essai de classification des crues maximales observées dans le monde. Cah. Orstrom Hydrol., IV, 19–46, 1967.

Herschy, R. W. (Ed.): World catalogue of maximum observed floods, IAHS Press, Wallingford, IAHS-AISH Publ. 284, 2003.

Jacobeit, J., Glaser, R., Luterbacher, J., and Wanner, H.: Links between flood events in central Europe since AD 1500 and large-scale atmospheric circulation modes, Geophys. Res. Lett., 30, 1172–1175, doi:10.1029/2002GL016433, 2003.

Keef, C., Svensson, C., and Tawn, J. A.: Spatial dependence in extreme river flows and precipitation for Great Britain, J. Hydrol., 378, 240–252, 2009.

Kundzewicz, Z. W., Ulbrich, U., Brucher, T., Graczyk, D., Kruger, A., Leckebusch, G. C., Menzel, L., Pinskwar, I., Radziejewski, M., and Szwed, M.: Summer Floods in Central Europe – Climate Change Track?, Nat. Hazards, 36, 165–189, 2005.

Langhammer, J. and Vilímek, V.: Landscape changes as a factor affecting the course and consequences of extreme floods in the Otava river basin, Czech Republic, Environ. Monit. Assess., 144, 53–66, doi:10.1007/s10661-007-9941-6, 2008.

Lloyd-Hughes, B. and Saunders, M. A.: A drought climatology for Europe. Int. J. Climatol., 22, 1571–1592, doi:10.1002/joc.846, 2002.

Mudelsee, M., Börngen, M., Tetzlaff, G., and Grünewald, U.: No upward trends in the occurrence of extreme floods in central Europe, Nature, 425, 166–169, 2003.

Müller, M. and Kašpar, M.: Quantitative aspect in circulation type classifications – an example based on evaluation of moisture flux anomalies, Phys. Chem. Earth, 35, 484–490, doi:10.1016/j.pce.2009.09.004, 2010.

Müller, M. and Kašpar, M.: Event-adjusted evaluation of weather and climate extremes, Nat. Hazards Earth Sys., 14, 473–483, doi:10.5194/nhess-14-473-2014, 2014.

Müller, M., Kašpar, M., Valeriánová, A., Crhová, L., Holtanová, E, and Gvoždíková, B.: Novel indices for the comparison of precipitation extremes and floods: an example from the Czech territory, Hydrol. Earth Sys. Sci., 19, 4641–4652, doi:10.5194/hess-19-4641-2015, 2015.

Munich Re: Topics Geo Natural catastrophes 2014: Analyses, assessments, positions, Munich Reinsurance Company, Munich, Germany, 2015.

Nied, M., Hundecha, Y., and Merz, B.: Flood-initiating catchment conditions: a spatio-temporal analysis of large-scale soil moisture patterns in the Elbe River basin, Hydrol. Earth Syst. Sci.,17, 1401–1414, doi:10.5194/hess-17-1401-2013, 2013.

Nissen, K. M., Ulbrich, U., and Leckebusch, G.: Vb cyclones and associated rainfall extremes over Central Europe under present day and climate change conditions, Meteorol. Z., 22, 649–660, doi:10.1127/0941-2948/2013/0514, 2014.

Rodda, H. J. E.: The Development and Application of a Flood Risk Model for the Czech Republic, Nat. Hazards, 36, 207–220, 2005.

Rodier, J. A. and Roche, M. (Eds.): World catalogue of maximum observed floods, IAHS Press, Wallingford, IAHS Publ. 143, 1984.

Schröter, K., Kunz, M., Elmer, F., Mühr, B., and Merz, B.: What made the June 2013 flood in Germany an exceptional event? A hydro-meteorological evaluation, Hydrol. Earth Sys. Sci., 19, 309–327, doi:10.5194/hess-19-309-2015, 2015.

Strahler,A. N.: Quantitative analysis of watershed geomorphology, Eos T. Am. Geophys. Un., 38, 913–920, 1957.

~~The Global Runoff Data Centre, 56068 Koblenz, Germany, available at: http://www.bafg.de/, 2015.~~

Uhlemann, S., Thieken, A. H., and Merz, B.: A consistent set of trans-basin floods in Germany between 1952–2002, Hydrol. Earth Sys. Sci., 14, 1277–1295, doi:10.5194/hess-14-1277-2010, 2010.

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences, 2nd ed., Academic Press, Burlington, USA, 2006.

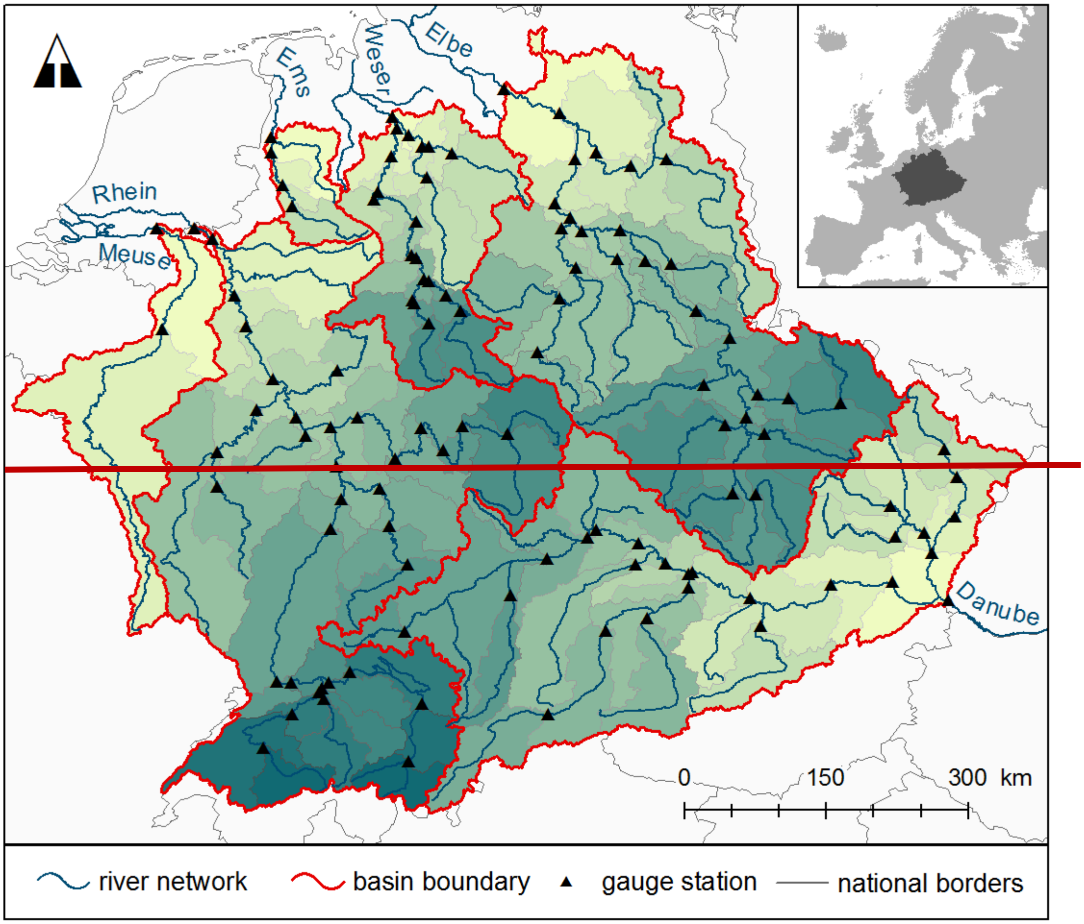
Table 1: List of 30 major floods according to the E_2, E_5 and E_{10} indices E_r index. The date is displayed in the YYYY/MM/DD format. The A/SL column refers to the proportion of the affected river length catchment size to the total length of the river network size of the area of interest. Warm half-year floods are in bold.

