Institute of Geoecology

Floods in Germany – Analyses of Trends, Seasonality and Circulation Patterns

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Abstract

Flood hazard estimations are conducted with a variety of methods. These include flood frequency analysis (FFA), hydrologic and hydraulic modelling, probable maximum discharges as well as climate scenarios. However, most of these methods assume stationarity of the used time series, i.e., the series must not exhibit trends. Against the background of climate change and proven significant trends in atmospheric circulation patterns, it is questionable whether these changes are also reflected in the discharge data.

The aim of this PhD thesis is therefore to clarify, in a spatially-explicit manner, whether the available discharge data derived from selected German catchments exhibit trends. Concerning the flood hazard, the suitability of the currently used stationary FFA approaches is evaluated for the discharge data. Moreover, dynamics in atmospheric circulation patterns are studied and the link between trends in these patterns and discharges is investigated.

To tackle this research topic, a number of different analyses are conducted. The first part of the PhD thesis comprises the study and trend test of 145 discharge series from catchments, which cover most of Germany for the period 1951–2002. The seasonality and trend pattern of eight flood indicators, such as maximum series and peak-over-threshold series, are analyzed in a spatially-explicit manner. Analyses are performed on different spatial scales: at the local scale, through gauge-specific analyses, and on the catchment-wide and basin scales.

Besides the analysis of discharge series, data on atmospheric circulation patterns (CP) are an important source of information, upon which conclusions about the flood hazard can be drawn. The analyses of these circulation patterns (after Hess und Brezowsky) and the study of the link to peak discharges form the second part of the thesis. For this, daily data on the dominant CP across Europe are studied; these are represented by different indicators, which are tested for trend. Moreover, analyses are performed to extract flood triggering circulation patterns and to estimate the flood potential of CPs. Correlations between discharge series and CP indicators are calculated to assess a possible link between them. For this research topic, data from 122 meso-scale catchments in the period 1951–2002 are used. In a third part, the Mulde catchment, a mesoscale sub-catchment of the Elbe basin, is studied in more detail. Fifteen discharge series of different lengths in the period 1910–2002 are available for the seasonally differentiated analysis of the flood potential of CPs and flood influencing landscape parameters.

For trend tests of discharge and CP data, different methods are used. The Mann-Kendall test is applied with a significance level of 10%, ensuring statistically sound results. Besides the test of the entire series for trend, multiple time-varying trend tests are performed with the help of a resampling approach in order to better differentiate short-term fluctuations from long-lasting trends. Calculations of the field significance complement the flood hazard assessment for the studied regions.

The present thesis shows that the flood hazard is indeed significantly increasing for selected regions in Germany during the winter season. Especially affected are the middle mountain ranges in Central Germany. This increase of the flood hazard is attributed to a longer persistence of selected CPs during winter. Increasing trends in summer floods are found in the Rhine and Danube catchments, decreasing trends in the Elbe and Weser catchments. Finally, a significant trend towards a reduced diversity of CPs is found causing fewer patterns with longer persistence to dominate the weather over Europe. The detailed study of the Mulde catchment reveals a flood regime with frequent low winter floods and fewer summer floods, which bear, however, the potential of becoming extreme.

Based on the results, the use of instationary approaches for flood hazard estimation is recommended in order to account for the detected trends in many of the series. Through this methodology it is possible to directly consider temporal changes in flood series, which in turn reduces the possibility of large under- or overestimations of the extreme discharges, respectively.

Zusammenfassung

Hochwasserabschätzungen werden mit Hilfe einer Vielzahl von Methoden ermittelt. Zu diesen zählen Hochwasserhäufigkeitsanalysen, die hydrologische und hydraulische Modellierung, Abschätzungen zu maximal möglichen Abflüssen wie auch Langzeitstudien und Klimaszenarien. Den meisten Methoden ist jedoch gemein, dass sie stationäre Bedingungen der beobachteten Abflussdaten annehmen. Das heißt, in den genutzten Zeitreihen dürfen keine Trends vorliegen. Vor dem Hintergrund des Klimawandels und nachgewiesener Trends in atmosphärischen Zirkulationsmustern, stellt sich jedoch die Frage, ob sich diese Veränderungen nicht auch in den Abflussdaten widerspiegeln.

Ziel der Dissertation ist daher die Überprüfung der Annahme von Trendfreiheit in Abflüssen und Großwetterlagen, um zu klären, ob die aktuell genutzten stationären Verfahren zur Hochwasserbemessung für die vorhandenen Daten in Deutschland geeignet sind. Zu prüfen ist des Weiteren, inwiefern regional und saisonal eine Verschärfung bzw. Abschwächung der Hochwassergefahr beobachtet werden kann und ob eindeutige Korrelationen zwischen Abflüssen und Großwetterlagen bestehen.

Den ersten Schwerpunkt der vorliegenden Dissertation bildet die deutschlandweite Analyse von 145 Abflusszeitreihen für den Zeitraum 1951–2002. Acht Hochwasserindikatoren, die verschiedene Aspekte der Hochwasser-Charakteristik beleuchten, werden analysiert und bezüglich möglicher Trends getestet. Um saisonalen Unterschieden in der Hochwassercharakteristik der einzelnen Regionen gerecht zu werden, werden neben jährlichen auch saisonale Reihen untersucht. Die Analyse von Maximalreihen wird durch Schwellenwertanalysen ergänzt, die die Hochwasserdynamik bzgl. Frequenz und Magnitude detaillierter erfassen. Die Daten werden auf verschiedenen Skalen untersucht: sowohl für jeden einzelnen Pegel wie auch für ganze Regionen und Einzugsgebiete.

Nicht nur die Analyse der Abflussdaten bietet die Möglichkeit, Bewertungen für die zukünftige Hochwasserabschätzung abzuleiten. Auch Großwetterlagen bilden eine bedeutende Informationsquelle über die Hochwassergefahr, da in der Regel nur ausgewählte Zirkulationsmuster die Entstehung von Hochwasser begünstigen. Die saisonal differenzierte Untersuchung der Großwetterlagen und die Prüfung einer Korrelation zu den Abflüssen an 122 mesoskaligen Einzugsgebieten bilden deshalb den zweiten Schwerpunkt der Arbeit. Hierzu werden tägliche Daten der über Europa dominierenden Großwetterlage (nach Hess und Brezowsky) mit Hilfe verschiedener Indikatoren untersucht. Analysen zum Hochwasserpotential der einzelnen Wetterlagen und weiterer Einflussfaktoren werden für das mesoskalige Einzugsgebiet der Mulde in einer separaten Studie durchgeführt. Für diese Detail-Studie stehen 15 Abflusszeitreihen verschiedener Länge im Zeitraum 1909–2002 zur Verfügung.

Um die Daten von Abflüssen und Großwetterlagen bezüglich vorhandener Trend zu testen, werden verschiedene Methoden genutzt. Der Mann-Kendall Test wird mit einem Signifikanzniveau von 10% (zweiseitiger Test) angewendet, was statistisch sichere Bewertungen ermöglicht. Neben der Prüfung der gesamten Datenreihe werden multiple zeitlich-variable Trendanalysen mit Hilfe eines Resampling-Ansatzes durchgeführt. Darüber hinaus werden räumlich differenzierte Analysen durchgeführt, um die saisonale Hochwassercharakteristik einzelner Regionen besser zu verstehen. Diese werden durch Tests zur Feldsignifikanz der Trends ergänzt.

Mit der vorliegenden Arbeit kann gezeigt werden, dass die Hochwassergefahr für einzelne Regionen im Winterhalbjahr signifikant steigt. Davon sind insbesondere Gebiete in Mitteldeutschland betroffen. Die Verschärfung der Hochwassergefahr durch eine längere Persistenz ausgewählter Großwetterlagen konnte ebenfalls für das Winterhalbjahr nachgewiesen werden. Sommerhochwasser zeigen zwar ebenfalls steigende, aber auch fallende Trends, die räumlich geclustert sind. Im Elbe- und Weser-Einzugsgebiet sinken die Abflüsse signifikant, im Donau- und Rheineinzugsgebiet steigen sie nachweisbar. Darüber hinaus ist eine signifikante Abnahme der Anzahl verschiedener Großwetterlagen sowohl im Sommer als auch im Winter zu verzeichnen. Bzgl. der Studie zum Mulde-Einzugsgebiet konnte ein zweigeteiltes Hochwasserregime nachgewiesen werden. In den Wintermonaten treten häufig kleine Hochwasser auf, die auch die Mehrheit der jährlichen Maximalwerte bilden. Sommerhochwasser sind seltener, können aber extreme Ausmaße annehmen. Ein Vergleich der geschätzten Jährlichkeiten mit verschiedenen Zeitreihen zeigt die Notwendigkeit der Berücksichtigung saisonaler Aspekte für die Bemessung von Hochwassern.

Aufgrund der Ergebnisse müssen die bisher genutzten stationären Verfahren als nicht mehr geeignet bewertet werden. Es wird daher die Nutzung instationärer Verfahren zur Abschätzung von Extremhochwasser und der damit verbundenen Bemessung von Schutzmaßnahmen empfohlen, um den teilweise vorliegenden Trends in den Daten Rechnung zu tragen. Durch diesen Ansatz ist es möglich, zeitlich dynamische Veränderungen im Hochwassergeschehen stärker zu berücksichtigen. Darüber hinaus sollten saisonale Aspekte des Einzugsgebietes Eingang in die Gefahrenabschätzung finden.

Contents

List of Abbreviations

For abbreviations of the circulation patterns see Table 3.1.

AMAXF	annual maximum discharge series
AMS	annual maximum discharge series
AO	Arctic oscillation
ASMAXF	summer maximum discharge series
AWMAF	winter maximum discharge series
CDF	cumulative distribution function
CI	confidence interval
CP	circulation pattern
FFA	flood frequency analysis
GEV	Generalized Extreme Value distribution
GL	General Logistics distribution
HQT	probability of a flood quantile
MK test	Mann-Kendall test
N	Number
NAO	North-Atlantic Oscillation
POTxF	peak-over-threshold series, annual number of discharge frequency
POTxM	peak-over-threshold series, discharge peaks above magnitude of x events per year
SL	significance level
SMS	summer maximum discharge series
TFPW	trend free pre-whitening
SPOTxF	peak-over-threshold series, number of discharge frequency in summer
WPOTxF	peak-over-threshold series, number of discharge frequency in winter

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1 Introduction

Germany has a well documented flood history dating back more than 1000 years. Chronicles across Germany report devastating damages, numerous fatalities and the outbreak of famine and serious diseases for a large number of flood events. Written documents for German catchments are available in archives spanning from Cologne to Dresden and from northern Italy to Hamburg (Weikinn, 1958; Pfister, 1999). Numerous floods have occurred in the course of the centuries, some locally, some regionally and a few countrywide. During the last two decades, several destructive flood events in the Rhine, Elbe and Danube catchments led to the public impression of an overall growing flood hazard.

In order to prevent and mitigate floods, first prevention measures such as dikes were constructed as early as the 12th century. To gain more detailed information on the discharge regime and flood generation along rivers, measurements of discharge and water level were implemented in the early 19th century (Pohl, 2004). In the beginning, measurements were undertaken only during flood events. Later, a detailed network of gauging stations was established, which now comprises more than 1000 stations with daily recordings throughout Germany. At the majority of gauges, discharge and water level are recorded automatically at regular intervals, from which daily means are calculated. From these measurements, series of e.g. annual maximum discharges are derived, which are used for the estimation of the flood hazard.

