Journal of Hydrology 371 (2009) 129–141

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002

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ARTICLE INFO

Article history:
Received 6 December 2007
Received in revised form 8 May 2008
Accepted 25 March 2009

This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Andreas Bardossy, Associate Editor

Keywords:
Floods
Trend
Non-stationarity
Climate change
Land use change
Germany

SUMMARY

During the last decades several destructive floods in Germany led to the impression that the frequency and/or magnitude of flooding has been increasing. In this study, flood time series are derived and analyzed for trends for 145 discharge gauges in Germany. A common time period of 52 years (1951–2002) is used. In order to obtain a country-wide picture, the gauges are rather homogeneously distributed across Germany. Eight flood indicators are studied, which are drawn from annual maximum series and peak over threshold series. Our analysis detects significant flood trends (at the 10% significance level) for a considerable fraction of basins. In most cases, these trends are upward; decreasing flood trends are rarely found and are not field-significant. Marked differences emerge when looking at the spatial and seasonal patterns. Basins with significant trends are spatially clustered. Changes in flood behavior in northeast Germany are small. Most changes are detected for sites in the west, south and center of Germany. Further, the seasonal analysis reveals larger changes for winter compared to summer. Both, the spatial and seasonal coherence of the results and the missing relation between significant changes and basin area, suggest that the observed changes in flood behavior are climate-driven.

Introduction

During the last decades several severe floods in different river basins in Germany (e.g., 1993 and 1995 Rhine; 1997 Odra; 1999, 2002 and 2006 Danube; 2002 and 2006 Elbe) caused extensive inundations and high flood damages (Grünewald et al., 1998; Disse and Engel, 2001; DKKV, 2004; Thieken et al., 2006). In the society and the media the impression grew that the flood situation is worsening in Germany, and that this perceived accumulation of large floods cannot be explained by natural variability. In view of the current debate on climate change, the worry that floods are becoming more severe or more frequent is rapidly gaining ground in the German public.

Flood estimation and flood design are traditionally based on the assumption that the flood regime is stationary. In particular, flood frequency analysis requires the flood data to be homogeneous, independent and stationary. Trends can have a profound effect on the results of flood frequency estimation and can undermine the usefulness of the concept of return period (Khaliq et al., 2006). If trends are present, flood estimation procedures have to allow for changing flood regimes, e.g., by assuming time-varying parameters of the flood frequency distribution (e.g., Strupczewski et al., 2001a, b).

There are many studies worldwide that analyze trends in different hydrological variables. Examples are the studies of Adamowski and Bocci (2001) on annual minimum, mean, and maximum streamflow, Kunkel et al. (1999) on extreme precipitation events, McNeil and Cox (2007) on stream salinity and groundwater levels, and Johnson and Stefan (2006) on lake ice cover, snowmelt runoff timing and stream water temperatures. However, only few studies can be found which focus on flood trends.

Table 1 summarizes the main findings of recent studies on flood trends. These studies have in common that large regions and a large number of discharge time series, measured at different gauges, are analyzed. This approach has two advantages. Firstly, it may be possible to identify spatial patterns in flood trends, and to distinguish basins which have been changing from those which have been stable. Secondly, the assessment of many gauges within one region may improve the signal-to-noise ratio. By studying single basins, existing trends may not be identifiable due to local noise and anthropogenic influences, such as river training works. The joint analysis of many basins decreases the influence of local noise. If trends can be identified that are coherent across several basins, these trends can be assumed to be a clear signal of change, and not the result of local, possibly random influences.

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doi:10.1016/j.jhydrol.2009.03.024

Table 1
Summary of recent studies on flood trends in observational data (annual maximum daily mean streamflow (AMAXF), peak over threshold (POT)).

Study	Region	No of stations	Observation period	Flood indicator				Main findings
				AMAXF	Seasonal AMAXF	POT	Other	
Svensson et al. (2005)	Worldwide	21	44–100 years; av. 68 years	X		X		• No general pattern of decreasing or increasing numbers or magnitudes of floods
Kundzewicz et al. (2005)	Worldwide	195	Varying periods; min. 40 years	X				• At 27 stations significant increases worldwide • At 31 stations significant decreases worldwide • At 137 stations • No significant changes no ubiquitous pattern worldwide
Adamowski and Bocci (2001)	Canada	248; pooled into 10 regions	1957–1997	X				• Significantly decreasing trends in western, northern and central-eastern Canada • Significantly increasing trends in central Canada and the Prairies
Burn and Hag Elnur (2002)	Canada	59 AMAXF; varying for other	1950–1997, varying periods	X			X	• For 1950-1997, in general, decreasing trends in AMAXF in the south and increasing trends in the northern regions of Canada
McCabe and Wolock (2002)	USA	400	1941–1999	X			X	• Relatively few sites with increasing/decreasing trends in AMAXF • Increases in AMAXF (and minimum and median streamflow) appear as step change around 1970 • Frequency of days with discharges >99th percentile shows increasing trends only at few sites
Douglas et al. (2000)	USA	1474	1874–1988 (av. 48 years)	X				• No trends in field significance in all three geographic regions (east, midwest, west) • No trends in field significance in all nine hydrologic regions
Franks (2002)	New South Wales (Australia)	40	Varying periods within 1910–1990	X				• Step change in AMAXF around the 1940s • Prior 1945 no floods of high magnitude, after 1945 marked increase
Lindström and Bergström (2004)	Sweden	43; pooled datasets	1901–2002	X	X			• Slight increase in AMAXF in northern Sweden • Summer and autumn floods increased considerably between 1970 and today • No increased frequency of floods with return periods >10 years for pooled data
Robson et al. (1998) and Robson (2002)	UK	890 for POT, 1000 for AMAXF, pooled across all sites	1941–1980; 1941–1990	X	X	X		• No significant trends for annual and seasonal flood time series • Quasi-cyclical fluctuations over 5–10 year periods in POT3 and AMAXF; could be linked to annual rainfall fluctuations

Climate change is not the only possible driver of change in flood time series. Germany is densely populated and has a long history of water resources management. Its basins and rivers cannot be assumed to be pristine. Most of the basins in Germany have undergone widespread land use changes, significant volumes of flood retention have been implemented in the last decades, and many rivers have experienced river training works (e.g., Helms et al., 2002; Lammersen et al., 2002; Mudelsee et al., 2004; Pfister et al., 2004a). In particular, the active floodplains of many rivers in Germany have been reduced through the construction of dykes. Pfister et al. (2004a) summarized the impacts of land use change in the Rhine catchment. Although the Rhine catchment has experienced widespread land use changes, significant effects on flooding could only be detected in small basins. There is no evidence for the impact of land use changes on the flood discharge of the Rhine river itself. These findings are in line with different studies, which found little or no influence of land use on flood discharge (Blöschl et al., 2007; Robinson et al., 2003; Svensson et al., 2006). Blöschl et al. (2007) argued that the impact of land use changes on floods is a matter of spatial scale. In small basins land use changes can significantly alter the runoff processes, effecting flood magnitude and frequency. However, these effects are expected to fade with increasing basin scale.

The general tendency of decreasing impacts with increasing basin scale does not apply to river training works. On the contrary, river training impacts are likely to increase with catchment size as there is a tendency for larger settlements and hence large-scale flood protection works at larger streams (Blöschl et al., 2007). The cumulative effects of river training works on floods in large basins are difficult to assess. Large-scale hydraulic models are necessary that are able to consider the effects of flood protection, such as river dykes, on the flood waves. Therefore, reliable quantifications of these effects are rare. To complicate matters, the effects are expected to vary with flood magnitude. For example, Apel et al. (in press) investigated the impact of dyke breaches along the lower Rhine. They showed that dyke overtopping and successive dyke breaching lead to large retention effects due to the inundation of the dyke hinterland. Since large retention volumes are activated as consequence of dyke failures, flood peaks are significantly reduced downstream of breach locations. These effects, however, occur only for rare floods with return periods larger than approximately 400 years (Apel et al., in press). Lammersen et al. (2002) analyzed the effects of river training works and retention measures on the flood peaks along the river Rhine. The construction of weirs along the upper Rhine in the years 1955–1977 accelerated the flood wave, leading to a higher probability that the flood peak of the Rhine coincides with the peaks of its tributaries, such as the Neckar. After 1977, extensive retention measures along the main stream have been planned and partially implemented. Averaged across many flood events, the river training works have increased the flood peaks at Cologne and the retention measures have decreased the peaks, however to a smaller extent. Today's flood peaks at Cologne are expected to be a few percent higher than before the extensive river training works in the 1950s.