Ranking	Flood Duration	E_2	A/L [%]	E_5	Ranking	A/L [%]	E_{10}	Ranking	A/L [%]
1	**2013/05/30 - 2013/06/17**	**1.50**	**78**	**0.88**	**1**	**57**	**0.61**	**1**	**44**
2	1988/03/25 - 1988/04/08	1.15	75	0.62	3	50	0.32	3	28
3	**2002/08/12 - 2002/08/23**	**1.09**	**43**	**0.64**	**2**	**32**	**0.48**	**2**	**28**
4	1981/03/11 - 1981/03/30	1.08	73	0.48	5	37	0.28	5	24
5	2011/01/14 - 2011/01/29	1.07	69	0.50	4	39	0.27	6	23
6	1982/01/01 - 1982/01/17	0.99	72	0.38	9	32	0.18	12	16
7	2006/03/29 - 2006/04/12	0.97	60	0.38	8	27	0.21	10	16
8	2003/01/03 - 2003/01/19	0.88	55	0.47	6	37	0.26	7	22
9	**1954/07/02 - 1954/07/21**	**0.87**	**46**	**0.44**	**7**	**28**	**0.30**	**4**	**22**
10	1974/12/08 - 1974/12/26	0.77	56	0.20	28	16	-	-	-
11	1979/03/06 - 1979/03/30	0.77	57	0.21	26	15	0.15	18	12
12	**1965/06/10 - 1965/06/20**	**0.75**	**49**	**0.32**	**13**	**26**	**0.14**	**22**	**12**
13	1956/03/04 - 1956/03/14	0.72	52	0.23	24	20	-	-	-
14	1999/02/21 - 1999/03/07	0.71	60	-	-	-	-	-	-
15	1995/01/25 - 1995/02/12	0.70	48	0.35	11	28	0.22	9	19
16	1986/12/31 - 1987/01/10	0.68	48	0.26	18	21	0.13	23	11
17	1968/01/16 - 1968/01/28	0.67	52	-	-	-	-	-	-
18	**1997/07/06 - 1997/07/24**	**0.66**	**29**	**0.30**	**14**	**13**	**0.21**	**11**	**10**
19	**1981/07/19 - 1981/07/30**	**0.65**	**37**	**0.35**	**10**	**26**	**0.16**	**15**	**12**
20	1998/10/30 - 1998/11/13	0.61	44	0.24	22	20	0.10	30	9
21	1980/02/05 - 1980/02/18	0.60	47	0.20	27	19	-	-	-
22	2002/02/27 - 2002/03/12	0.59	48	-	-	-	-	-	-
23	**1958/06/29 - 1958/07/16**	**0.58**	**33**	**0.29**	**15**	**21**	**0.12**	**27**	**9**
24	**1997/07/19 - 1997/08/02**	**0.58**	**31**	**0.26**	**19**	**15**	**0.16**	**14**	**11**
25	1970/02/23 - 1970/02/28	0.58	38	0.32	12	26	0.22	8	20
26	1993/12/21 - 1993/12/30	0.56	37	0.26	16	21	0.14	19	12
27	1987/03/26 - 1987/04/11	0.55	41	-	-	-	-	-	-
28	**1985/08/06 - 1985/08/28**	**0.53**	**34**	**0.25**	**20**	**20**	-	-	-
29	**1965/05/30 - 1965/06/10**	**0.53**	**33**	-	-	-	-	-	-
30	1994/04/13 - 1994/04/27	0.53	37	0.23	25	18	0.12	25	10
34	**2010/06/03 - 2010/06/14**	-	-	**0.24**	**23**	**21**	-	-	-
35	2011/01/04 - 2011/01/14	-	-	0.20	30	16	0.12	24	11
39	**1977/08/24 - 1977/09/13**	-	-	**0.20**	**29**	**14**	-	-	-
40	**1977/08/01 - 1977/08/16**	-	-	-	-	-	**0.11**	**29**	**9**
44	**2005/08/22 - 2005/08/26**	-	-	**0.24**	**21**	**17**	**0.15**	**17**	**11**
47	**1999/05/20 - 1999/05/27**	-	-	**0.26**	**17**	**19**	**0.17**	**13**	**13**
60	**2010/05/18 - 2010/06/01**	-	-	-	-	-	**0.15**	**16**	**11**
65	**1999/05/13 - 1999/05/19**	-	-	-	-	-	**0.14**	**20**	**12**
66	1955/01/14 - 1955/01/21	-	-	-	-	-	0.14	21	13
72	1983/04/10 - 1983/04/21	-	-	-	-	-	0.12	26	11
87	**1983/05/25 - 1983/05/31**	-	-	-	-	-	**0.12**	**28**	**11**