Flood hazard estimation

A large variety of approaches is currently available for the estimation of flood hazards, upon which flood protection measures are designed. Some popular methods are the estimation of maximized discharges, the use of model chains and flood frequency analysis (FFA). As an example, the FFA approach will be described in more detail.

FFA is a tool for estimating the magnitude of a flood for a given return period. For this, the exceedance probability of a flood is estimated. It is defined to be the probability of a discharge or water level exceeding a defined value within a given time period (Merz, 2006). The reciprocal of this probability is defined to be the return period. Thus, it is the statistically estimated time frame between two floods of a prescribed extent.

The statistical distribution functions used for FFA are simple representations of all hydrological processes behind the series. Two- to four-parametric functions can be fitted to observed data (Hosking and Wallis, 1997). The most common methods for FFA use as input data annual maximum series (AMAXF) and peak over threshold (POT) series (Institute of Hydrology, 1999). In addition, seasonal maximum series or seasonal POT series can be used, for instance, if one flood process type (e.g., flash floods) is of special interest.

Independence, homogeneity and stationarity are required characteristics of the data to legitimate flood frequency analysis (Stedinger, 2000; Kundzewicz and Robson, 2004). However, changes in climate, land use or the vulnerability of the study area question the existence of stationary conditions (Merz, 2006). This is critical since stationarity of the data is often assumed (Kundzewicz et al., 2005). The presence of trends in the data can have an important impact on the results of flood estimation as they can lead to over- or underestimations of the return period (Khaliq et al., 2006). In turn, this can falsify estimations of discharge and water level for a given return period. As flood protection measures are based on these results, testing the data for trends is crucial for ensuring valid estimates. If trends are detected in the data, flood estimation procedures have to be adjusted by considering changing regimes, e.g. by introducing time-varying parameters of the flood frequency distribution (e.g. Strupczewski et al., 2001a; Zhang et al., 2004; Khaliq et al., 2006).

Trend detection in discharge data

Numerous test statistics are available for trend detection (e.g. Kundzewicz and Robson, 2004; Svensson et al., 2005). Examples for widely used tests for detecting step changes in the data are the Mann-Whitney test and the Student's t test. Tests for gradual trends include, e.g., the test statistic for linear regression and the Mann-Kendall test. Most tests define certain requirements for the data. Hydrologic datasets are usually not normally distributed, which particularly applies to flood data. This reduces the number of suitable trend tests. The Mann-Kendall test is a robust test, which sets no requirements with respect to the distribution of the data. For this reason, the test is suitable for the assessment of trends in extremes (Kendall, 1975). It is described in detail by Douglas et al. (2000) and Yue et al. (2002b).

Besides testing the entire data set for trends, it is important to pay attention to different time periods and their respective trend behaviour. For instance, in a subseries of a dataset a visual increase might not be significant at a given significance level. However, if a few years are added to the series, this only visually detectable increase might result in a significant trend. McCabe and Wolock (2002) present multiple time-varying trend tests that calculate trends for all possible combinations of time lengths in a series. Through this methodology it is possible to distinguish recent changes from trends that are stable over longer time periods. Moreover, cycles of upward and downward periods may become apparent.

The significance of trends across a region can be assessed through the test for field significance (Douglas et al., 2000; Burn and Hag Elnur, 2002; Svensson et al., 2006). Here, the number of observed significant trends is compared with the number expected within a given region. Based on this test, it is possible to draw conclusions on the significance of changes for the entire region in question.

Deciding which significance level to set is crucial for the trend results. A trend tested with a significance level of 20% only indicates a potential direction, whereas a trend based on a significance level of 5% is robust and reliable (e.g. Belz et al., 2004; Kundzewicz and Robson, 2004).

A review of literature reveals that many studies have been conducted worldwide on trends in hydrological variables such as streamflow, water quality or snowmelt. In contrast, studies that focus on trends in floods are more seldom and often focus on catchments in North-America. Large-scale flood trend studies focusing on the European continent are rarely found. Robson et al. (1998) and Robson (2002) investigate flood trends in the UK, Lindström and Bergström (2004) in Sweden. For Germany, flood trend studies are not yet available for the entire country. Recent studies are found only for parts of the Rhine catchment such as Lammersen et al. (2002), Pfister et al. (2004a) or Pinter et al. (2006). Investigations on parts of the Elbe and Weser catchments were carried out by Helms et al. (2002) and Mudelsee et al. (2006). However, it is not possible to draw a comprehensive picture of flood trends for the entire country.

Atmospheric circulation patterns

Besides discharge series, data on prevailing atmospheric circulation patterns (CP) are an important source of information on the flood hazard, since only selected CPs favour the development of floods in Germany (e.g., Caspary and Bárdossy, 1995). Thus, the investigation of CPs provides relevant insights into the relationship between the atmosphere and flood generation and facilitates the assessment of the impact of climate change on the flood hazard.

Information about CPs across Europe is available from a number of different sources. They are either derived by 500 hPa geopotential height fields from reanalyses data or from classification schemes, which can be of manual or automated mode. Well-known classification schemes are provided by Hess and Brezowsky (1952) for all of Europe and Lamb (1972) for north-west Europe with a focus on the British Isles. Lamb (1972) introduces a classification scheme known as "Lamb's daily weather types (DWT)" that is derived on a daily basis from flow directions over the British Isles. This system has been automated by an objective determination method for the circulation patterns (Jones et al., 1993). The deficiency of the Lamb model is the small spatial scale, which concentrates on areas over and near to the British Isles (James, 2007). Therefore, it is difficult to apply this scheme to Germany.

The "Catalogue of Großwetterlagen in Europe 1881–2004" by Hess and Brezowsky (1952) provides information on the daily dominant circulation pattern across Europe. It is derived from pressure systems over Europe as well as from location of frontal zones. The catalogue distinguishes 30 different CPs. They comprise zonal, mixed and meridional circulation forms (for details see Table 3.1). This widely used classification scheme is currently the only one available that captures the large-scale European pattern, while still focusing on local details (James, 2007). Although the entire daily European atmospheric situation is described by only one pattern, the dataset is very valuable with respect to the analysis of atmospheric variability and climate change analyses (Bárdossy and Filiz, 2005; Werner et al., 2008).

The influence of CPs on floods has not yet been studied in detail. Kingston et al. (2006) review studies on the connection between climate, streamflow and atmospheric circulations (esp. North-Atlantic Oscillation (NAO) and the Arctic Oscillation (AO)). Bouwer et al. (2008) correlate four atmospheric indicators and winter flood discharges at 11 gauges in Central Europe. They find annual maximum discharges to react more sensitive to variability in atmospheric variables than mean discharges. Correlations between trends in the NAO index and floods across Europe are conducted by Svensson et al. (2006). McKerchar and Henderson (2003) found changes in several hydrological variables in New Zealand which are consistent with changes in the Interdecadal Pacific Oscillation.

For Germany, the link between changes in atmospheric circulations and flood trends has only been analyzed in selected regions (e.g. Pfister et al., 2004a; Mudelsee et al., 2006; Pinter et al., 2006). Belz et al. (2007) find increases in wet CPs, areal precipitation and discharge in the Rhine catchment area for the period 1951–2000. However, they do not correlate these variables. For south-western Germany, an increase in the westerly cyclonic pattern in winter, leading to a dramatic increase in the flood hazard, is detected by Caspary and Bárdossy (1995). Regions in eastern Germany are investigated by Mudelsee et al. (2004). Downward flood trends in the Elbe and Odra catchments are detected in winter, but no significant changes during summer. Moreover, floods are correlated with CPs.

All of these studies are limited to selected regions in Germany. Thus, a countrywide picture of the link between trends in floods and atmospheric patterns cannot be drawn based on current knowledge.

Flood seasonality in German catchments

The flood regime in Germany is strongly determined by the seasonality. Winter floods dominate the flood regime in most catchments. Only the southern tributaries of the Danube river are dominated by summer floods. Changes in the flood-generating processes can have a significant impact on the seasonality of floods, as shown by Kundzewicz (2008) for many European regions. For instance, floods due to snow melting are expected to decrease in Eastern and Central Europe. This in turn can have a profound impact on the dominance of flood process types in a region. In the following, a brief overview is given about the flood seasonality and triggering CPs in the large German river basins.

Large parts of the Weser and Rhine catchments are dominated by winter floods, which are often caused by westerly, south-westerly and north-westerly circulation types (Beurton and Thieken, 2009). High pressure systems are rarely responsible for floods in this region. Floods occur predominantly during mild and wet episodes in winter. The flood generation due to snow melting plays a particularly important role in the upper parts of the Rhine catchment, i.e. in Switzerland and the middle mountain ranges of the Black Forest. The river system of the Weser is as a typical middle-mountain river system with flash floods due to the fast concentration in the steep valleys (Staatliches Amt für Umwelt und Arbeitsschutz, 2005).

The Elbe and Odra catchments are also mainly dominated by winter floods; however, summer flooding does occur. The runoff seasonality of both river basins is strongly influenced by the middle-mountain ranges in the Czech Republic, Poland and Germany. Small but frequent floods dominate during winter and the snow melting season, which are largely triggered by westerly and north-westerly cyclonic patterns. Summers are often dry with low flows. A larger percentage of high pressure systems, especially during fall and winter, and the occurrence of Vb-weather regimes distinguish the region from the western part of the country (Beurton and Thieken, 2009). Torrential storms and long-lasting rains can cause extreme flood events, such as along the Odra in 1997 or along the Elbe in 2002 (Grünewald et al., 1998; DKKV, 2003).

The flood seasonality of the Danube differs depending on the region. The uppermost section as well as the tributaries coming from the north are dominated by winter and spring floods associated with snow-melting, which are mainly caused by westerly patterns of varying sub-directions. In contrast, the southern tributaries have an alpine runoff regime with maxima during the summer months. High pressure systems dominate. However, the Vb-weather regime plays also an important role in causing extreme floods.

This short overview illustrates the necessity of conducting studies that consider seasonal aspects for each region in Germany.

1.1 Purpose & objectives

The aim of the PhD thesis is therefore to clarify, in a spatially-explicit manner, whether the available discharge data of German catchments exhibit trends. Besides the analysis of annual series, a possible increase or decrease in the flood hazard is evaluated on different spatial scales for the winter and summer seasons. The suitability of the currently used stationary FFA approaches is evaluated for the studied discharge data. Moreover, indicators derived from atmospheric circulation patterns are studied and tested for trends. Finally, their link to flood discharges is investigated for most of the country.

In sum, two main research questions are extracted from this overall research topic:

- Can significant flood trends be detected in Germany?
- Is there a link between trends in CPs and trends in flood discharges?

Since both questions are tackled in a spatially and seasonally-differentiated manner, no separate research question is posed with respect to seasonality.

A number of different analyses is performed in order to find appropriate answers to these questions. Series of daily mean discharge across Germany are studied and tested for trends for each single station and for aggregated regions. The seasonality and trend patterns of eight flood indicators, such as maximum series and peak-over-threshold series, are analyzed in a spatially-explicit manner for varying time periods between 1951 and 2002. The significance of trends for entire regions is assessed with the help of the field significance. In order to study the possible link between CPs and discharge, these data are tested for trends for varying time periods. The flood potential of selected CPs is assessed for different return periods. Moreover, CP data are correlated with discharge data.