The detection of coherent flood trends at many sites in a geographic region may allow distinguishing climate-related changes from other anthropogenic changes. Although local effects and anthropogenic influences, such as flood control measures, may markedly influence the at-site flood behavior, such changes are not expected to cause coherent changes over a large geographical area.

Table 1 lists nine recent studies which analyzed flood trends in a large number of basins. All studies used the annual maximum streamflow (AMAXF) as flood indicator. Other indicators, that are less often used, are peak over threshold time series (POT) or streamflow percentiles. In two cases only, seasonal AMAXF have been used, differentiating between summer and winter floods. Table 1 shows that there are no ubiquitous flood trend patterns and that seasonally and regionally different patterns in flood trends have to be expected. This result calls for trend analyses that take into consideration seasonal and spatial differences. Most of the studies compiled in Table 1 have their regional focus on north-America. Only few studies on flood trends in Europe, covering large regions or entire countries, could be found. These are the studies of Robson et al. (1998) and Robson (2002) for UK, and of Lindström and Bergström (2004) for Sweden. Besides, there are recent studies on flood trends for large areas or sub-catchments such as Lammersen et al. (2002) and Pfister et al. (2004a), or Pinter et al. (2006), who studied issues on the flood hazard for parts of the Rhine catchment. Also studies for parts of the Elbe and Weser catchments were compiled, e.g., by Helms et al. (2002) or Mudelsee et al. (2006).

Main problems of flood trend analysis are data availability and data reliability. Many discharge time series are short and are not suited for analyzing extreme events. Kundzewicz et al. (2005) suggested a minimum length of 50 years for flood trend detection. For some gauges there are systematic discharge observations in the range of 100 years or even more. Such time series are very valuable; however, the quality of these data has to be examined carefully. Lindström and Bergström (2004) emphasised the need to balance availability and reliability: very long discharge time series might not be reliable, but reliable series might be too short.

There exist some studies on flood trends in Germany, which are however restricted to specific regions or catchments. Mudelsee et al. (2006) analyzed flood trends during the last 500 years in the Werra catchment (sub-catchment of the Weser). Winter flood hazard showed an increase during the last decades, whereas the summer flood hazard showed a long-term decrease from 1760 on. Mudelsee et al. (2004) analyzed winter and summer flood trends at six gauges at the middle Elbe and middle Odra and found significant downward trends in the occurrence rates of winter floods and no significant trends for summer floods during the 20th century. Moreover, they found significant variations of occurrence rates for heavy floods during the past centuries and notable differences between Elbe and Odra. Similarly, Grünewald (2006) illustrated that the seasonal distribution of floods at the gauge Dresden/Elbe varied significantly during the last 1000 years. Caspary and Bárdossy (1995) analyzed AMAXF of gauges along the river Enz in south-western Germany (sub-catchment of the Rhine) for the period of 1930–1994. They identified significant upward trends in AMAXF. Bendix (1997) found significant trends in magnitude, whereas Pinter et al. (2006) found significant upward flood trends in magnitude as well as frequency in the Rhine catchment at the gauges Cologne (1900–2002) and Bonn. An increased flooding probability was also suggested for the middle and lower Rhine by Pfister et al. (2004a). In the Danube and Rhine catchments (for five gauges with varying time periods) upward trends in AMAXF were detected by Caspary (1995) and Caspary and Bárdossy (1995). KLIWA (2007) analyzed flood trends of 158 gauges in southern Germany. Long time series of 70–150 years mostly revealed no trends. However, the study of the last 30 years showed at many gauges significant upward trends in AMAXF. Moreover, the frequency of winter floods increased since the 1970s in many basins.

This compilation of the trend analyses for German rivers shows that there is no unambiguous pattern of flood trends across Germany. Further, the studies available are limited to selected regions or single basins. There is no comprehensive study on flood trends in Germany which covers the entire country. This gap is filled by this paper for the period 1951–2002. This is a period with (1) a good coverage of discharge sites with reliable observations and (2) significant increases of concentrations of atmospheric greenhouse gases. 'Data and Methodology' introduces the data and the methods, respectively. In 'Results' the results are presented for eight flood indicators. Finally, the findings are discussed against the background of studies on recent temporal changes in atmospheric circulation patterns ('Discussion'). In particular, it is discussed if the identified changes are caused by climate variability or by other drivers.

Data

Discharge time series were obtained from the water authorities of different federal states in Germany. Since the data are part of the hydrometric observation network of the water authorities in Germany, the observations are regularly checked and can be assumed to be of good reliability, although it is acknowledged that flood peak measurements are frequently associated with considerable errors. Sites were selected with a catchment size of at least 500 km^2. In that way, small catchments were excluded from the analysis but still a large number of gauging stations and a satisfying spatial coverage of Germany were obtained. Although there is considerable uncertainty about the scale where changes in land use and land management in a specific basin cannot be seen anymore in the basin flood hydrograph (Blöschl et al., 2007), 500 km^2 seems a reasonable choice for the lower limit. Beyond that scale, most of the effects of land use and land management are expected to have been faded out (e.g., Ihringer, 1996; Michaud et al., 2001; Bronstert et al., 2002). A common time period between 1.11.1951 and 30.10.2002 was used (hydrological year in Germany: 1 November–31 October). Small gaps in the data of up to one year were marked as "missing values". This was necessary at only five gauges. Time series with larger successive gaps were excluded from the analysis. Finally, time series of mean daily streamflow from 145 gauges in Germany were included in the analysis. They are relatively homogeneously distributed across Germany (Fig. 1). Forty-three stations are located in the Danube catchment, 37 in the Rhine catchment, 32 in the Elbe catchment and 27 in the Weser catchment. The catchments of Ems and the small German part of the Odra are represented by four and two gauge stations, respectively. Only the Maas and the Baltic Sea catchments are not represented in the study. Germany is located in the thermal-hydrologic transition zone between the Atlantic Western Europe and the continental climate in eastern Germany. The entire country is influenced throughout the year by westerly atmospheric circulation types. However, the influence decreases from west to east. The Rhine and Weser catchments are dominated by westerly, north-westerly and south-westerly circulation types with associated mid-latitude cyclone rainfall (Beurton and Thieken, 2009). High pressure systems occur rarely except for spring, and Vb-weather-regimes are infrequent in north-eastern part. Floods occur predominantly during the mild and wet winter. The Weser as well as parts of the upper Rhine catchments are found in the transition zone from Atlantic to continentally influenced climates. There, floods also occur mainly during the winter time however the share of summer flood events increases from west to east (Beurton and Thieken, 2009). The Elbe, Danube and Odra catchments are characterized by a smaller influence of westerly, north-westerly and south-westerly circulation types, a larger share of high pressure