Ranking	Flood duration			E_r	A/S [%]
1	1988/03/25	-	1988/04/08	7948	76
2	2003/01/03	-	2003/01/23	7299	65
3	**2002/08/11**	**-**	**2002/08/23**	**6621**	**44**
4	1981/03/11	-	1981/03/30	6351	54
5	1956/03/03	-	1956/03/20	5961	65
6	1982/01/06	-	1982/01/17	5930	63
7	1970/02/23	-	1970/02/28	5708	57
8	1995/01/25	-	1995/02/12	5661	55
9	1998/10/29	-	1998/11/13	5423	55
10	2006/03/29	-	2006/04/09	5289	43
11	1993/12/21	-	1994/01/03	5165	51
12	1987/01/01	-	1987/01/10	5053	49
13	1980/02/05	-	1980/02/24	4761	56
14	**1954/07/09**	**-**	**1954/07/21**	**4569**	**40**
15	2002/02/27	-	2002/03/15	4239	49
16	**1965/06/10**	**-**	**1965/06/20**	**4207**	**44**
17	1988/03/17	-	1988/03/26	4125	46
18	1994/04/13	-	1994/04/23	3959	38
19	1968/01/16	-	1968/01/27	3817	41
20	1987/03/26	-	1987/04/06	3392	33
21	1974/12/08	-	1974/12/18	3253	34
22	1999/03/03	-	1999/03/13	3212	37
23	**1981/07/20**	**-**	**1981/07/29**	**3105**	**31**
24	1982/01/31	-	1982/02/05	2866	36
25	1994/01/02	-	1994/01/16	2843	31
26	1967/12/24	-	1967/12/28	2802	31
27	1984/02/07	-	1984/02/12	2757	30
28	2002/03/21	-	2002/03/25	2754	35
29	1979/03/12	-	1979/03/30	2725	32
30	1955/01/14	-	1955/01/25	2621	30

Table 2: Same as Table 1 but for the $E_{1.5r}$ index.

Ranking	Flood duration			$E_{1.5r}$	A/S [%]
1	**2002/08/11**	**-**	**2002/08/23**	**3580**	**44**
2	2003/01/03	-	2003/01/23	2926	65
3	1981/03/11	-	1981/03/30	2442	54
4	1988/03/25	-	1988/04/08	2256	76
5	1995/01/25	-	1995/02/12	2150	55
6	**1954/07/09**	**-**	**1954/07/21**	**2026**	**40**
7	2006/03/29	-	2006/04/09	2021	43
8	1993/12/21	-	1994/01/03	1720	51
9	1970/02/23	-	1970/02/28	1621	57
10	1987/01/01	-	1987/01/10	1351	49
11	1998/10/29	-	1998/11/13	1166	55
12	**1965/06/10**	**-**	**1965/06/20**	**1092**	**44**
13	**1981/07/20**	**-**	**1981/07/29**	**973**	**31**
14	**1999/05/16**	**-**	**1999/05/26**	**936**	**23**
15	1982/01/06	-	1982/01/17	892	63
16	1956/03/03	-	1956/03/20	819	65
17	**2005/08/22**	**-**	**2005/08/26**	**811**	**22**
18	1994/04/13	-	1994/04/23	782	38
19	1988/04/01	-	1988/04/14	608	21
20	**1958/07/05**	**-**	**1958/07/16**	**576**	**21**
21	1988/03/17	-	1988/03/26	575	46
22	1974/12/08	-	1974/12/18	566	34
23	1955/01/14	-	1955/01/25	504	30
24	1984/02/07	-	1984/02/12	499	30
25	1983/04/09	-	1983/04/16	483	24
26	1968/01/16	-	1968/01/27	430	41
27	**1997/07/06**	**-**	**1997/07/10**	**428**	**21**
28	**1985/08/06**	**-**	**1985/08/12**	**427**	**19**
29	1967/12/24	-	1967/12/28	419	31
30	1987/03/26	-	1987/04/06	382	33


Elbe
Weser
Ems
Rhein
Meuse
Danube
0
150
300 km
river network
basin boundary
gauge station
national borders

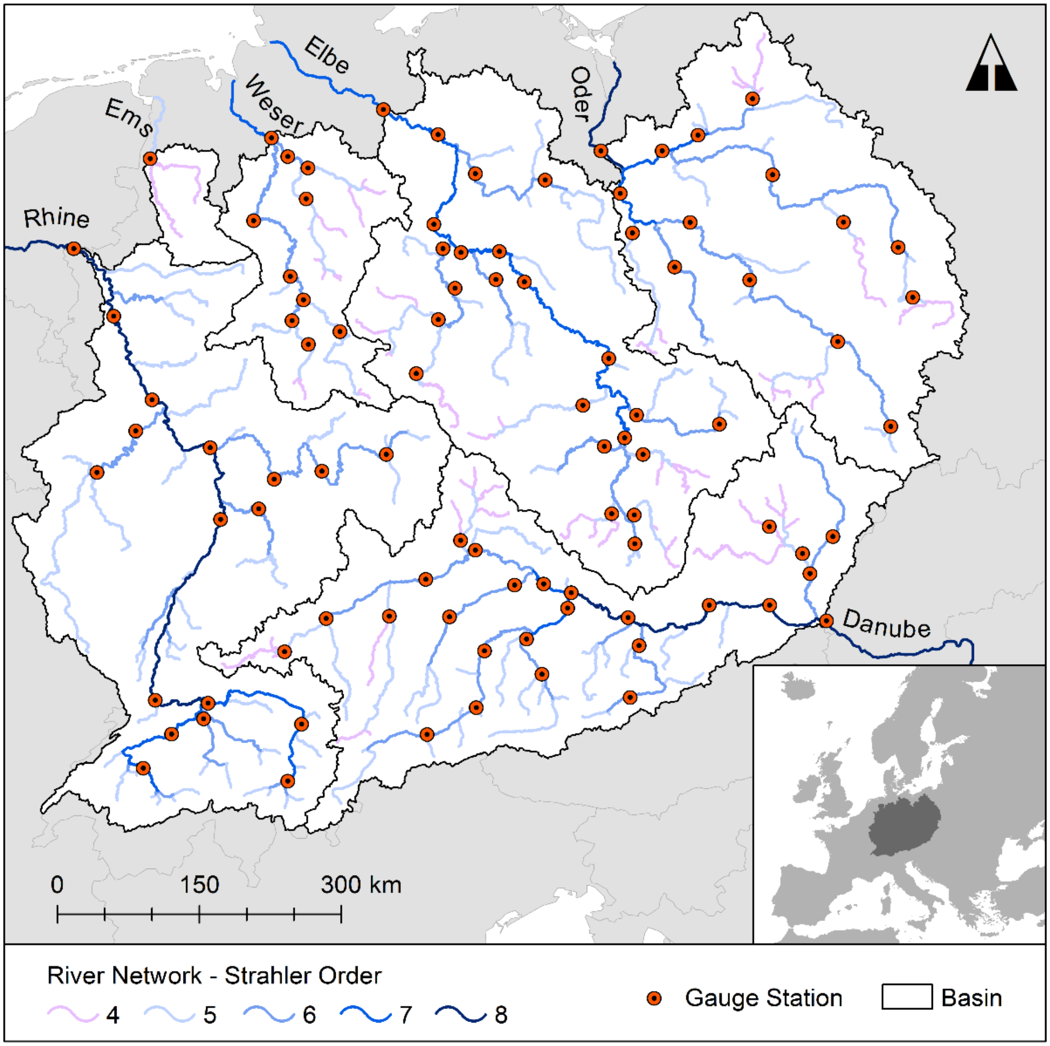


Figure 1: Gauge stations in the area of interest. ~~Their subcatchments are~~ Strahler stream order is distinguished by color.