1.2 Study areas

Investigations for this PhD thesis are carried out on different spatial scales, namely gauge-specific and on the catchment-wide and basin scales. Two different study areas are investigated in the thesis. The first area covers most of Germany. The large drainage basins of Weser, Rhine, Elbe, Ems, Odra and Danube are represented altogether by 145 gauge stations. Due to limited data availability, the drainage basin of the Odra is only represented by two stations. Unfortunately, information from the catchments of the Baltic and North Seas is completely lacking. Figure 1.1 gives an overview about the location of the investigated regions and the location of the gauge stations.

The second study area is the Mulde catchment, a sub-catchment of the Elbe river basin in south-eastern Germany (Fig. 1.1, right). The German-Czech bor-

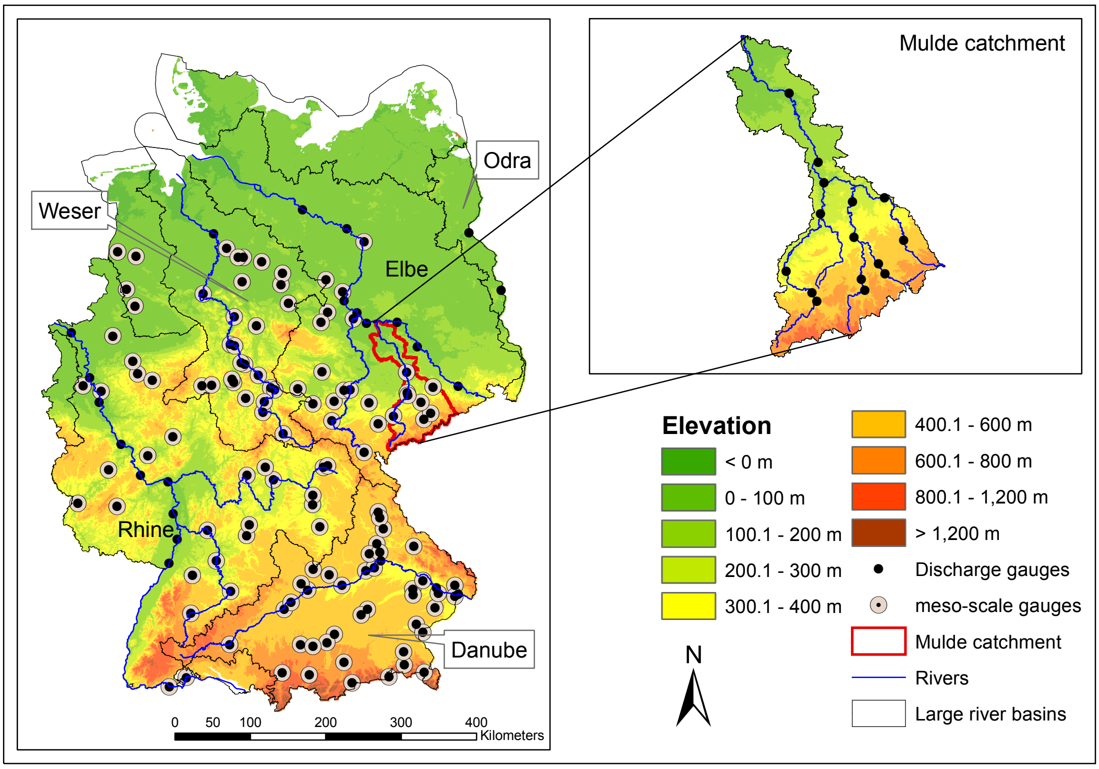

Figure 1.1: Study areas and location of discharge gauges: left: 145 discharge gauges in Germany (grey circles indicate gauges of meso-scale catchments); right: The Mulde catchment in south-eastern Germany with 15 discharge gauges

Aspect		Chapter II Flood trends in Germany	Chapter III Trends in floods & circulation patterns	Chapter IV Regional Analysis
Studied time period		1951–2002	1951–2002	1910–2002
Temporal resolution	daily data		X	X
	annual series	X	X	X
	seasonal series	X	X	X
	peak over threshold	X		
Spatial resolution	basin scale	X	X	
	catchment based	X	X	X
	gauge specific	X	X	X
Topics	seasonality	X	X	X
	flood statistics	X	X	X
	flood trends	X	X	
	circulation patterns		X	X
	landscape parameters			X

Table 1.1: Research aspects of the thesis

der marks the southern boundary. The catchment has a size of 6171 km^2 (at the gauge Bad Düben). The river disembogues into the Elbe River north of the city of Dessau. The steep mountain ranges in the south lead to fast runoff generation in the tributaries, whereas runoff generation is much slower in the lowlands. This catchment was chosen for its very good data base of long discharge series and the direct availability of digital information about different catchment characteristics.

1.3 Outline of the thesis

This introductory part is followed by three chapters. They were written as stand-alone manuscripts that have either been published or are awaiting publication in international peer-reviewed journals. The full reference of each article (i.e. chapter) is provided below its abstract. Given the overlap of data and topics, it is unavoidable that small excerpts or tables occur in more than one chapter. Table 1.1 gives an overview of the data and aspects covered in the thesis.

Chapter 2 investigates, seasonally differentiated, the presence of trends in discharge data from all gauges presented in Fig. 1.1 (left). The size of the catchments ranges from 500 km^2 to 159300 km^2. Eight flood indicators, which focus on different flood characteristics, are derived from daily mean discharge series. Conclusions are drawn for the large river basins of Elbe, Rhine, Danube and Weser concerning trends in winter and summer floods, respectively.

Based on the findings in Chapter 2, Chapter 3 investigates the relationship between trends in CPs and flood trends for 122 meso-scale catchments with areas from 500 km^2 to 27088 km^2. The catchments represent a subset of the dataset in Chapter 2. In Fig. 1.1 (left), all gauges with a grey border represent this subset of data. In both chapters, a common period of 52 years (1951–2002) is used. Four indicators are derived from daily CP data reflecting the frequency and persistence of these patterns across Europe. These are tested for trends. Analyses to extract flood triggering CPs are performed for three large regions in Germany. In addition, multiple time-varying trend tests are conducted for flood and CP indicators. Finally, discharge series and CP frequencies are correlated. Conclusions are drawn on the link between atmospheric circulation patterns and floods for Germany.

A detailed analysis of the Mulde catchment in Saxony (6171 km^2) is presented in Chapter 4, which focuses on flood triggering catchment characteristics and circulation patterns. Datasets of 15 gauges with different lengths (42 to 92 years) are studied (Fig. 1.1, right). Note that some of these gauges are not part of the datasets investigated in the Chapters 2 and 3. The influence of the seasonality and different indicators such as precipitation, soil or landuse on flood generation is studied. In addition, flood frequency analyses are performed for all data, and the flood potential is estimated for different return periods and CPs. Finally, conclusions on flood frequency analysis are presented, concerning the use of seasonally differentiated maximum series for such estimations.

Overall conclusions, arising from the research findings in the three chapters, are presented in Chapter 5. Finally, recommendations and an outlook with further research foci are presented.

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

Abstract

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.

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2.1 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 2.1 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.

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

Study	Region	No of stations	Observation period	Flood indicator: AMAXF	Flood indicator: Seasonal AMAXF	Flood indicator: POT	Flood indicator: Other	Main findings
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 & 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 & 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 & 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 geogr. 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 & 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

Table 2.1: Summary of recent studies on flood trends in observational data (Annual maximum daily mean streamflow (AMAXF), Peak over threshold (POT))

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 approx. 400 years (Apel et al., in press). Lammersen et al. (2002) analysed 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 1955–77 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 behaviour, such changes are not expected to cause coherent changes over a large geographical area.

Table 2.1 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 2.1 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 2.1 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), 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 20^{th} 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 5 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. Section 2 and 3 introduces the data and the methods, respectively. In section 4 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 (section 5). In particular, it is discussed if the identified changes are caused by climate variability or by other drivers.

2.2 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 to 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. 2.1). 43 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 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, 2003). 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 144323 km^2) in the Rhine catchment and Donauwoerth (catchment size 15037 km^2) in the Danube catchment (Fig. 2.1). These gauges were selected because their behaviour 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 behaviour 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.

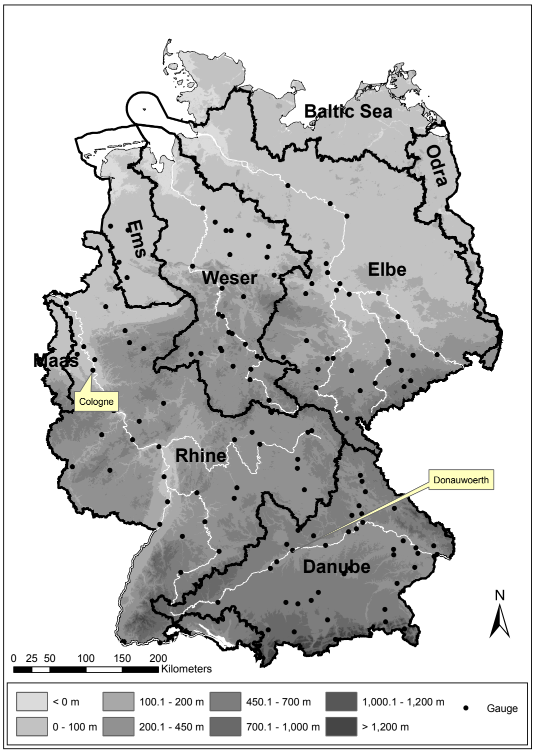

Figure 2.1: Location of the analyzed gauges, main rivers, large river basins and elevation above sea level (in m)

Eight flood indicators, which are listed in Table 2.2, were included in our study.

Flood indicator	Abbreviation	Remarks
Annual maximum daily mean streamflow [m^3/s]	AMAXF	Maximum discharge for each hydrological year (1 Nov - 31 Oct)
Annual winter maximum daily mean streamflow [m^3/s]	AWMAXF	Maximum discharge for each hydrological winter (1 Nov - 31 Mar)
Annual summer maximum daily mean streamflow [m^3/s]	ASMAXF	Maximum discharge for each hydrological summer (1 Apr - 31 Oct)
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 3 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

Table 2.2: Flood indicators studied for all gauges

These comprise annual maximum streamflow series (AMAX) as well as peak over threshold series (POT). Annual maximum 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 < 45000 km^2; 10 days for catchments between 45000 and 100000 km^2; 20 days for catchments > 100000 km^2. In our study, 85% of the catchments are smaller than 45000 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.