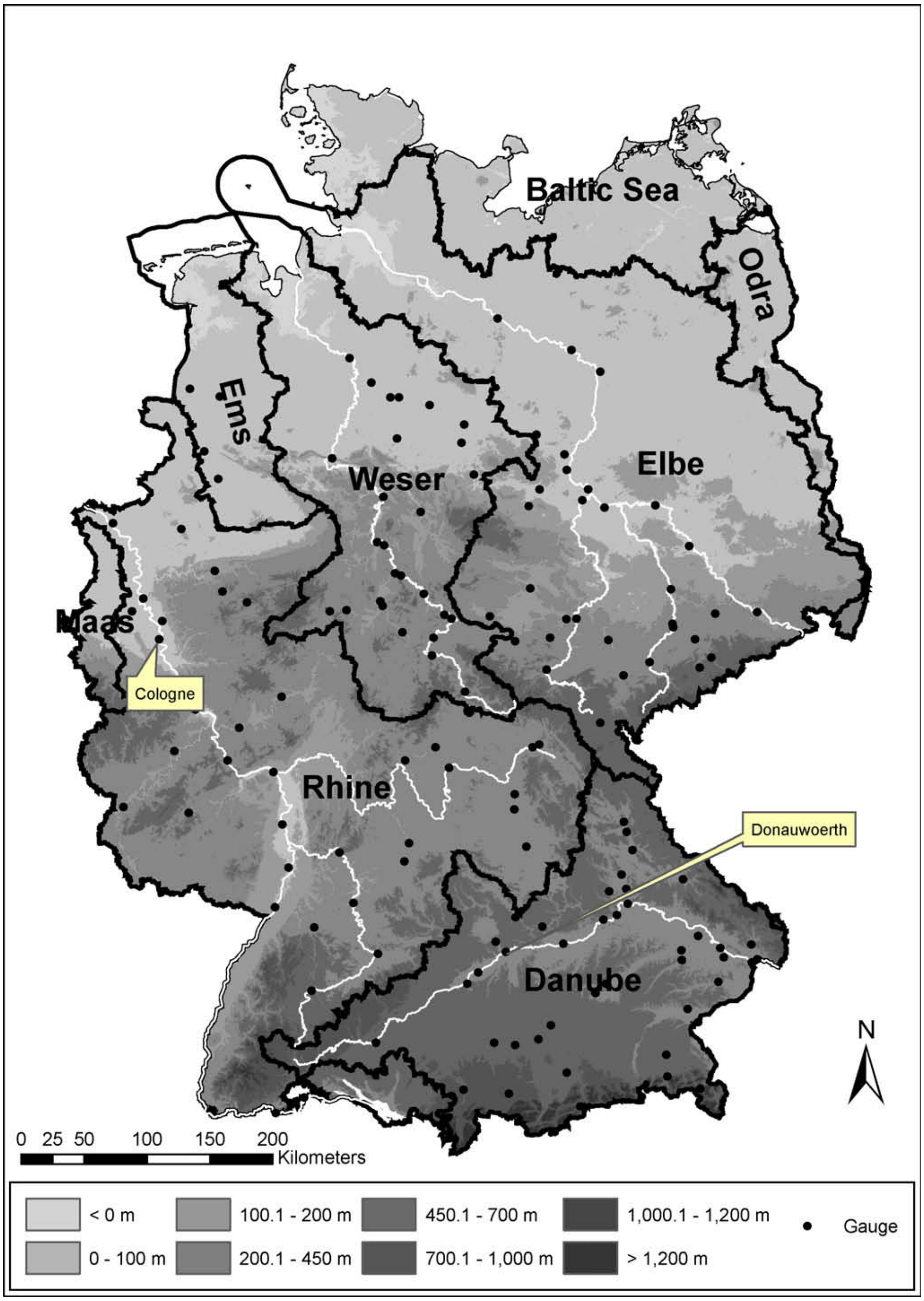

Fig. 1. Location of the analyzed gauges, main rivers, large river basins and elevation above sea level (in m).

systems, and the occurrence of Vb-weather regimes. The Vb-weather regime is a trough over Europe, which can bring long-lasting heavy rainfalls causing destructive floods in these catchments. Although winter floods dominate in the Elbe, Odra and northern Danube catchments, summer floods can reach remarkable discharges as experienced in 1997, 2002, 2005 (DKKV, 2004). The southern part of the Danube catchment is dominated high pressure systems, especially during fall and winter. Westerly, north-westerly and south-westerly circulation types are less frequent. In this region, summer floods dominate.

Selected results are shown exemplarily for the gauges Cologne (catchment size 144,323 km^2) in the Rhine catchment and Donauwoerth (catchment size 15,037 km^2) in the Danube catchment (Fig. 1). These gauges were selected because their behavior can be seen to be representative for most gauges in Germany. The gauge Cologne is dominated by winter floods and slowly rising water levels, which is typical for most gauges in the Rhine, Weser, as well as parts of the Elbe catchments. The discharge behavior at Donauwoerth (Danube) is dominated by summer floods and represents gauges in the mountain ranges with faster runoff regimes, especially in the catchments of Elbe and Danube.

Eight flood indicators, which are listed in Table 2, were included in our study. These comprise annual maximum streamflow series (AMAX) as well as peak over threshold series (POT). Annual maxi-

Table 2
Flood indicators studied for all gauges.

Flood indicator	Abbreviation	Remarks
Annual maximum daily mean streamflow (m^3/s)	AMAXF	Maximum discharge for each hydrological year (1 November–31 October)
Annual winter maximum daily mean streamflow (m^3/s)	AWMAXF	Maximum discharge for each hydrological winter (1 November–31 March)
Annual summer maximum daily mean streamflow (m^3/s)	ASMAXF	Maximum discharge for each hydrological summer (1 April–31 October)
Peak-over-threshold magnitude (m^3/s)	POTXM	Discharge peaks above threshold; on average X events per year
Peak-over-threshold frequency	POT3F	Annual number of discharge peaks above threshold; on average three events per year
Summer peak-over-threshold frequency	SPOT3F	Annual number of summer discharge peaks above threshold
Winter peak-over-threshold frequency	WPOT3F	Annual number of winter discharge peaks above threshold

mum daily mean streamflow, i.e. the largest daily mean streamflow that occurs in each hydrological year, is the most common indicator in flood trend studies. In some studies, POT series are used since they are considered to include more information and thus allowing to reveal better the temporal pattern of flood occurrence (Svensson et al., 2006). Besides the detection of trends in flood magnitude, they offer the possibility to analyze the flood frequency, i.e. changes in the number of floods occurring each year.

We selected the 52 largest independent flood events (POT1) and another series with on average three events per year for the POT time series (POT3). For our time frame of 52 years (1951–2002) the POT3 samples include the largest 156 independent discharge peaks. In order to ensure independence of the different flood events, we tested different time spans of 10, 20 and 30 days. Svensson et al. (2005) used thresholds which depended on catchment size: 5 days for catchments <45,000 km^2; 10 days for catchments between 45,000 and 100,000 km^2; 20 days for catchments >100,000 km^2. In our study, 85% of the catchments are smaller than 45,000 km^2. Following Svensson et al. (2005) a 10 day time span would be sufficient for most gauges. Visual inspection of the hydrographs of some of the larger catchments as well as the spatial distribution on the map of the trend results of the different flood indicators with different time spans supported the time frame of 10 days to be sufficiently long to ensure independence of the extracted flood peaks. POT1 and POT3 variables were selected by the magnitude of the flood events (POT1M, POT3M) and the frequency per year (POT3F). For this, the number of POT3M events for every year was counted.

In addition to the annual flood time series, seasonal time series were derived, distinguishing between winter (1 November–31 March) and summer (1 April–31 October). For example, the annual winter maximum streamflow time series (AWMAXF) consists of the largest daily mean discharge of the winter period of each year. In the case of the POT time series, POT3F was separated in summer and winter events. For example, the winter POT3F time series (WPOT3F) indicates the number of floods within the winter period, given that, on average, three events were selected per year.

Methodology

There are different possibilities for testing for change in hydrological time series (e.g., Kundzewicz and Robson, 2004). In this study we used the Mann–Kendall test (Kendall, 1975), a robust non-parametric test. The Mann–Kendall test is particularly useful for the analysis of extreme, not necessarily normally-distributed data (Kunkel et al., 1999). It has been used by many studies on trends in hydrological time series (e.g., Chen et al., 2007). We applied the 2-sided option with 10% significance level.

The Mann–Kendall test requires the data to be serially independent. von Storch and Cannon (1995) found that, if the data are positively serially correlated, the Mann–Kendall test tends to overestimate the significance of a trend. To correct the data for serial correlation, the procedure of trend free pre-whitening (TFPW) was applied, which is described in detail in Yue et al. (2002, 2003). Firstly, the trend of a time series is estimated by the non-parametric trend slope estimator developed by Sen (1968). This estimation of the trend slope β is more robust than a normal linear regression (Yue et al., 2003). β is the median of all pair wise slopes in the time series:

$$\beta = median\left[\frac{x_j - x_i}{j - i}\right] \quad \text{for all } i < j;\ x_i,\ x_j = \text{discharge values in years } i,\ j \tag{1}$$

Secondly, the calculated trend is removed from the original series:

$$Y_t = X_t - \beta * t \tag{2}$$

with X_t being the original time series and t is the time.

Third, the lag1-autocorrelation (*acf*) is calculated. If no significant autocorrelation is found, the Mann–Kendall test is directly applied to the original time series. Otherwise, the lag1-autocorrelation is removed from the time series:

$$Y'_t = Y_t - acf * Y_{t-1} \tag{3}$$

The Y'_t time series should now be free of a trend and serial correlation. Finally, the firstly removed trend is included back into the time series.

$$Y''_t = Y'_t + \beta * t \tag{4}$$

The resulting time series Y''_t is a blended time series including the original trend but without autocorrelation.