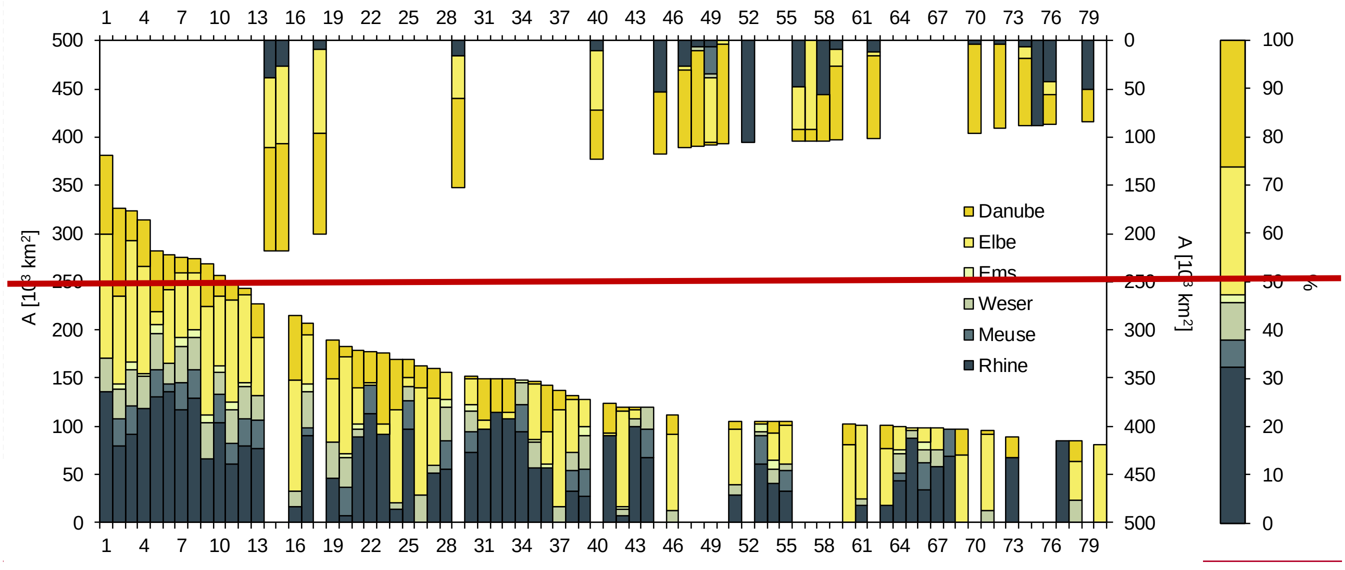


Figure 2: The 80 largest flood events in the study area from 1950 to 2010 according to the size of the affected area *A*. Cold and warm half-year floods are depicted on the bottom and the top x-axis, respectively. Contributions of individual river basins to the flood event area are distinguished by color. Their contribution to the total area of interest is shown in the right bar.

5

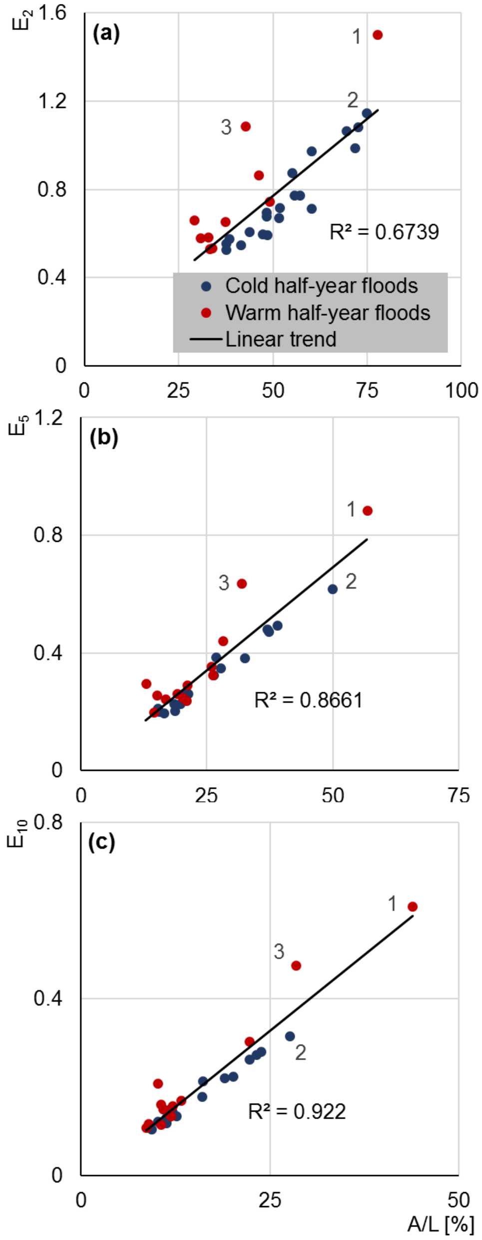


Figure 2: Relationship between the proportion of the affected river length (x-axis) and the flood extremity E (y-axis) according to E_2 (a), E_5 (b) and E_{10} (c). R^2 indicates the value of the coefficient of determination.