2.3 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 Navarra (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. (2002a, 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:

$$\beta = \frac{x_j - x_i}{j - i} \tag{2.1}$$

for all $i < j$; x_i, x_j = discharge values in years i, j. Secondly, the calculated trend is removed from the original series:

$$Y_t = X_t - \beta * t \tag{2.2}$$

with X_t being the original time series and t 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:

$$Y_t^{'} = Y_t - acf * Y_{t-1} \tag{2.3}$$

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.

$$Y_t^{''} = Y_t^{'} + \beta * t \tag{2.4}$$

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

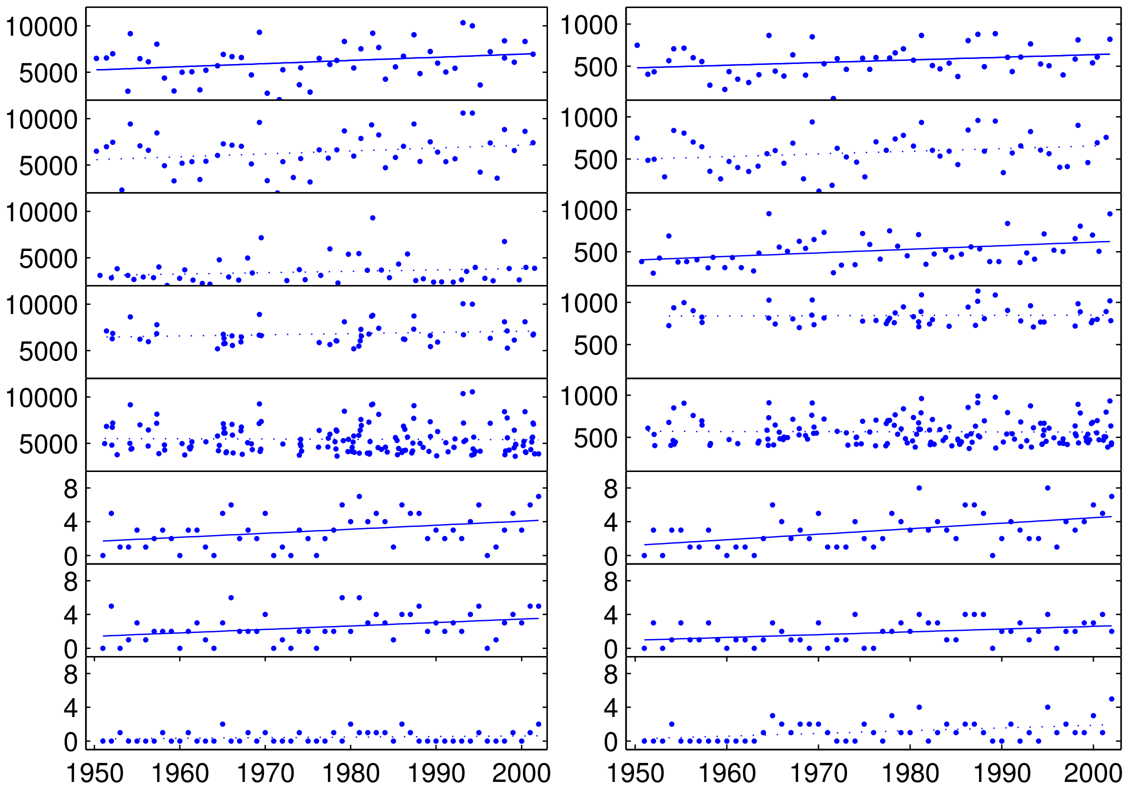

Figure 2.2: Observations and linear regression trends in the flood indicators given in Table 2.2. Solid lines indicate significant trend (10% significance level), dotted lines indicate no trend. Left column: gauge Cologne; right column: gauge: Donauwoerth. From top to bottom: AMAXF, AWMAXF, ASMAXF, POT1M, POT3M, POT3F, WPOT3F, SPOT3F

year set obtained in step 1. In this way, the spatial correlation of observation values is preserved, whereas the temporal order is destroyed.

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, 2 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.

2.4 Results

2.4.1 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. 2.1).

Fig. 2.2 shows the observations and the linear regression trends in the eight flood indicators given in Table 2.2. 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. 2.3 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.

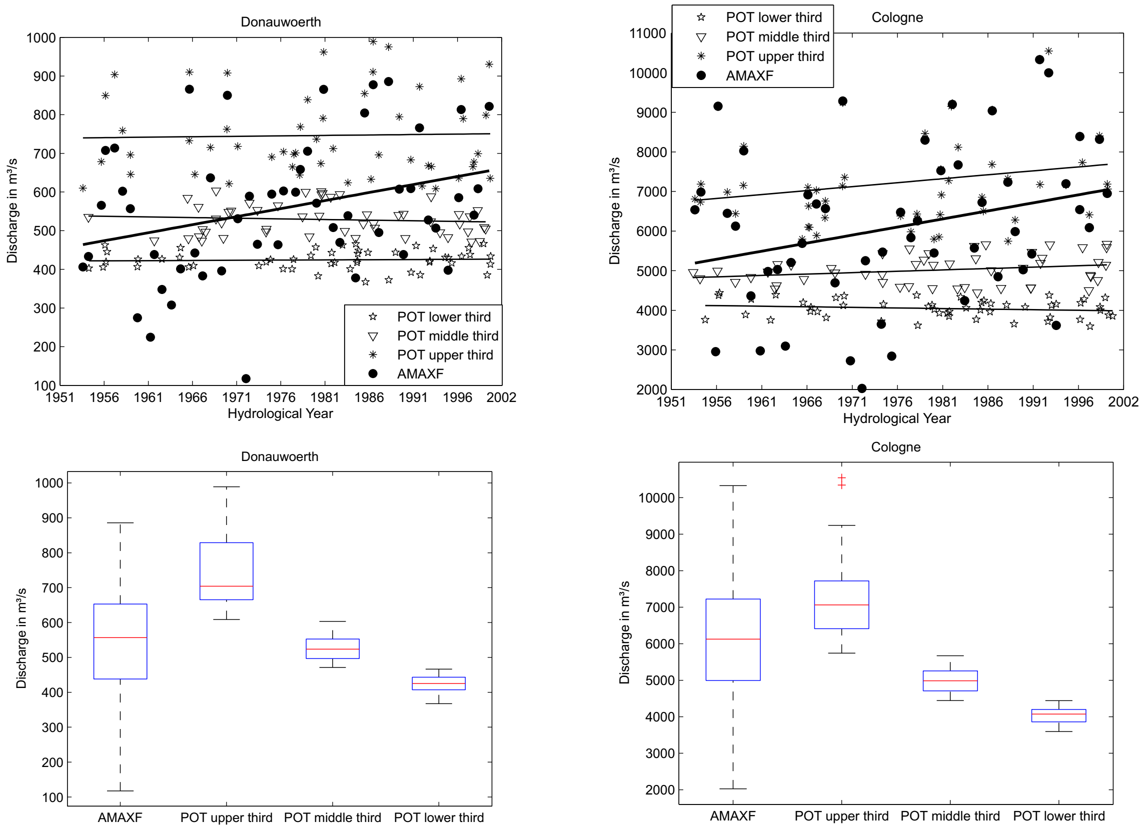

Figure 2.3: Observations and linear regression trends in AMAXF and in the three time series that resulted from the stratification of POT3M in the upper, middle and lower third (upper panel). Lower panel: Boxplots of the four samples (Red line: median; box: interquartile range; whiskers: minimum and maximum value; crosses: outliers)

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 behaviour (Fig. 2.2). 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 (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.

2.4.2 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):

$$\Delta X_R = \frac{X^*_{2002} - X^*_{1951}}{\overline{X}} * 100\% \quad (2.5)$$

X^*_{2002} and X^*_{1951} is 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. 42% 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.

Figure 2.4 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. 2.5; 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).

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. 2.5; right). Only gauges in central and northern Germany in the catchments of Weser, Odra and Elbe show downward trends, whereas the upward trends are ex-

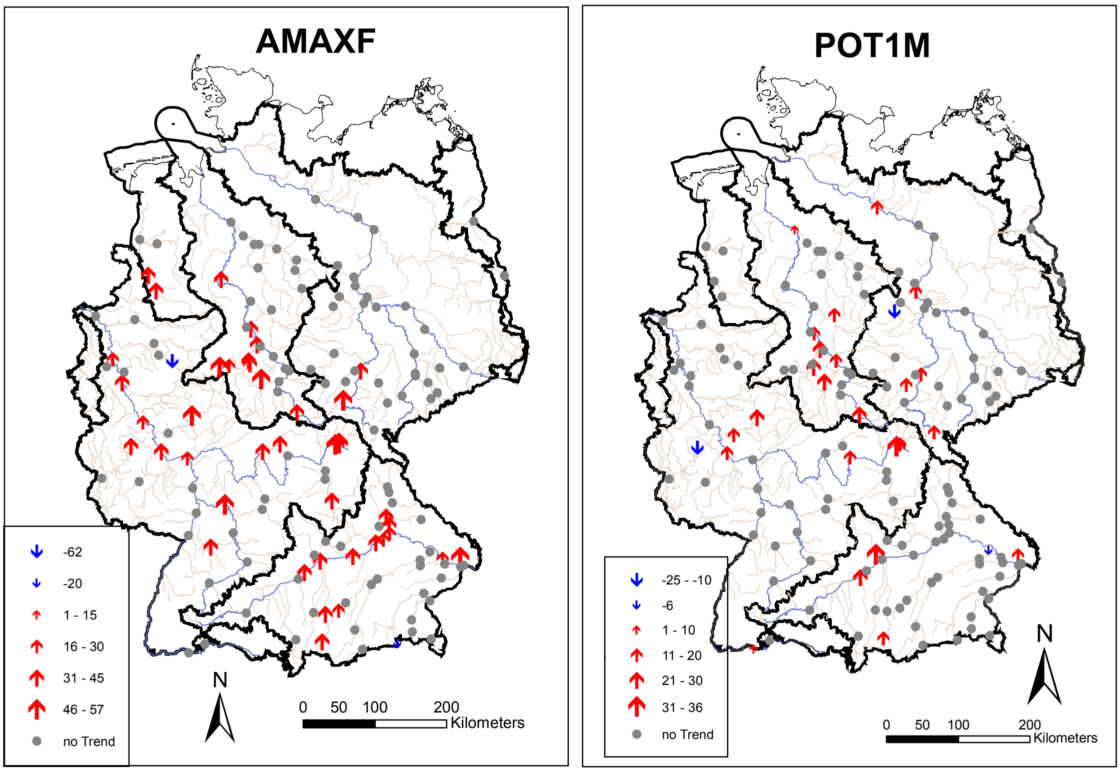

Figure 2.4: Spatial distribution of trends in annual maximum daily mean streamflow - AMAXF (left) and in peak-over-threshold magnitude with on average one event per year - POT1M (right); (Upward arrows: significant increasing trend; downward arrows: significant decreasing trend; circles: no significant trend; size of arrows: relative change within 52 years; Mann-Kendall test, 2-sided option; 10% significance level)

clusively 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 behaviour 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