In trend detection studies, that analyze many sites within a region, it is interesting to assess the field significance, i.e. the significance of trends across the region (Douglas et al., 2000; Burn and Hag Elnur, 2002; Svensson et al., 2006). This is done by comparing the number of observed significant trends with the number expected within the region. Douglas et al. (2000) found that the existence of spatial correlation between sites may inflate the results of change detection, if the spatial correlation is not accounted for. They proposed a bootstrapping test for assessing the field significance of trends with preserving the cross-correlation among sites. However, this approach might be suitable only for the case that the majority of trends in a region are uniform, i.e. either upward or downward (Yue et al., 2003). Therefore, we applied a slightly refined approach, proposed by Yue et al. (2003), which assesses the field significance of upward and downward trends separately.

In short, the test works as follows (for details see Yue et al., 2003):

1. The selected range of years is resampled randomly with replacement. A new set is obtained with different year order but with the same length.
2. The observation values of each site are rearranged according to the new year set obtained in step 1. In this way, the spatial correlation of observation values is preserved, whereas the temporal order is destroyed.

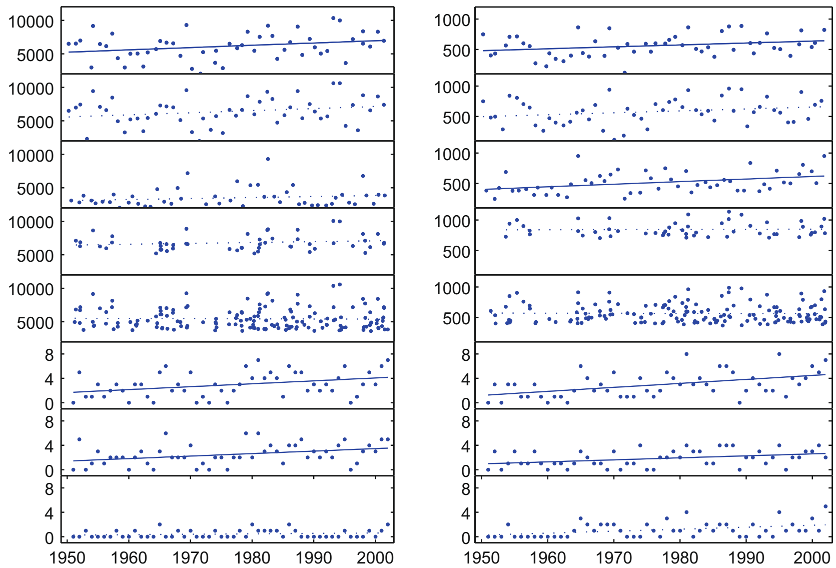

Fig. 2. Observations and linear regression trends in the flood indicators given in Table 2. Solid lines indicate significant trend (10% significance level), dotted lines indicate no trend. Left column: gauge Cologne; right column: gauge: Donauwoerth. From top to bottom: AMAXF, AWMAXF, ASMAXF, POT1M, POT3M, POT3F, WPOT3F, and SPOT3F.

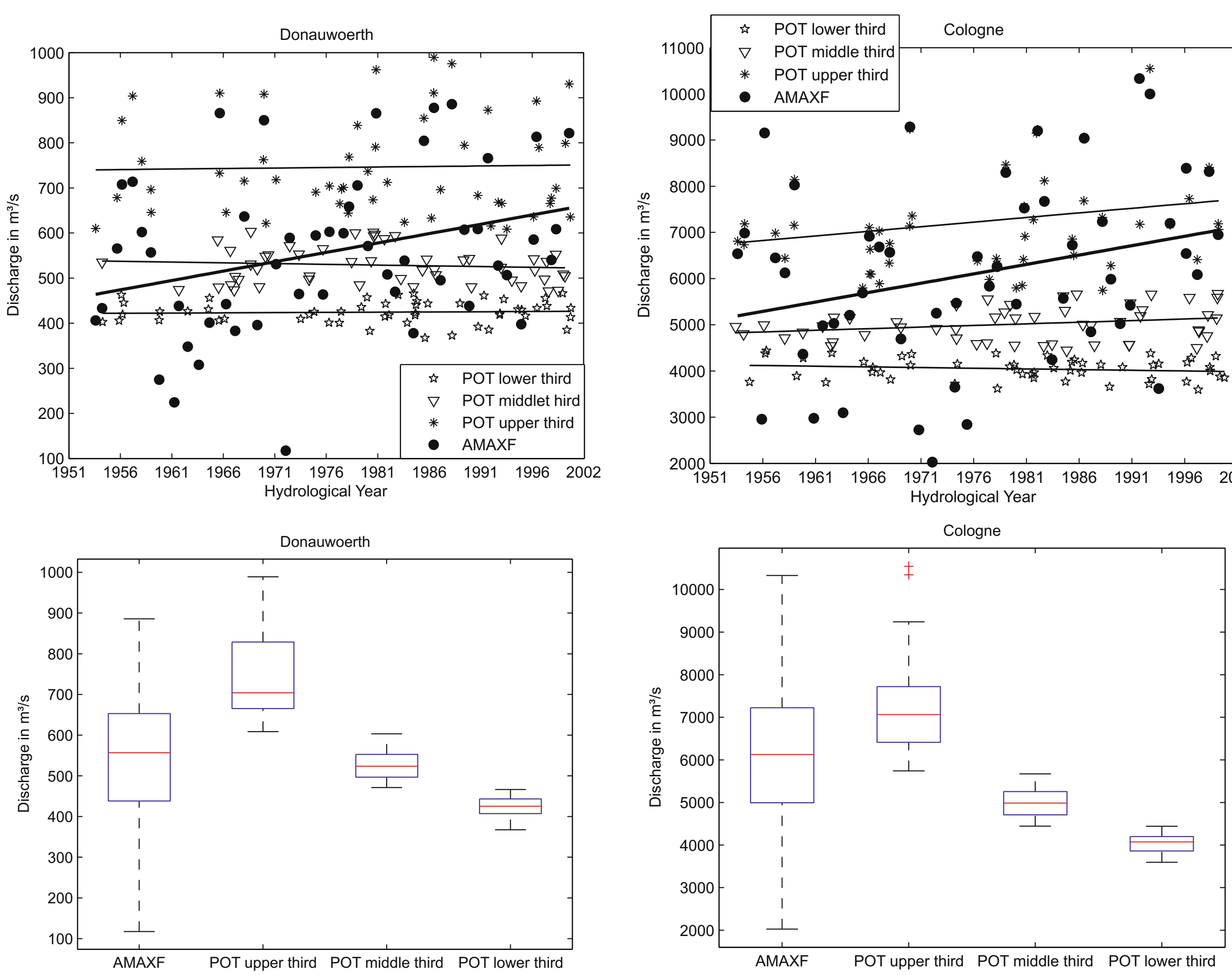

Fig. 3. Observations and linear regression trends in AMAXF and in the three time series that resulted from the stratification of POT3M in the upper, middle and lower third (upper panel). Lower panel: Boxplots of the four samples (red line: median; box: interquartile range; whiskers: minimum and maximum value; crosses: outliers). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. The Mann–Kendall test is applied to the synthetic time series of each site. At the given significance level, the number of sites with significant upward trends (N^*_{up}) and downward trends (N^*_{down}), respectively, is counted.
4. By repeating steps 1–3 1000 times, two samples with a sample size of 1000 each are obtained.
5. The probability of the number of significant upward (downward) trends N^{obs}_{up}(N^{obs}_{down}) for the observed time series is assessed by comparing N^{obs}_{up}(N^{obs}_{down}) with the empirical cumulative distribution of N^*_{up}(N^*_{down}). If this probability is smaller than the significance level, then the trend is judged to be field-significant.

Results

Results for the gauges Cologne/Rhine and Donauwoerth/Danube

We are mainly interested in the question, if there are coherent spatial patterns of flood trends across Germany during the last five decades. However, to facilitate the understanding of the spatial results, the trend analyses are exemplarily discussed for the gauges Cologne/Rhine and Donauwoerth/Danube (locations see Fig. 1).

Fig. 2 shows the observations and the linear regression trends in the eight flood indicators given in Table 2. For both sites, significant upward trends in AMAXF were found. The comparison of the annual maxima with the seasonal maxima shows that, in the case of Cologne, AMAXF is determined by floods in the winter season. Summer floods are significantly smaller than winter floods. Both seasonal time series show upward trends, however, they are not significant at the 10% significance level. In the case of Donauwoerth, summer floods are only slightly smaller than winter floods. Increasing trends were detected in both seasons; however, the trend in the winter season is not significant. Although the linear regression trends in AMAXF and AWMAXF have equal gradients, the trend in AWMAXF is not significant due to the larger standard deviation of AWMAXF.