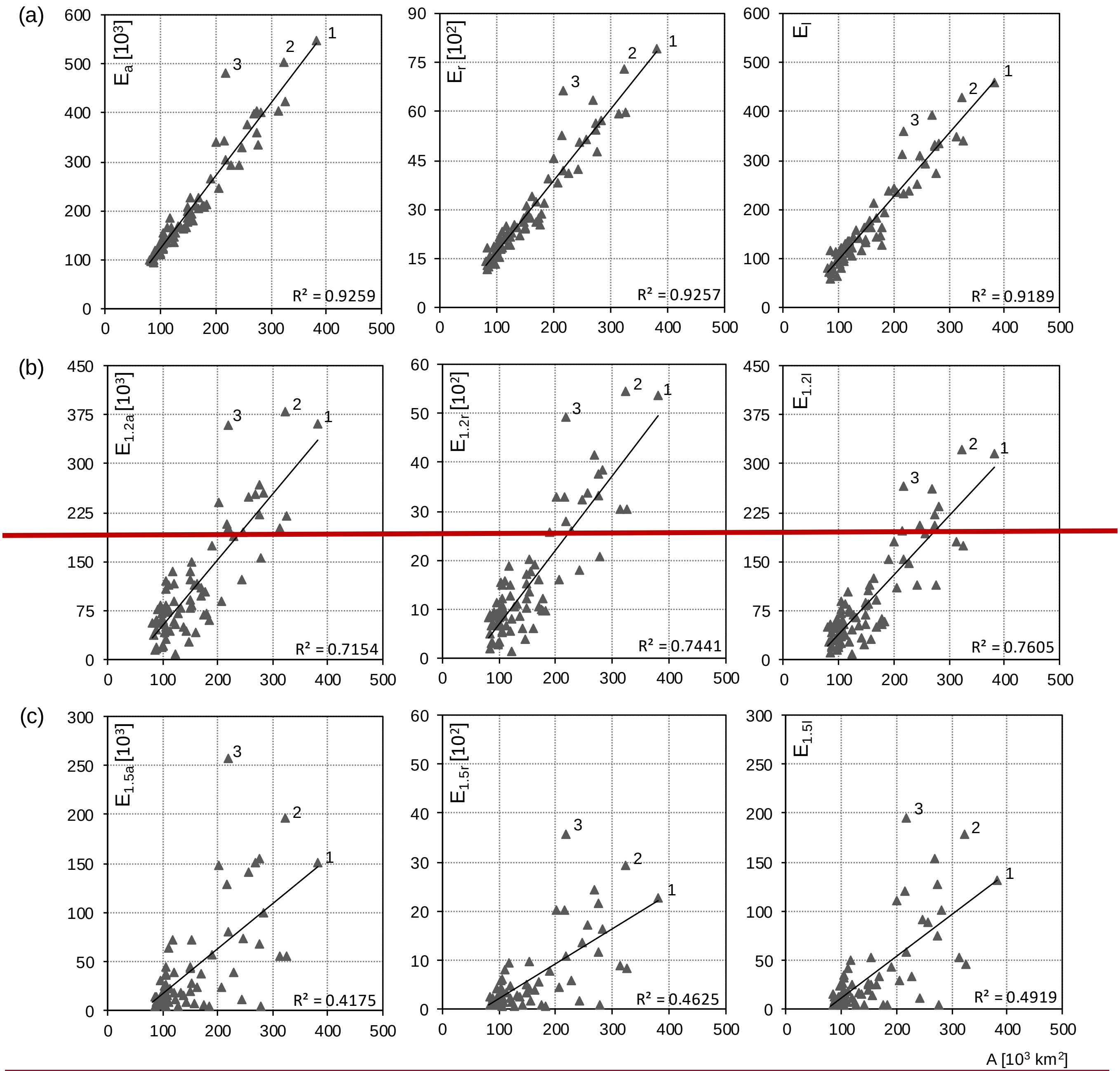


Figure 3: Relationship between the affected area A (x-axis) and the flood extremity according to nine index variants. Solid lines depict linear trends in the data; R^2 indicates the value of the coefficient of determination. Selected floods are highlighted: March/April 1988 (1); January 2003 (2); August, 2002 (3).

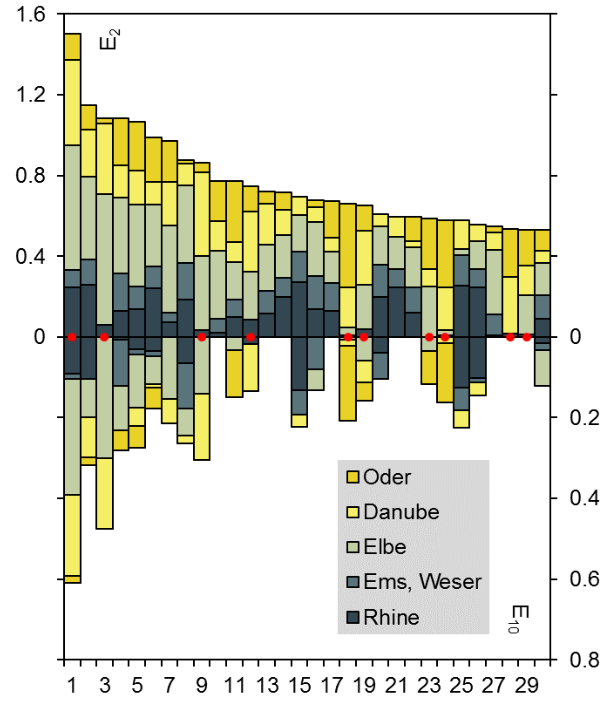


Figure 3: The 30 largest flood events in the study area from 1951 to 2013 according to E_2 and the corresponding events according to E_{10}. Missing bars indicate events which are not included in the set of 30 largest floods compiled by E_{10}. Contributions of individual river basins to the index value are distinguished by color. Red dots indicate warm half-year floods.