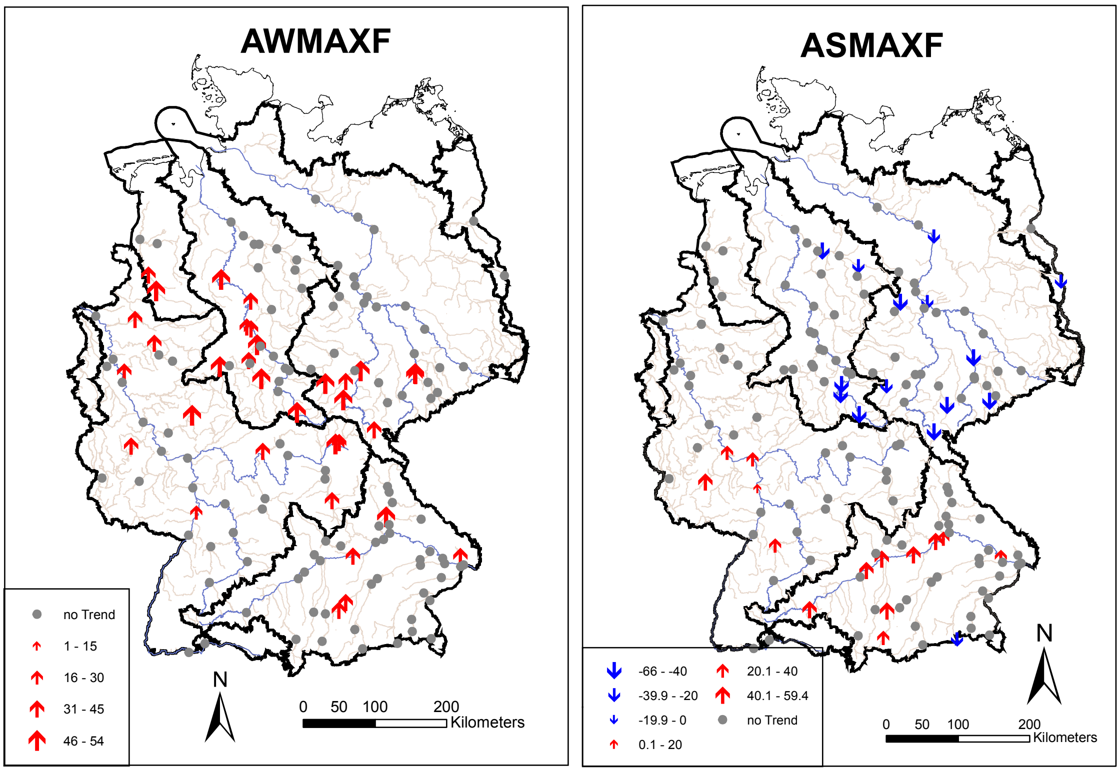

Figure 2.5: Spatial distribution of trends in seasonal maximum series - AWMAXF (winter, left map), ASMAXF (summer, right map); (Upward arrows: significant increasing trend; downward arrows: significant decreasing trend; circles: no significant trend; size of arrows: relative change within 52 years; Mann-Kendall test, 2-sided option; 10% significance level)

exception of two gauges in the Elbe catchment, only gauges in the Rhine and Danube catchments show a significant change in flood frequency (Fig. 2.6). 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. 2.7). Again, the Rhine and Danube catchments are mainly affected by the changes in the flood discharge behaviour.

Table 2.3 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 behaviour. No field significance could be found for decreasing trends for all flood indicators. The changes in the summer flood behaviour (ASMAXF, SPOT3F) are too small to be counted as field significant.

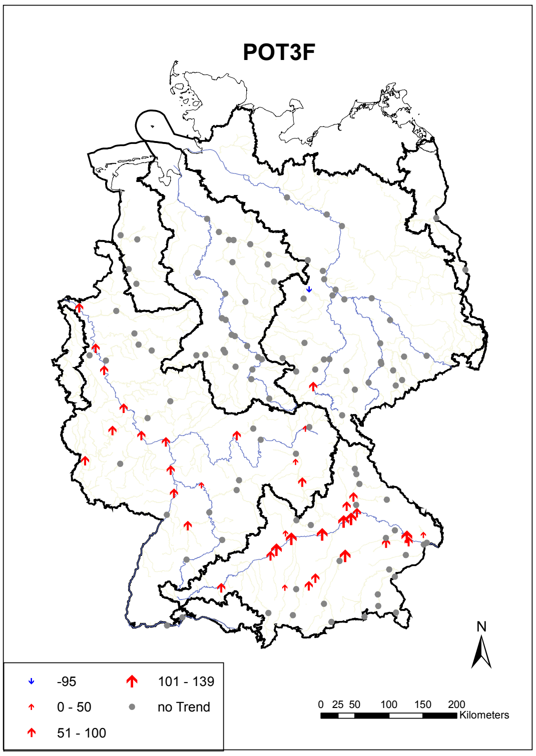

Figure 2.6: Spatial distribution of trends in the peak-over-threshold frequency - POT3F (Upward arrows: significant increasing trend; downward arrows: significant decreasing trend; circles: no significant trend; size of arrows: relative change within 52 years; Mann-Kendall test, 2-sided option; 10% significance level)

2.4.3 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. 2.8). 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.

2.5 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 behaviour 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. 2.9 which highlights the fraction of gauges with significant changes, stratified according to flood indicators and according to the large river basins Danube (D), Rhine

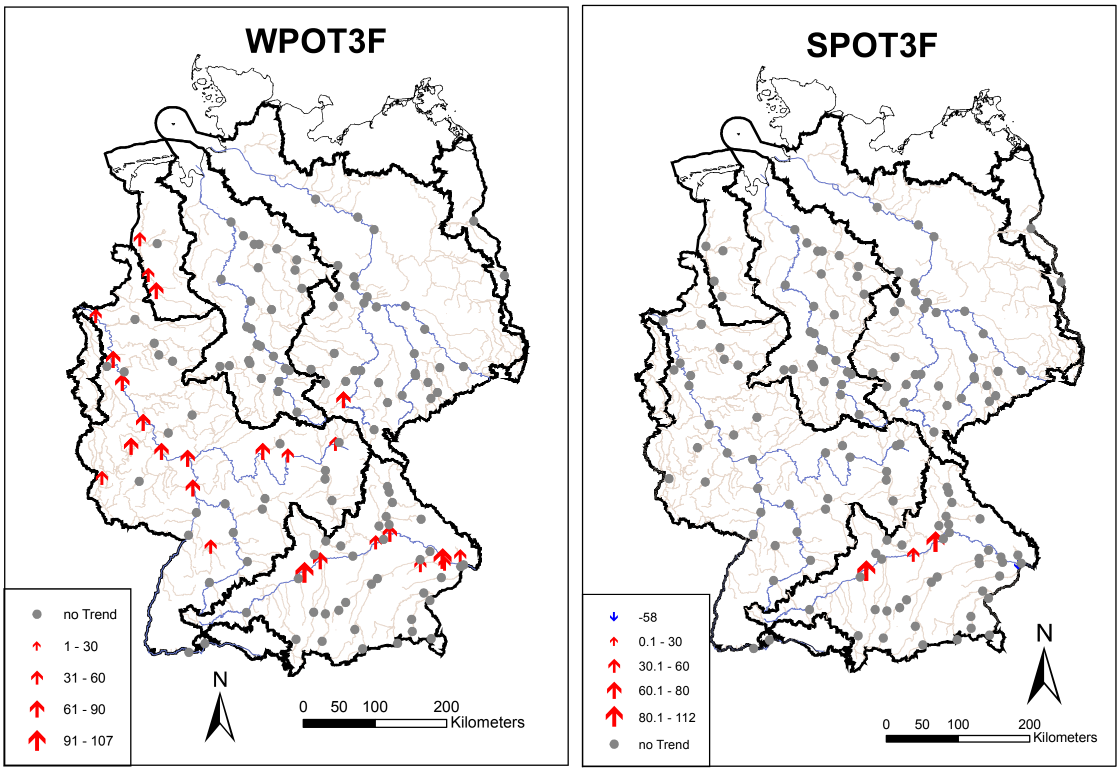

Figure 2.7: Spatial distribution of trends in seasonal peak-over-threshold frequency - WPOT3F (winter, left map), SPOT3F (summer, right map); (Upward arrows: significant increasing trend; downward arrows: significant decreasing trend; circles: no significant trend; size of arrows: relative change within 52 years; Mann-Kendall test, 2-sided option; 10% significance level)

(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, the upward trends of AMAXF in the Danube basin are mainly dominated by upward trends in summer floods. However,

	% 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

Table 2.3: Percentages of gauges showing significant trends; bold numbers indicate field significance

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 behaviour 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 northwesterly patterns decreased at the same magnitude (Mittelgebirge Weser,

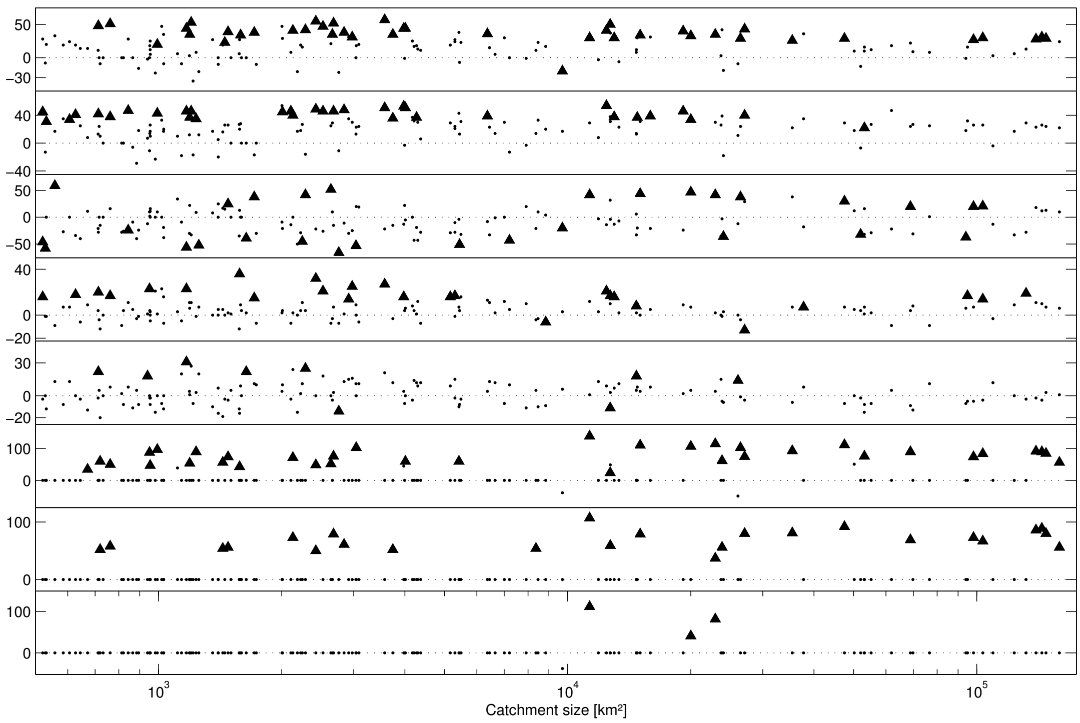

Figure 2.8: Relative change [%] as function of basin area. Triangles indicate significant changes at the 10% significance level. From top to bottom: AMAXF, AWMAXF, ASMAXF, POT1M, POT3M, POT3F, WPOT3F, SPOT3F

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 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).