Contrary to AMAXF, no trends in POT1M and POT3M were identified for both gauges. Actually, both trend lines of POT3M show small decreases. That means that a significant increase in the number of discharge peaks above the threshold does not necessarily comply with a significant increase in the magnitude of these peaks – a result that was also found by Svensson et al. (2005). To understand this discrepancy, the POT3M time series were further separated in the upper, middle and lower third. Fig. 3 compares AMAXF with these three samples. The POT thirds have a much smaller range compared to AMAXF. For both gauges, the POT time series show no or only mild increases, whereas AMAXF grows significantly. This marked increase is mainly a result of several very small annual floods that were lower than the POT3M threshold. Interestingly, these small discharge values occurred exclusively during the first half of the time period. The larger discharge peaks, represented by POT upper third, increased only slightly.

The POT3F time series of both gauges show a very similar behavior (Fig. 2). Trends in POT3F are upward and significant. For both sites, the frequency of discharge peaks above the POT3M threshold increased, although the magnitude of these events

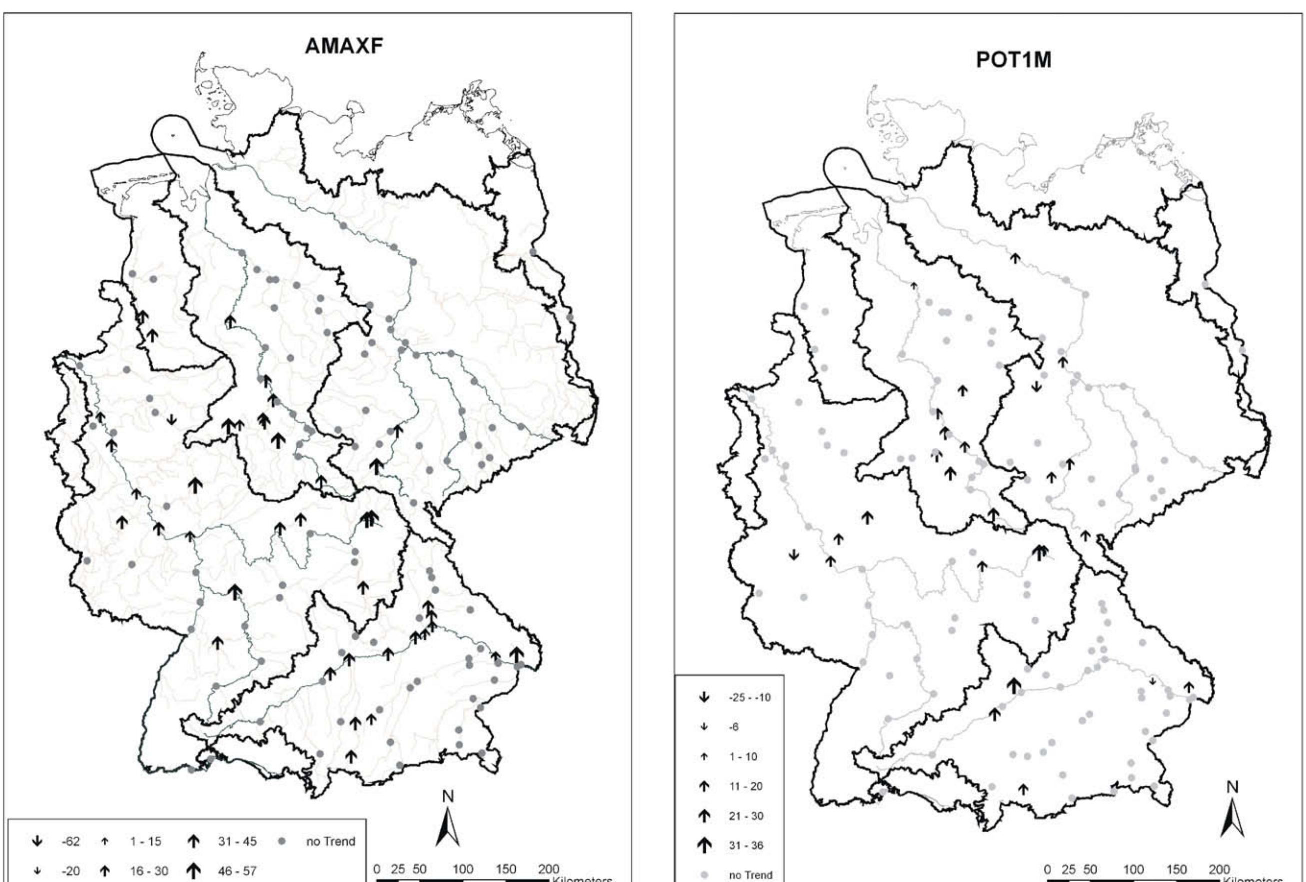

Fig. 4. Spatial distribution of trends in annual maximum daily mean streamflow – AMAXF (left) and in peak-over-threshold magnitude with on average one event per year – POT1M (right); (upward arrows: significant increasing trend; downward arrows: significant decreasing trend; circles: no significant trend; size of arrows: relative change within 52 years; Mann–Kendall test, 2-sided option; 10% significance level).

(POT3M) did not experience a significant change. The seasonal separation of POT3F yielded significant increasing trends for winter (WPOT3F), i.e. the number of high discharge events during the winter season grew. For both cases, the number of discharge peaks in summer (SPOT3F) above the POT3M threshold increased as well; however, this increase does not suffice to be significant.

Spatial distribution of significant trends

In this section the spatial distribution of significant upward and downward trends is shown and the field significance is calculated for the different flood indicators. All maps showing the magnitude and direction of significant trends use the same markers: Upward arrows indicate significant increasing trends, and downward arrows show significant decreasing trends. The size of the arrows corresponds in all maps to the relative increase ΔX_R within 52 years (1951–2002):

$$\Delta X_R = \frac{X^*_{2002} - X^*_{1951}}{\overline{X}} \cdot 100\%$$

X^*_{2002} and X^*_{1951} are the value of the estimated trend line at the end and at the start of the analyzed time period, respectively. $\overline{X}$ is the mean value of the time series of the period 1951–2002.

The majority of the 145 gauges showed at least one significant result when analyzed for trend in the eight flood indicators. In the Elbe catchment, no trend in any of the flood indicators was found for nearly 60% of the gauges, whereas in all other catchments 50–75% of the gauges showed at least one significant trend. Forty-two percent of the Danube gauges, 46% of the Rhine gauges and 30% of the Weser gauges showed at least two significant trends. These numbers already hint to regional differences: The sites in the Elbe basin showed less change in flood indicators compared to sites in the Rhine, Weser and Danube catchments.

Fig. 4 shows the spatial distribution of significant trends in AMAXF. At 41 gauges (28% of all sites) significant increasing trends were detected, whereas only two gauges showed significant decreasing trends. An interesting spatial pattern emerges: all sites with significant trends are located in the southern, western and central parts of Germany. A relatively sharp line from northwest to southeast can be drawn, which separates the region with trends from the region without trends. Along the middle and lower Rhine main river as well as along the Danube main river most of the gauges show significant trends. In the Weser and Elbe catchments there are only some gauges with increasing trends in the upper reaches of some sub-catchments.

The trend analyses for the winter maxima gave similar results as the analyses for the annual maxima. Significant upward trends in winter maxima were identified at 23% of all sites. No significant downward trends were detected. The spatial pattern is only slightly different: The gauges with significant upward trends for annual winter maximum are found in a diagonal band stretching from northwest to southeast of Germany (Fig. 5; left). North and south of this band were no or only non-significant trends detected. In the Rhine and Danube catchments, the lower number of trends in AWMAXF, compared to AMAXF, is mainly due to a smaller number of significant trends along the main rivers (Rhine, Danube).