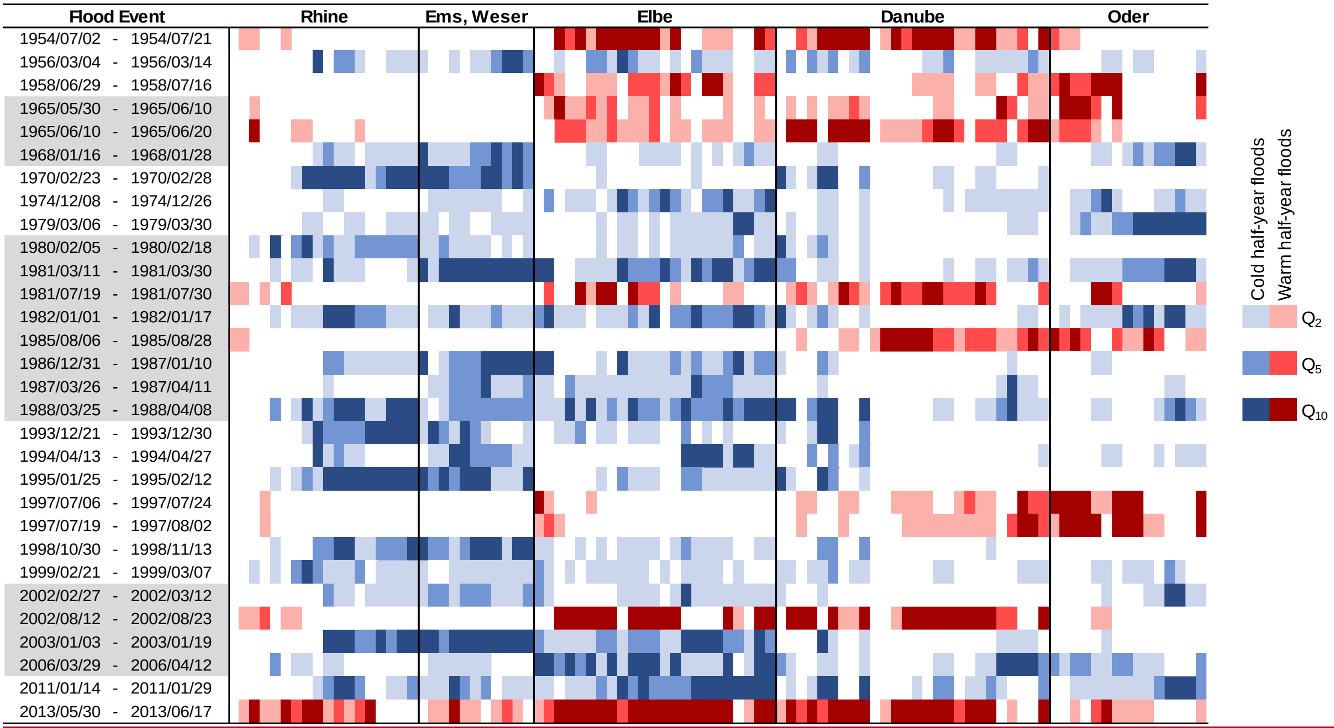
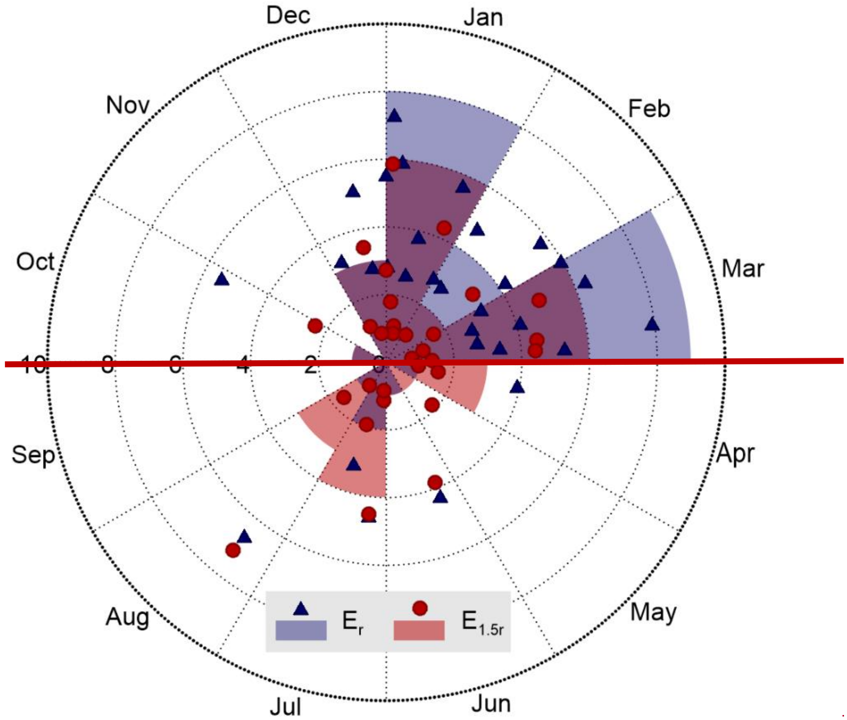


Figure 4: The occurrence of discharges equal to or greater than 2, 5 and 10-year flood at individual stations during each of the 30 maximum floods according to E_2 index. The basins are indicated at the top of the chart; the stations are arranged according to their position downstream.



Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
10
8
6
4
2
0
E_r
$E_{1.5r}$

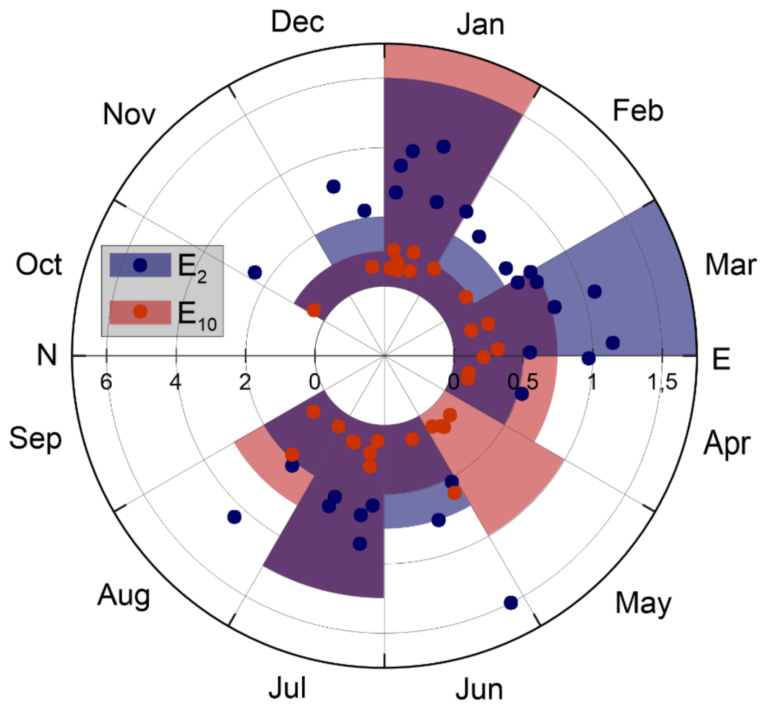
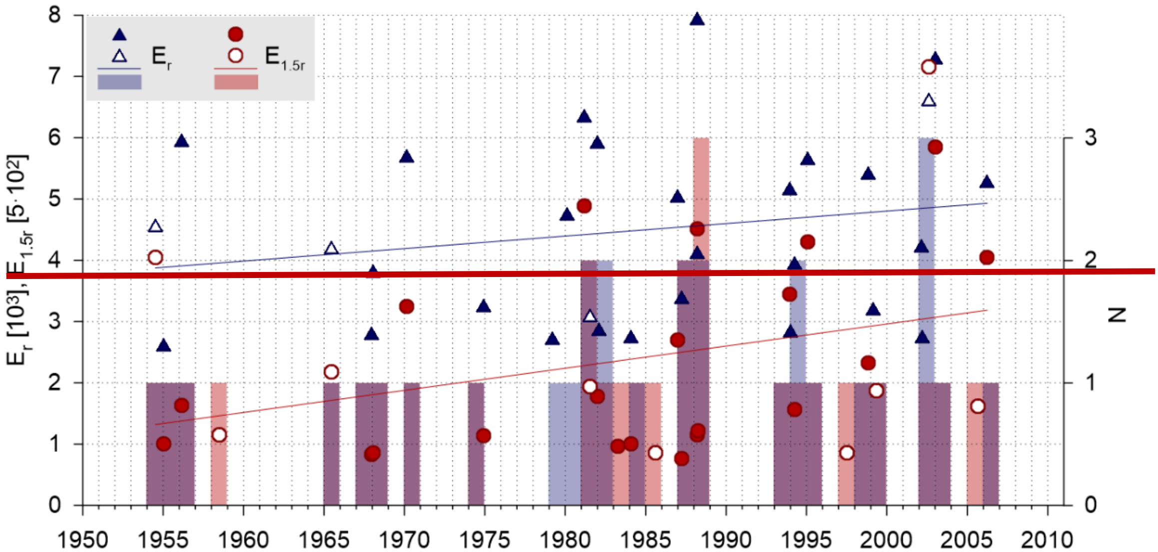