2.6 Conclusion

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 as-

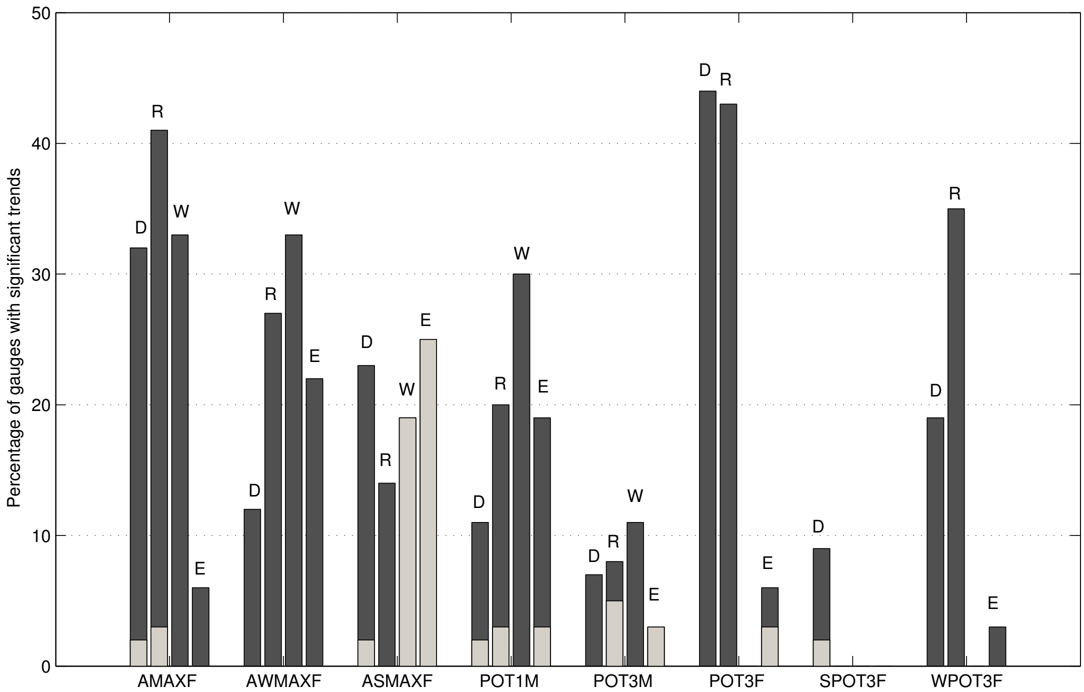

Figure 2.9: Percentages of gauges with significant trends per catchment and flood indicator. Dark grey bars show percentage of upward trends, light grey bars show percentages of downward trends; abbr. for the catchments are D - Danube, R - Rhine, W - Weser, E - Elbe

sessing the spatial and seasonal coherence of flood trends: Basins with significant trends were spatially clustered. Changes in flood behaviour 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 behaviour 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. (2004) for a smaller area, orographic obstacles heavily influence the spatial distribution of the rainfall and runoff processes. A changing behaviour 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 behaviour for changes when estimates for flood design or flood risk management are needed.

Acknowledgements

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3 Changes in the flood hazard through changing frequency and persistence of circulation patterns

Abstract

The link between trends in circulation patterns and trends in the flood magnitude is studied for 122 meso-scale catchments in Germany for a period of 52 years (1951–2002). Flood trends, significant at the 10% level, are detected for a large number of catchments. The catchments are pooled into three regions, based on flood seasonality and flood trends. Field-significant increasing trends are found for winter in Regions West and East. For summer, increasing and decreasing flood trends are detected for Regions South and East, respectively. The temporal behaviour of three flood indicators of each region is compared to atmospheric indicators derived from circulation patterns. Significantly increasing frequency and persistence of flood-prone circulation patterns intensify the flood hazard during the winter season throughout Germany. Moreover, a trend towards a reduced diversity of circulation patterns is found causing fewer patterns with longer persistence to dominate the weather over Europe. This indicates changes in the dynamics of atmospheric circulations which directly influence the flood hazard. Longer persistence of circulation patterns which in general do not favour large precipitation amounts may lead to large runoff coefficients due to soil-moistening and hence cause floods.

Petrow, Th., J. Zimmer, and B. Merz. 2009. Changes in the flood hazard through changing frequency and persistence of circulation patterns. Natural Hazards and Earth System Sciences, 9, 1409–1423.

3.1 Introduction

Changes in the atmospheric dynamics and their links to hydrological processes are an important aspect in the discussion about climate change. During the last decades, many devastating floods occurred in Europe giving rise to the discussion whether or not flood-triggering atmospheric patterns may have significantly changed. Many studies evaluated trends in climatic variables such as the North-Atlantic Oscillation (NAO), changes in ENSO phenomenon (El Nino/Southern Oscillation) or in circulation patterns (CP) and linked these with precipitation or temperature. CPs are either derived by 500 hPa geopotential height fields from reanalyses data or from classification schemes, for instance by Hess and Brezowsky (1952). Bárdossy and Caspary (1990) used the CP catalogue of Hess and Brezowsky for the period 1881–1989 and found significant changes in the frequency of daily, seasonal and annual data of several CPs leading to milder and wetter winters in Europe. Steinbrich et al. (2005) showed for south-western Germany (Baden Wuerttemberg) that the link between CPs and large precipitation events varies strongly depending on the seasonal and regional conditions. They found most of the analyzed heavy precipitation events to be triggered by only few CPs. Werner et al. (2008) detected CP and precipitation trends in the Elbe catchment in the period 1951–2003. During the winter season, the number of days with precipitation tripled. Also, increases in frequency and duration of west and north-west circulation patterns were observed (Werner et al., 2008). Pauling and Paeth (2007) identified an increase in extreme winter precipitation during the last 300 years over Europe. Casty et al. (2005) found a close correlation between the NAO index and temperature and precipitation indices in the European Alps during the last 500 years. A clear relation between precipitation and NAO was detected by Feidas et al. (2007) for Greece for the period 1955–2001. They observed downward trends in winter and annual precipitation which were correlated with rising trends in the hemispheric circulation modes of the NAO. Santos et al. (2007) emphasized the strong link between NAO and heavy precipitation events over Europe.

Only few studies investigated the link between atmospheric and flood indicators. Kingston et al. (2006) reviewed on studies about the connection between climate, streamflow and atmospheric circulations (esp. NAO and Arctic Oscillation (AO)). Svensson et al. (2006) reported correlations between trends in the NAO index and floods for Europe. McKerchar and Henderson (2003) found changes in several hydrological variables in New Zealand which were consistent with changes in the Interdecadal Pacific Oscillation. Jacobeit et al. (2006) determined large-scale CP for historical flood events with the help of Reanalysis data. They identified CPs that are relevant for the flood hazard in Europe. The most important CPs for triggering prominent discharge peaks are (1) for summer the Vb-pattern, westerly flows with southerly components as well as troughs and (2) for winter westerly winds with changing north/south components. A study of meso-scale snow-free catchments in France and Spain by Bárdossy and Filiz (2005) identified flood-producing circulation patterns with the help of large-scale sea-level pressure fields. Bouwer et al. (2006) identified a closer relationship between mean winter discharge and WZ circulation patterns (after Hess and Brezowsky, 1952) than between discharge and NAO. Bouwer et al. (2008) calculated correlations of four atmospheric variables (NAO, AO, westerly-cyclonic circulation pattern, sea-level pressure differences) and winter precipitation to annual mean and maximum winter discharges at 11 gauges in Central Europe. They found that annual maximum discharges are more sensitive to changes in atmospheric circulations than mean discharges. So far, the relationship between peak discharges and atmospheric variables has been investigated for Germany only for selected regions. Belz et al. (2007) analyzed flood discharges, CPs according to Hess and Brezowsky, and areal precipitation for the Rhine catchment. CPs were classified into wet and dry patterns. The pattern WZ was studied in more detail, since it is the most frequent pattern and comprises the days with the largest precipitation amounts. Belz et al. (2007) found increasing trends in wet CPs (which also contain WZ), areal precipitation and discharge for the period 1951–2000. An even higher significance level of increasing trends was found for winter maximum discharges compared to increasing trends in annual maximum discharges. Caspary and Bárdossy (1995) found an increase in the pattern WZ for winter, leading to a dramatic increase in the flood hazard for south-western Germany. Mudelsee et al. (2004) studied flood trends in the Elbe and Odra catchments and found downward trends in winter and no significant changes during summer.

Since these studies are limited to selected regions in Germany, a countrywide picture of trends in floods and atmospheric patterns cannot be drawn. Our study closes this gap by presenting results of flood trends and trends in circulation patterns for 122 meso-scale catchments across Germany for the period 1951–2002. The trend behaviour of eight flood indicators at 145 gauges (500–159300 km^2) in Germany was already analyzed for the same period by Petrow and Merz (2009). Their findings form the basis for the here presented study. Petrow and Merz (2009) detected trends in peak discharge, which were spatially and seasonally clustered. A missing relation between discharge changes and basin area suggests that the observed changes in flood behaviour are climate-driven. In contrast to the study by Petrow and Merz (2009), we here present results of time-varying multiple trend tests both for flood and CP indicators. McCabe and Wolock (2002) also used this approach and found patterns of significant changes in different discharge variables in the United States for the period 1941–1999. For the evaluation of a possible link between flood and atmospheric patterns, correlations between peak discharges and CPs were computed similar to other studies (e.g. Feidas et al., 2007; Bouwer et al., 2008).

The gauges were pooled into regions (cf. Douglas et al., 2000; Merz and Blöschl, 2009). The pooling into three regions reflects different flood regimes across Germany. A catchment-independent pooling was favoured over a catchment-based approach to account for the characteristic seasonality of peak discharges in each region. Moreover, the flood trend results observed by Petrow and Merz (2009) showed that regions of similar flood trends do not necessarily coincide with catchment borders. Thus, the catchment-independent approach enables us to draw a more precise picture of the observed changes. For all regions conclusions are finally presented to what extent parallels between trends in flood magnitudes and trends in circulation patterns can be found.

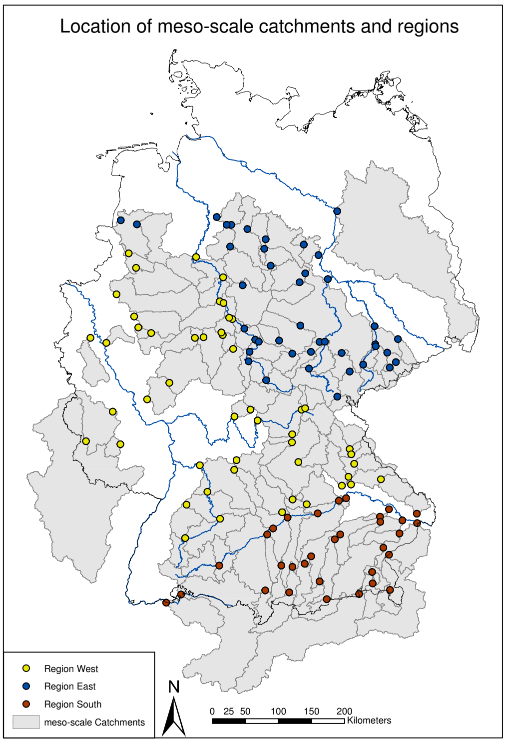

Figure 3.1: Discharge gauges of 122 meso-scale catchments and their assignment to one of the three regions. Catchment borders illustrate the spatial coverage of the dataset.

3.2 Data

3.2.1 Discharge Data

Discharge data of meso-scale catchments were used for this study. We included catchments of at least 500 km^2 in order to minimize the influence of land management measures on the flood behaviour (Bronstert et al., 2002). The largest analyzed catchment is the river Mosel at the gauge Cochem (27088 km^2). A common time period between 1 November 1951 and 30 October 2002 was used (hydrological year in Germany: 1 November to 31 October). Svensson et al. (2006) suggest a minimum length of 50 years for the analysis of flood trends. Shorter time series may not capture a possible trend, whereas very long series of up to 100 years may have other shortcomings as for instance changes of the measuring procedure over time. The chosen time period was seen as compromise between a minimum length and the requirements for reliability and availability of data.