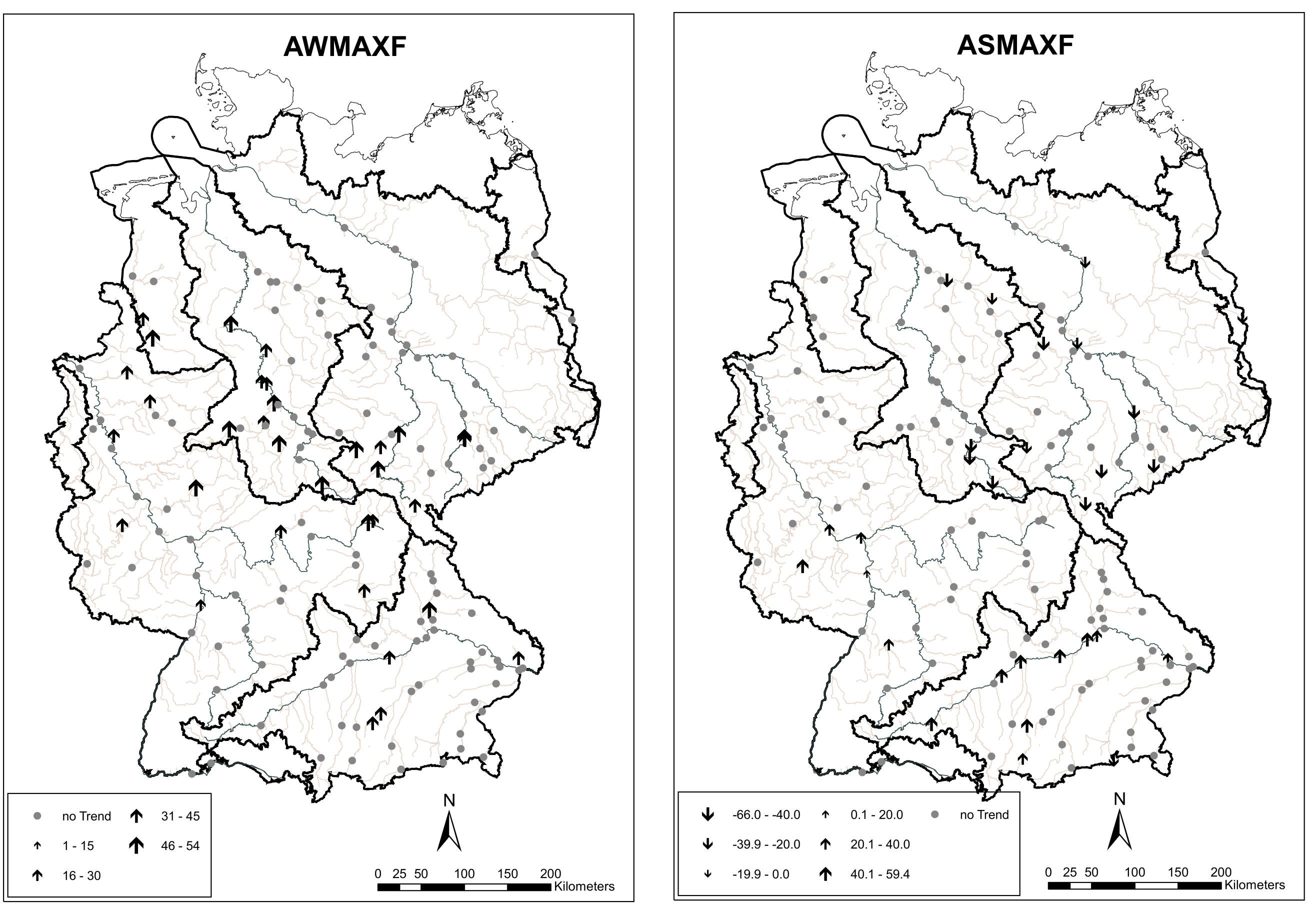

Fig. 5. Spatial distribution of trends in seasonal maximum series – AWMAXF (winter, left map), ASMAXF (summer, right map) (upward arrows: significant increasing trend; downward arrows: significant decreasing trend; circles: no significant trend; size of arrows: relative change within 52 years; Mann–Kendall test, 2-sided option; 10% significance level).

A smaller number of significant trends (29 gauges corresponding to 20% of all gauges) were found for the summer maxima (ASMAXF). In contrast to AWMAXF, where all detected trends are upward, the trend analysis of ASMAXF resulted in the same number of upward and downward trends. Moreover, there is a clear spatial distinction between the regions with upward and downward trends, respectively (Fig. 5; right). Only gauges in central and northern Germany in the catchments of Weser, Odra and Elbe show downward trends, whereas the upward trends are exclusively found at gauges in southern and western Germany in the Rhine and Danube catchments.

At 18% of the gauges significant trends in the POT1M time series could be detected. Due to the spatial concentration in central Germany field significance was observed. As could be expected, many gauges show significant trends in AMAXF as well as in POT1M. A similar spatial pattern was detected for the POT2M variable (not shown), with however less significant trends (16%). The POT3M time series show almost no significant trends across Germany. Only 7% of the gauges have significant trends. These are not spatially clustered, but are rather randomly distributed all over Germany (not shown). The gauges Cologne/Rhine and Donauwoerth/Danube are two examples for this behavior where significant changes in AMAXF are not matched with significant changes in POT3M.

In contrast to POT3M, significant trends in the peak-over-threshold frequency POT3F were identified at many gauges: 25% of all gauges show an increasing trend, 1% a decreasing trend. With the exception of two gauges in the Elbe catchment, only gauges in the Rhine and Danube catchments show a significant change in flood frequency (Fig. 6). The relative change of the POT3 frequency is rather large with values up to 140%. This upper value means that the number of discharge peaks above the threshold has increased approximately fivefold, from one event per year in the 1950s to five events per year at the end of the study period. The spatial distribution of gauges with significant trends is very similar to the result of AMAXF. Again, a relatively sharp line from northwest to southeast Germany can be observed which separates the region of no trend from the one with positive trends. The seasonal separation of the POT3F variable illustrates very well that the majority of the positive trends is caused by significant upward trends in the frequency of the winter floods, whereas POT3F summer events only increase at three gauges in the Danube catchment (Fig. 7). Again, the Rhine and Danube catchments are mainly affected by the changes in the flood discharge behavior.

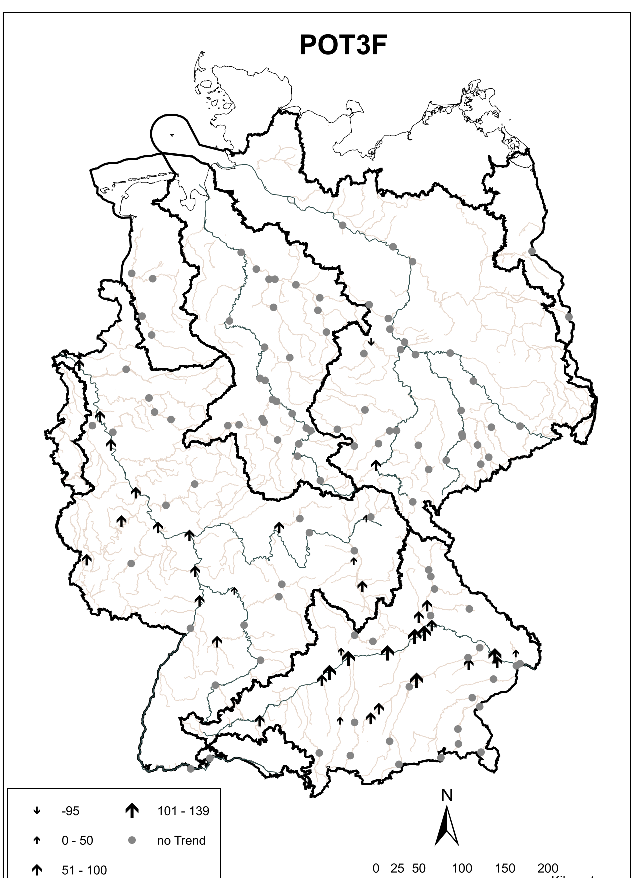

Fig. 6. Spatial distribution of trends in the peak-over-threshold frequency – POT3F (upward arrows: significant increasing trend; downward arrows: significant decreasing trend; circles: no significant trend; size of arrows: relative change within 52 years; Mann–Kendall test, 2-sided option; 10% significance level).

Table 3 summarizes the results for the eight flood indicators. Field significance at the 10% significance level was detected for AMAXF, AWMAXF, POT3F and WPOT3F. In all four cases, upward trends are the cause for the changes in flood behavior. No field significance could be found for decreasing trends for all flood indicators. The changes in the summer flood behavior (ASMAXF, SPOT3F) are too small to be counted as field significant.

Scale-dependency

Finally, it is assessed if a scale-dependency can be found in the trend analyses, i.e. it is assessed if large changes are related to small or large basins, respectively. To this end, the relative changes in each flood indicator were plotted against the basin area, and significant changes were marked (Fig. 8). No scale-dependency can be observed. There are no spatial scales where significant changes are concentrated. On the contrary, significant changes and no changes, respectively, are found at all spatial scales.