Figure 54: Seasonal distribution of 30 maximum floods according to E_{r2} and $E_{1.5r10}$ indices. The number of extreme floods in individual months N is depicted by shading; the mixed color indicates overlapping data. The signs represent mean calendar days of the eventswhen individual floods began; the distance of the sign from the center of the diagram reflects the flood extremity given by the value of E_{r2} [10^3] and $E_{1.5r10}$ [$5\cdot10^2$].


E_r
$E_{1.5r}$
E_r [10^3], $E_{1.5r}$ [$5\cdot10^2$]
N
0
1
2
3
4
5
6
7
8
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

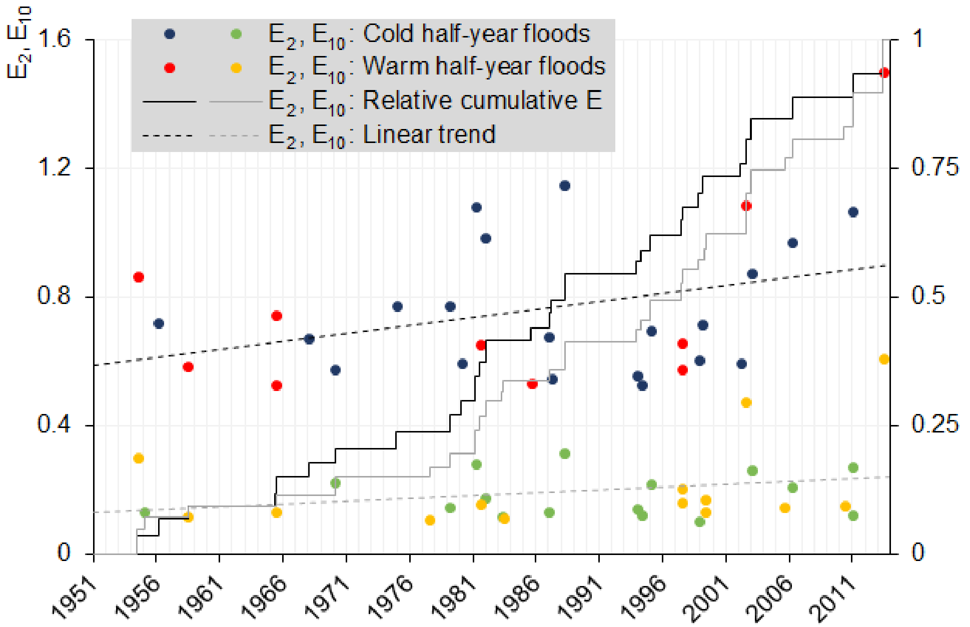
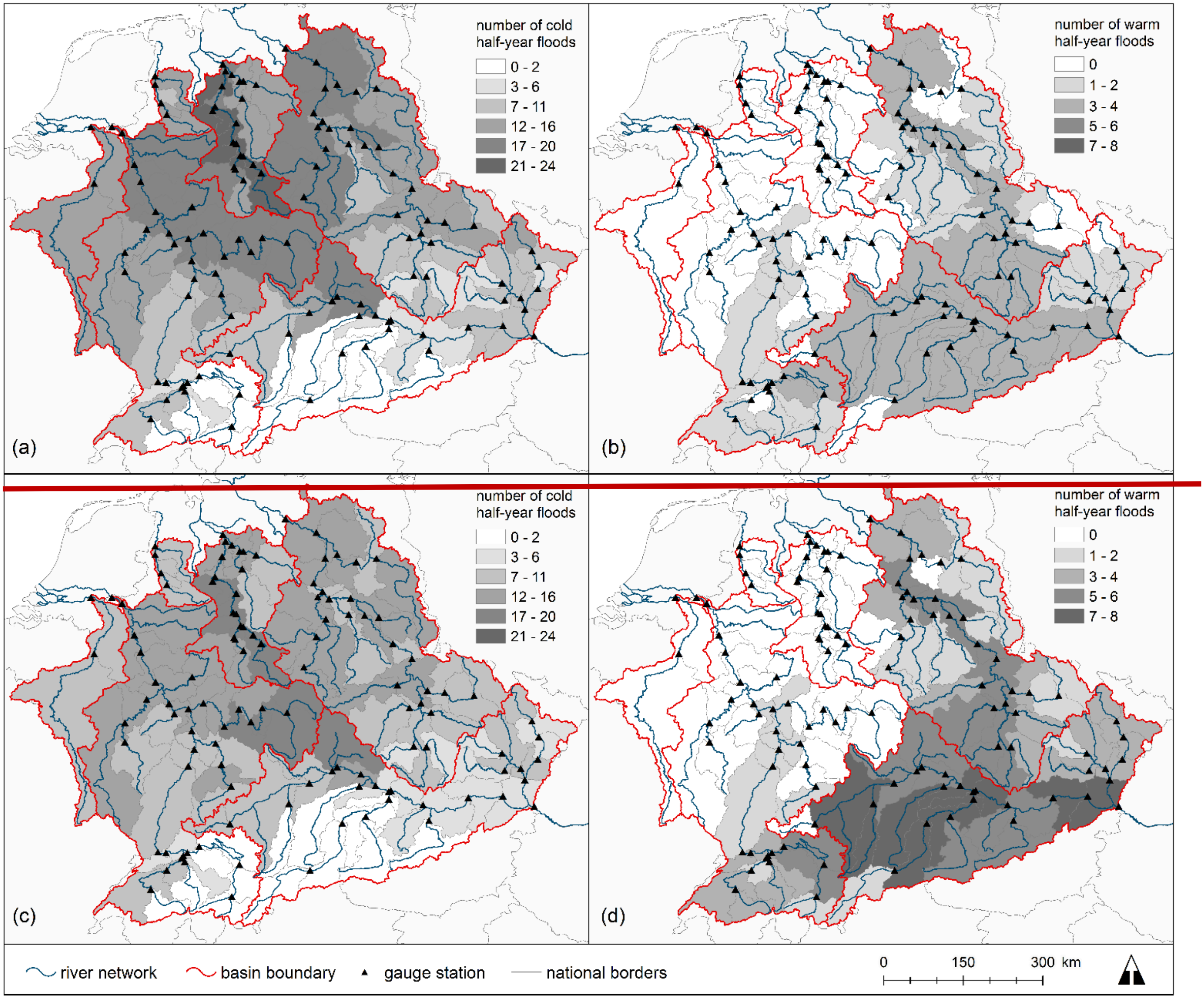