Each of the 122 gauges was assigned to one of three regions (Fig. 3.1), which are characterized by homogeneous seasonal flood histograms and flood trends. The regions were extracted through a GIS-based multi-criteria analysis. Histograms of the seasonal flooding frequencies as presented by Beurton and Thieken (2009) as well as trend results of eight flood indicators by Petrow and Merz (2009) were compared in a spatially-explicit manner in order to identify homogeneous regions. A change in the assignment of gauges to one or the other region is visible along the main rivers of Danube and Weser. This is caused by differences in seasonal histograms of the flood indicators. For instance, the assignment of the gauges along the Danube to Region South can be explained by the dominance of summer maximum discharges which is characteristic for the southern tributaries rather than for the northern ones.

Figure 3.1 gives an overview of the location of the gauges and regions.

Region West (yellow dots) comprises 49 discharge gauges which are located in the Rhine, Weser, Ems and Danube catchments. This region has a winter dominated flood regime. Frequently, westerly winds cause flooding especially during winter. Trends in winter maximum discharges increase both in magnitude and frequency (Petrow and Merz, 2009). Summer floods play a minor role.

Region East (blue dots) consists of 41 gauges in the Weser, Ems and Elbe catchments. Maximum discharges occur predominantly during winter in this region, however, summer peak discharges have a larger share than in Region West and can reach remarkable extents as experienced in 2002 and 2005 (DKKV, 2004; Beurton and Thieken, 2009). Winter floods increase in Region East, whereas summer floods decrease. This is the only region in Germany, in which summer floods significantly decrease (Petrow and Merz, 2009).

Region South is represented by 32 gauges which are located in the Rhine and Danube catchments. Two gauges are located in the Rhine catchment, all other gauges are located either along the main river of the Danube or along its southern tributaries. The two gauges in the Rhine catchment have larger shares of winter discharges compared to the other gauges in the Danube catchment. The Danube region is dominated by summer flood events. However, winter peak discharges significantly increase in magnitude at many gauges in the region (Petrow and Merz, 2009).

In this study, three flood indicators were analyzed for each gauge. These comprise annual maximum streamflow series (AMAXF) as well as seasonal maximum series (AWMAXF and ASMAXF). Annual maximum 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. The analysis of seasonal maximum series enables a more differentiated picture of flood trends. Annual winter maximum discharge series (AWMAXF) were derived from data between 1 November and 31 March of the following year and consist of the largest daily mean discharge of each winter season. Summer maximum discharge series (ASMAXF) were derived for the period of 1 April - 31 October.

3.2.2 Circulation patterns

For the analysis of trends in circulation patterns different classification systems are available, which are either manual (based on subjective knowledge) or automated numerical schemes. The widely used manual classification scheme by Hess and Brezowsky (1952) is currently the only one available, which captures the large-scale European pattern, while still focusing on local details (James, 2007). Buishand and Brandsma (1997) compared three classification schemes of CPs and found that the subjective Großwetterlagen classification by Hess and Brezowsky (1952) yields equally good results as the two other objective schemes. Therefore, the scheme by Hess and Brezowsky (1952) was used in this study. Moreover, the use of this classification facilitates the comparison of our results to other studied conducted for German catchments.

Daily data of the "Catalogue of Großwetterlagen in Europe 1881–2004" after Hess and Brezowsky (1952) was available for this study (Gerstengarbe and Werner, 2005). The catalogue provides a subjective classification for every day about the dominant circulation pattern (CP) over Europe which is derived based on the spatial distribution of pressure systems over Europe as well as the location of frontal zones. The catalogue distinguishes 30 different CPs (one is classified to be a "transition class"). The CPs comprise the zonal circulation form, the mixed circulation form as well as the meridional circulation form (Table 3.1).

The most important CPs with respect to the flood hazard in Germany are WZ, WS, NWZ, and TRM. The first three patterns are frequent and comprise 25% of the overall distribution for Germany. These are westerly winds of varying direction (from north to south). The pattern TRM is better known to be the "Vb-weather pattern" and is represented by a trough over Central Europe (van Bebber, 1891). Low pressure systems move from the Gulf of Genoa northwards to Poland. Large precipitation amounts can be accumulated and may be enhanced along the northern slopes of the Alps and the mountain ranges in Central and Eastern Europe. Several destructive floods were triggered by TRM, as experienced for instance in the Elbe and Danube catchments in 2002 and 2005 (Ulbrich et al., 2003).

The influence of a CP on the flood regime varies from region to region. Peak discharges in Region West are often caused by westerly, south-westerly and north-westerly circulation types (Beurton and Thieken, 2009). High pressure systems are rarely responsible for floods in Region West. Floods occur predominantly during mild and wet episodes in winter. Region East is also largely influenced by westerly winds, however, the north-westerly pattern plays a more important role than in Region West. A larger share of high pressure systems and the occurrence of Vb-weather regimes distinguish the region from Region West. Region South is dominated by high pressure systems, especially during fall and winter. Westerly, north-westerly and south-westerly circulation types are less frequent compared with the other regions. Peak discharges occur predominantly during summer.

Daily data of the CPs were analyzed for trends in four variables:

1. the number of days of each CP per year,
2. the number of events of each CP per year (independently of its length), and
3. the mean duration of each CP per year, and
4. the maximum duration of each CP per year.

These variables were analyzed on an annual basis and for winter and summer seasons. The number of days per year gives an indication of the frequency. The number of events was counted, independently of the CP length, in order to gain information about the variability of CP. The persistence of CP is particularly important for the flood hazard. There are numerous examples of long-lasting CPs that are accompanied by a sequence of weaker precipitation events, which finally cause large floods.

Form of Circulation	No.	Circulation pattern name	Abbr.
Zonal Circulation	1	West wind, anti-cyclonic	WA
	2	West wind, cyclonic	WZ
	3	Southern west wind	WS
	4	Angular west wind	WW
Mixed circulation	5	South-west wind, anti-cyclonic	SWA
	6	South-west wind, cyclonic	SWZ
	7	North-west wind, anti-cyclonic	NWA
	8	North-west wind, cyclonic	NWZ
	9	High pressure system, Central Europe	HM
	10	High pressure bridge over Central Europe	BM
	11	Low pressure system, Central Europe	TM
Meridional circulation	12	North wind, anti-cyclonic	NA
	13	North wind, cyclonic	NZ
	14	High pressure Iceland-Norwegian Sea, anti-cyclonic	HNA
	15	High pressure Iceland-Norwegian Sea, cyclonic	HNZ
	16	High pressure, British Isles	HB
	17	Trough Middle Europe	TRM
	18	North-east wind, anti-cyclonic	NEA
	19	North-east wind, cyclonic	NEZ
	20	High pressure Fennoscandia, anti-cyclonic	HFA
	21	High pressure Fennoscandia, cyclonic	HFZ
	22	High pressure Norwegian Sea-Fennoscandia, anti-cyclonic	HNFA
	23	High pressure Norwegian Sea-Fennoscandia, cyclonic	HNFZ
	24	South-east wind, anti-cyclonic	SEA
	25	South-east wind, cyclonic	SEZ
	26	South wind, anti-cyclonic	SA
	27	South wind, cyclonic	SZ
	28	Low Pressure, British Isles	TB
	29	Trough, Western Europe	TRW
	30	Transition, no classification	U

Table 3.1: Classification of the circulation form and its specific pattern after Hess and Brezowsky (1952)

To each value of the discharge AMAXF series of each gauge, the flood triggering CP was assigned, in order to evaluate the link between changes in CP over time and flood trends. Depending on the catchment size, a time lag of one to three days was applied (Duckstein et al., 1993; Frei et al., 2000; Bárdossy and Filiz, 2005). For small catchments with 500–5000 km^2, a time lag of one day was assumed, catchments with 5001–20000 km^2 had a time lag of two days and larger catchments of three days. For example, a catchment of 600 km^2 had an AMAXF entry on 19 March 1951. Then, it was assumed that the flood triggering CP occurred on 18 March 1951. Although there is some uncertainty when assigning a "mean" concentration time to all catchments of a certain size range, the time lag is regarded to be sufficiently precise, especially when considering that the median persistence of CPs is from three to five days. Except for the transition class "U" (CP 30), all CPs persist for at least three days and often up to 10 days.

3.3 Trend detection

The robust non-parametric Mann-Kendall (MK) test and a resampling approach were used for detecting trends both in peak discharge and circulation patterns (Kendall, 1975). The MK test is particularly useful for the analysis of extremes and requires no specific distribution. It has been used by a variety of studies on hydro-meteorological trends (e.g. Chen et al., 2007; Feidas et al., 2007). We applied the two-sided option with 10% significance level. The MK test requires the data to be serially independent. von Storch and Navarra (1995) found that, if the data are positively serially correlated, the 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. (2002a, 2003) and Petrow and Merz (2009). In short, a trend of a time series is estimated by the non-parametric trend slope estimator (Sen, 1968). A possible trend is then removed from the original series. Thereafter, the lag1-autocorrelation is calculated. If no significant autocorrelation is found, the MK test is directly applied to the original time series. Otherwise, the lag1-autocorrelation is removed from the time series. The data series is now regarded to be free of trend and serial correlation. Finally, the firstly removed trend is included back into the time series resulting in a series that includes the original trend without autocorrelation.

Discharge data were analyzed for each gauge separately and aggregated for each region as a regional composite. These composite series were derived as follows: series of AMAXF (analogue ASMAXF, AWMAXF) from every gauge were drawn. For all time series the TFPW-methodology was applied. After that, all series were normalized (by subtracting the mean and dividing the result by the standard deviation of the time series). Then, the regional composite was calculated by averaging all normalized discharge time series of a given region. The TFPW procedure causes in some instances small deviations, which lead to larger magnitudes of seasonal MAXF compared to AMAXF (cf. Fig. 3.2).

Maximum discharge and CP time series were analyzed for trends not only for the entire period (1951–2002), but also with the help of moving windows of varying time lengths (multiple trend tests). Through this methodology it is possible to detect changes in trends over time and to distinguish recent trends from trends that are stable over longer time periods (McCabe and Wolock, 2002). All possible periods of 20 to 52 years within the investigated time series were analyzed for trends. The trend matrix shows for each variable and changing time periods the resulting significance level. These levels were derived by means of a resampling approach.