Discussion

The analysis of trends in eight flood indicators for 145 gauges across Germany yields a number of interesting results. Overall, it can be summarized that the flood hazard in Germany increased during the last five decades, particularly due to an increased flood frequency. Marked differences emerge when looking at the spatial and seasonal patterns and at different flood indicators. An important observation is that sites with upward and downward flood trends are spatially clustered. Changes in the flood behavior in northeast Germany are small. Most changes were detected for sites in the west, south and center of Germany. Further, the seasonal analysis revealed larger changes for winter compared to summer.

The results are summarized in Fig. 9 which highlights the fraction of gauges with significant changes, stratified according to flood indicators and according to the large river basins Danube (D), Rhine (R), Elbe (E) and Weser (W). Mostly increasing trends were detected, with large shares of significant trends in AMAXF and POT3F. Approximately 1/3 of the sites in the western and southern parts of Germany (Danube, Rhine, Weser) have significant upward trends in AMAXF, whereas there are almost no upward trends in eastern Germany (Elbe). Upward trends in AMAXF in the Rhine and Weser basins can be attributed to trends in the winter season, since the flood regime is dominated by winter floods, i.e. the largest share of annual maxima in the Weser basin and in the middle and lower Rhine basin occurs in the winter season. This is also the reason, why the relatively large number of gauges with downward trends in maximum summer floods in the Weser basin is not reflected in the AMAXF.

Compared to Rhine and Weser, the sites in the Danube catchment are much more influenced by summer floods. Accordingly,

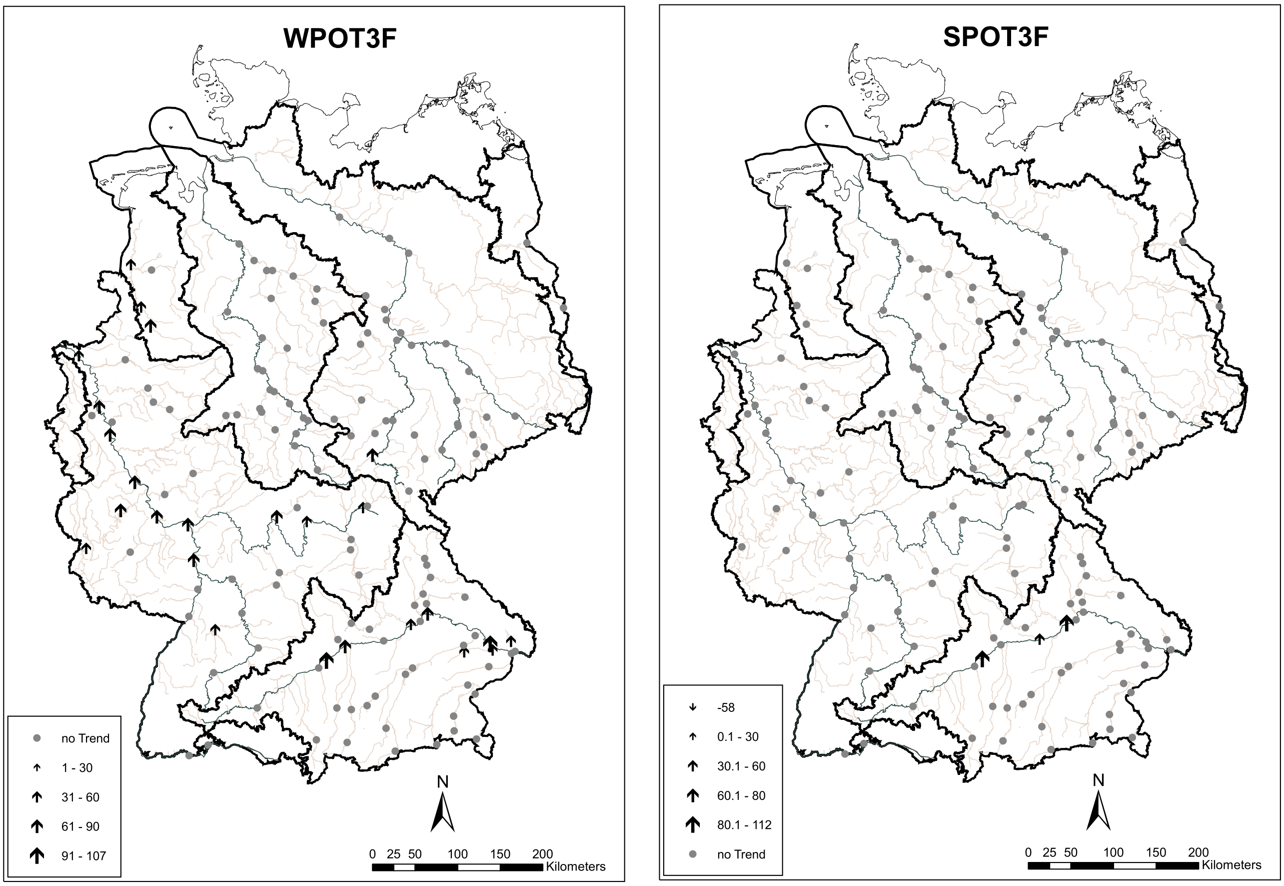

Fig. 7. Spatial distribution of trends in seasonal peak-over-threshold frequency – WPOT3F (winter, left map), SPOT3F (summer, right map) (upward arrows: significant increasing trend; downward arrows: significant decreasing trend; circles: no significant trend; size of arrows: relative change within 52 years; Mann–Kendall test, 2-sided option; 10% significance level).

Table 3
Percentages of gauges showing significant trends; bold numbers indicate field significance.

	% of gauges with		
	Increasing trend	Decreasing trend	No trend
AMAXF	**28**	1	71
AWMAXF	**23**	0	77
ASMAXF	10	10	80
POT1M	**17**	2	81
POT3M	5	2	93
POT3F	**25**	1	74
SPOT3F	2	1	97
WPOT3F	**17**	0	83

the upward trends of AMAXF in the Danube basin are mainly dominated by upward trends in summer floods. However, also the frequency of floods (POT3F) increased significantly at many gauges, especially along the main river Danube, which is visible in both seasonal POT3F. An increasing frequency in the winter is supposed to be caused by higher winter temperatures, and hence, earlier snow melting in the mountain ranges.

The annual maxima for the Elbe gauges showed a small number of significant changes with a similar share of upward trends in winter (AWMAXF) and downward trends in summer (ASMAXF). Increasing trends in the winter maxima were mostly found in the Saale catchment, which is the most western sub-catchment of the Elbe river basin and which shows a similar trend pattern as the neighbouring Weser catchment. The sites with decreasing trends in summer flood magnitude are rather randomly distributed in space.

The spatial and seasonal coherence of the results suggests that the observed changes in flood behavior are climate-driven. This conclusion is further supported by the missing relation between significant changes in the discharge series and basin area. Impact of land-cover changes or of river training works would be expected to show scale-dependency. However, from our analysis we conclude that there are no preferred spatial scales where significant changes could be detected.

Therefore, it is interesting to evaluate, whether or not our results are in line with studies on changes in climate. To this end, our results are qualitatively compared to those of recent investigations that analyze changes in atmospheric circulation patterns. It has been shown that there is a close link between the occurrence and persistence of atmospheric circulation patterns and floods in Germany (e.g., Bárdossy and Caspary, 1990; Pfister et al., 2004a; Petrow et al., 2007).

Gerstengarbe and Werner (2005) compared daily data of two time periods (1881–1910 and 1975–2004) and found for the summer large upward trends in the frequency of circulation patterns from the south (tripled frequency with a step change in the 1940s). During the same time period the north-westerly patterns decreased at the same magnitude (Mittelgebirge Weser, Elbe). Gerstengarbe and Werner (2005) found small decreases for the summer in the westerly, northern and easterly circulation patterns.