Figure 56: Interannual variability of 30 major floods according to E_{r2} and $E_{1.5r10}$. The number N of major floods in individual years is depicted by shading; the mixed color indicates overlapping data. The symbols represent the extremity of cold and warm half-year floods (solid symbols) and warm half-year floods (hollow symbols) with respect to E_{r2} [10^3] and $E_{1.5r10}$ [$5 \cdot 10^2$]; Solid linesLines depict the linear trends and relative cumulative values ofin the flood extremity.


number of cold half-year floods
0 - 2
3 - 6
7 - 11
12 - 16
17 - 20
21 - 24
(a)
number of warm half-year floods
0
1 - 2
3 - 4
5 - 6
7 - 8
(b)
number of cold half-year floods
0 - 2
3 - 6
7 - 11
12 - 16
17 - 20
21 - 24
(c)
number of warm half-year floods
0
1 - 2
3 - 4
5 - 6
7 - 8
(d)
river network
basin boundary
gauge station
national borders
0
150
300 km

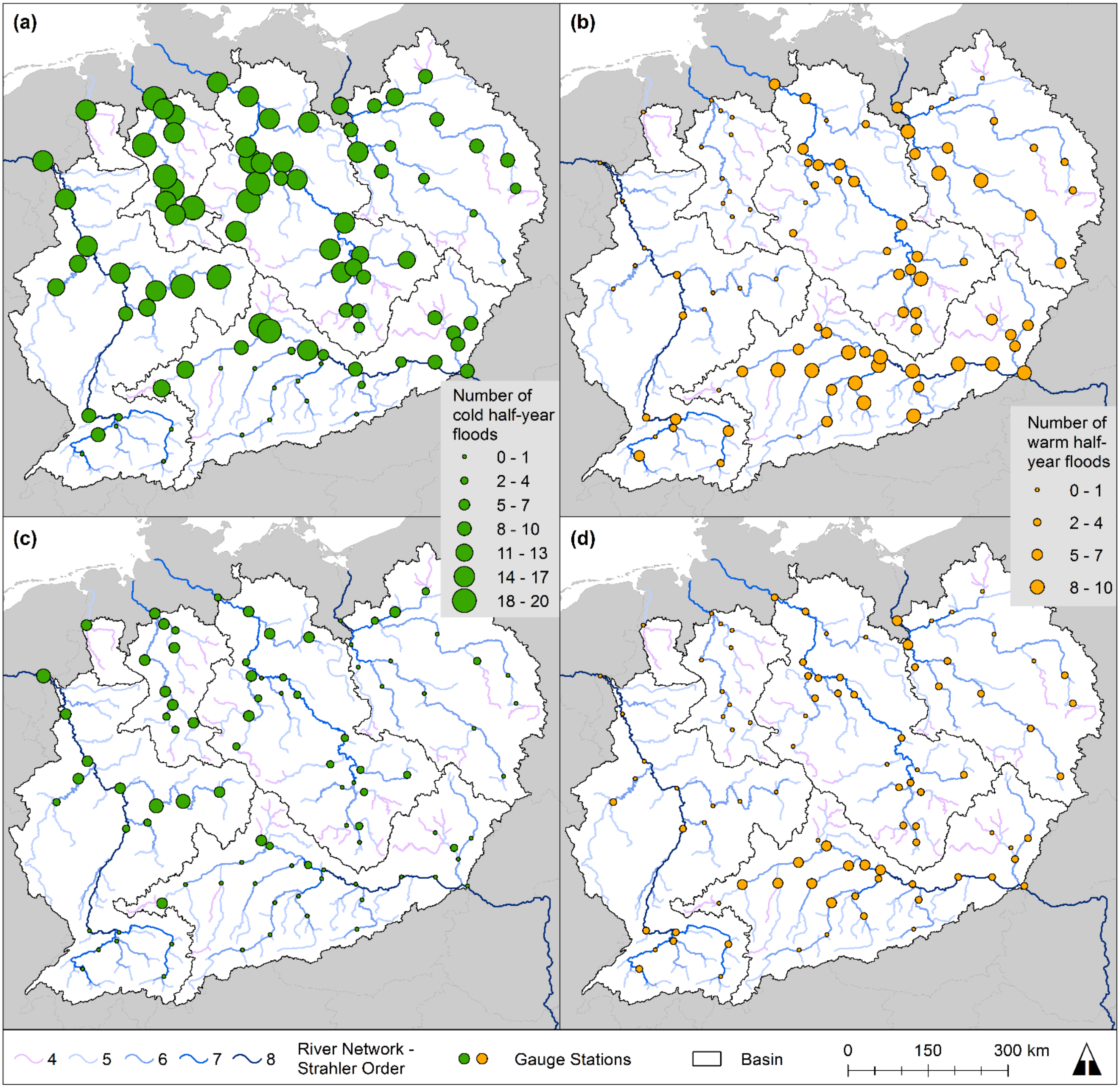


Figure ~~6~~7: Spatial distribution of 30 maximum floods according to $E_{~~r~~2}$ (a, b) and $E_{~~1.5r~~10}$ (c, d). The numbers of cold (a, c) and warm (b, d) half-year floods identified in individual gauge stations during~~subcatchments during 1950–2010~~1951-2013 are depicted by circle size~~shading~~.