For the winter, Gerstengarbe and Werner (2005) found increasing trends of westerly atmospheric circulation types. Additionally, a longer duration period of the persistence of the circulation patterns was observed. This yields a larger flood hazard through circulation patterns which are generally not very prone to cause flood

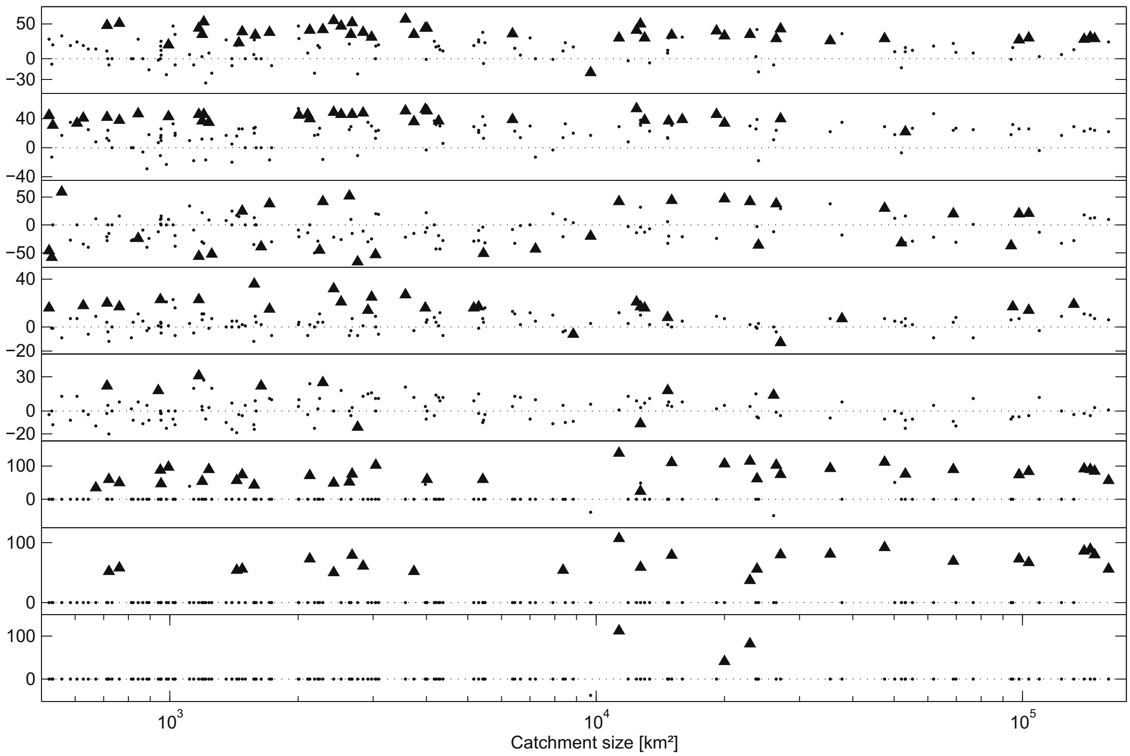

Fig. 8. Relative change (%) as function of basin area. Triangles indicate significant changes at the 10% significance level. From top to bottom: AMAXF, AWMAXF, ASMAXF, POT1M, POT3M, POT3F, WPOT3F, and SPOT3F.

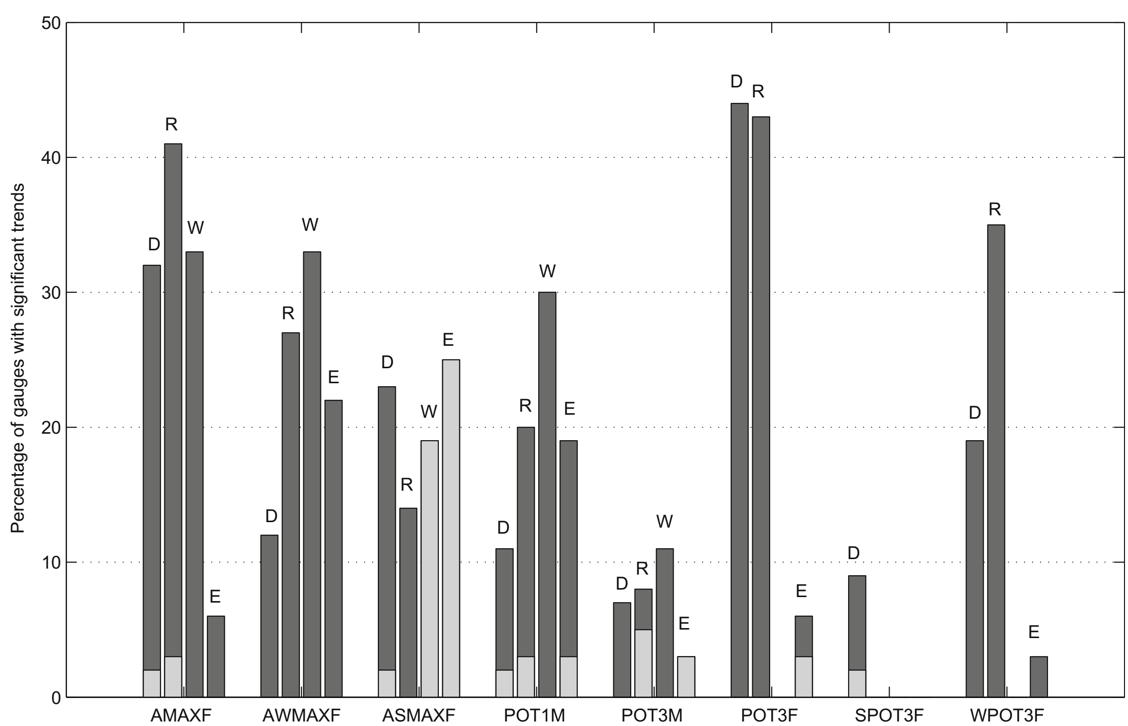

Fig. 9. Percentages of gauges with significant trends per catchment and flood indicator. Dark grey bars show percentage of upward trends, light grey bars show percentages of downward trends; abbr. for the catchments are D – Danube, R – Rhine, W – Weser, E – Elbe.

events but may be increasingly hazardous due to a longer persistence time. Long-lasting westerly atmospheric circulation types cause eventually a large-scale saturation, leading to rapid runoff processes. This is then finally observed in upward trends of the AWMAXF in the northern Rhine, Weser and Elbe catchments as well as in the upward trends of WPOT3F in the Rhine catchment. For the middle and lower stretches of the Rhine, increased flooding probabilities for the winter season have been suggested by Pfister et al. (2004a). During the second half of the 20th century increased winter rainfall totals and intensities have been observed. At the same time, strong links between changes in atmospheric circulation patterns and flood occurrence have been identified. Increasing westerly atmospheric circulation types correlate with increasing winter precipitation and are supposed to be responsible for the increase in flood probabilities.

Moreover, Gerstengarbe and Werner (2005) found a decreasing percentage of easterly circulation patterns during the winter, which cause cold and dry winters especially in the catchments of Odra, Elbe and the Weser. UBA (2006) found significant upward trends in winter temperatures during the last 100 years. These findings also fit our results of upward trends in the winter maximum discharges in the Elbe and Weser catchments, which are caused by more rain induced flood events due to milder winters and an intensified zonal circulation (Gerstengarbe and Werner, 2005; UBA, 2006).

Conclusions

Our study of flood trends at 145 runoff gauges, distributed all over Germany, shows that there is no ubiquitous increase of flood magnitude and/or frequency in the second half of the 20th century, as it is often asserted in the media. However, significant flood trends were detected for a considerable fraction of basins. In most cases, these trends are upward; decreasing flood trends were rarely found and were not field-significant. The joint analysis of many sites within one region allowed assessing the spatial and seasonal coherence of flood trends: Basins with significant trends were spatially clustered. Changes in flood behavior in northeast Germany are small. Most changes were detected for sites in the west, south and center of Germany, i.e. in the catchments of Rhine, Weser and Danube. The seasonal analysis revealed larger changes for winter compared to summer. From the results we concluded that the observed changes in flood behavior are climate-driven. It was possible to qualitatively link our results to trends in frequency and persistence of atmospheric circulation patterns above Europe. As already shown by Pfister et al. (2004b) for a smaller area, orographic obstacles heavily influence the spatial distribution of the rainfall and runoff processes. A changing behavior of circulation patterns is likely to cause changes in rainfall totals, which in turn heavily affects discharge and water levels in the rivers. The relationship between circulation patterns, flood magnitude and/or frequency and the influence of the topography will be further investigated. Our findings underline the need to thoroughly analyze the flood behavior for changes when estimates for flood design or flood risk management are needed.

Acknowledgements

We thank the GeoForschungsZentrum Potsdam (GFZ) and the Helmholtz Association of National Research Centres for their financial support. The study was part of the Helmholtz Young Scientists Group "Information and modelling systems for large-scale flood situations" at GFZ. We dedicate our special thanks to the authorities that provided data.

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