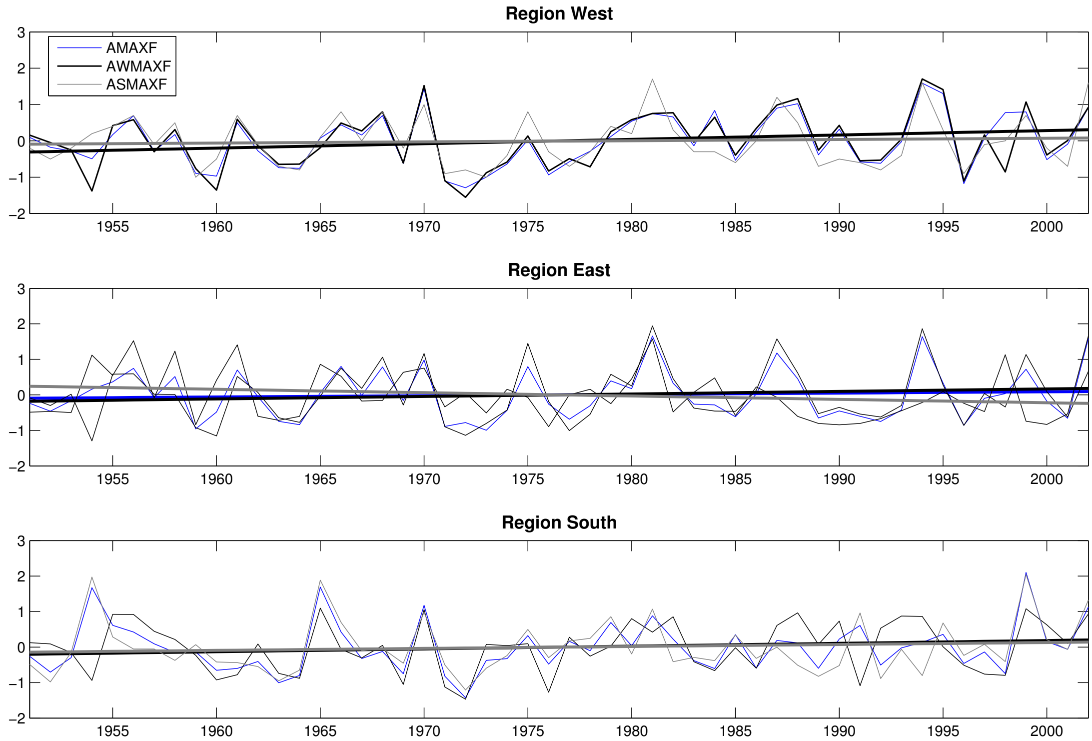

Figure 3.2: Composite maximum discharge time series with trends per region and flood indicator (note: in Region West the trend lines of AMAXF and AWMAXF are almost the same and therefore not easily distinguishable)

1. The time series is resampled randomly without replacement. A new time series is obtained with the same values but different year order.

2. A linear trend line is fitted to the new time series and its slope is calculated.

3. By repeating steps 1 and 2 1000 times, a sample of slope values of size 1000 is obtained.

4. The significance level of the observed time series is determined by comparing its slope with the empirical cumulative distribution of the slope values of the resampled time series.

In regional trend detection studies 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). Douglas et al. (2000) determined the field significance by calculating a regional critical value for the Mann-Kendall test, which is derived through a bootstrapping approach. The number of stations to show a trend by chance for the specific region is determined. Thereafter, the number of observed trends is compared with the number of expected trends for 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 and proposed a bootstrapping test for assessing the field significance of trends while preserving the cross-correlation among sites. However, this approach might only be suitable 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. A detailed description of the methodology can be found in Yue et al. (2003) or Petrow and Merz (2009).

3.4 Results

3.4.1 Trends in flood data

Composite discharge time series of the three maximum series are shown for all regions in Fig. 3.2. Upward trends (MK test, 10% SL) were found for all three composite series for Regions West and South and for winter and annual maximum series for Region East. A downward trend was detected for the composite summer maximum series (ASMAXF) of Region East. Many trend lines in Fig. 3.2 have almost the same slope and are therefore not easily distinguishable. Discharge data of each gauge were tested with the MK test for upward and downward trend (SL 10%). Table 3.2 shows the results for the flood indicators and regions. Large differences are evident in the number of trends per variable and region.

Many upward trends were found in the Regions West and South. The three gauges with upward AMAXF trends in Region East are clustered in the southern part of the region and are located in the vicinity of gauges with trends of Region West (Petrow and Merz, 2009). Upward trends in AWMAXF are spatially clustered in Central Germany affecting the northern part of Region West and the southern part of Region East. A different pattern evolves for the summer series: downward trends are, except for one gauge in Region South, exclusively found in Region East, whereas upward trends are concentrated in Region South. In the following, trend results of different time lengths of the composite series are presented, which offer the possibility to study the temporal variability of flood trends.

Figure 3.3 shows multiple trend tests (MK test, 10% SL) for varying time periods of the composite series of AMAXF, AWMAXF and ASMAXF for the three regions. Upward trends are reflected in Figures 3.3, 3.8 and 3.9 by numbers from 95 to 100, and downward trends by numbers from 5 to 0, respectively. The x-coordinate shows the starting year and the y-coordinate the ending year of the analyzed period, leading to time series lengths of 20 to 52 years. The result of the trend test for the time period 1951–1970 is given in the lower left corner of the trend matrix. In the upper left corner the result of the entire series (1951–2002) can be found. On the diagonal, trend results of 20-year time period are shown, beginning in the lower left corner with the period 1951–1970, progressing with a step of one year and ending in the upper right corner with the period 1983–2002. In the first row the results for

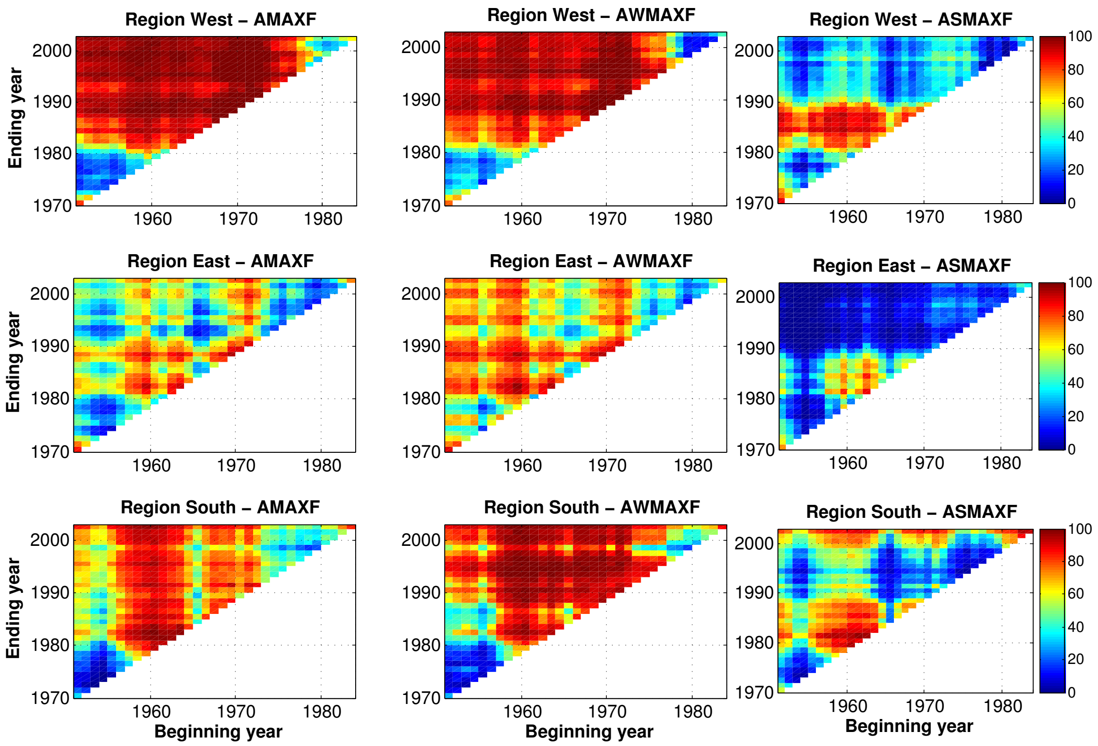

Figure 3.3: Significance level of trends of different flood indicators for varying time periods for Region West (first row), Region East (second row), and Region South (third row). Results between 95 and 100 indicate upward trends, results between 0 and 5 downward trends.

Region West are shown, in the second row for Region East and finally in the third row for Region South. In the following, the results are discussed for each region separately.

3.4.1.1 Region West

Many upward trends are evident for Region West for AMAXF and AWMAXF. Both matrices have similar patterns (Fig. 3.3). Time series of different lengths ending latest in 1982 show a slightly downward tendency. Also, series of the last 20 to 25 years show small downward tendencies. All other time series which cover different time periods ending in 1982 or later show increases (mostly significant). Time series with at least 30 years show almost always upward trends. Interestingly, a relatively fast change of increases and decreases can be seen. The analysis of the diagonal with time periods of 20 years shows at first a period of decreasing annual and winter maximum discharges which ends in the beginning year 1962. This is followed by a period until 1977 where upward trends are detectable. From the beginning year 1978 onward, the time series show again no or only minor downward changes in the discharge data. This general pattern is more or less clearly seen for all regions for

Region	Flood indicator	Number of gauges with upward trend	Number of gauges with downward trend
West	AMAXF	**21**	1
(49 gauges)	AWMAXF	**20**	0
	ASMAXF	3	0
East	AMAXF	3	0
(41 gauges)	AWMAXF	**8**	0
	ASMAXF	0	**12**
South	AMAXF	**9**	1
(32 gauges)	AWMAXF	4	0
	ASMAXF	**8**	1

Table 3.2: Result of MK test (10% SL) of different flood indicators for each region (bold numbers indicate field significance)

AMAXF and AWMAXF.

Multiple trend test were also performed for each gauge and flood variable. A relatively heterogeneous spatial pattern resulted (not shown). As it can be expected, the summation per variable of the individual matrices of all gauges revealed a good correlation with the regional composite for each variable.

Although the regional composite of the winter maximum discharge shows a very similar pattern compared to the annual maximum discharge, the downward tendencies of the last 20 to 25 years are more pronounced during winter. In contrast to AMAXF, a spatial pattern of the temporal trend behaviour is visible for AWMAXF. The gauges in the northern part of Region West show all similar patterns and dominate the composite. All other gauges have changing patterns over time. These results are not shown here due to the limited readability when plotting a large number of matrices onto a regional map.

Summer maximum discharges play a minor role in Region West. The trend pattern of ASMAXF (Fig. 3.3) differs greatly for the last two decades. Decreases of different magnitudes are detectable for all time series since 1990. During the first years of the analyzed time span, the downward changes are similar to those in AMAXF and AWMAXF. Over the entire period, there are however nearly no significant trends detectable.

3.4.1.2 Region East

Although the seasonal distribution of flood events is similar to Region West with a majority of large discharges occurring during winter, the trend pattern for Region East shows many differences compared to Region West (Fig. 3.3, second row). A very heterogeneous pattern is visible for AMAXF with almost no trends. Periods of increasing and decreasing discharges alternate. Although the pattern of AWMAXF is dominated by increasing discharges, these are usually not significant at the 10% SL. The overall picture has some similarity to AWMAXF of Region West with clustered periods of upward and downward cycles.

In contrast, the summer series show

many downward trends (significant at the 10% SL), especially for time series ending in 1989 or later. There is a relatively sharp change from no trend towards a downward trend. Nearly all time series, which cover (parts of) the last two decades, show downward trends. The overall pattern is more pronounced compared to Region West.

3.4.1.3 Region South

Upward trends were detected for the three flood indicators in Region South (Fig. 3.3, third row). The AMAXF results show upward trends for a relatively short time frame beginning around 1960. Additionally, there are a few downward trends in short time series in the early 1950s, which can be found in all three flood indicators. Although the winter maximum discharge shows many upward trends, this pattern is not visible in AMAXF. The reason lies in the large percentage of summer events in AMAXF. Thus, the absence of significant trends in ASMAXF causes the small number of trends in AMAXF. Downward and upward cycles are more pronounced in AWMAXF, whereas the changes in AMAXF and ASMAXF are less abrupt. Changes of the summer series reveal a more variable picture. Here, upward and downward periods dominate the pattern. Most of them are not significant.

3.4.2 Identification of flood triggering circulation patterns

In order to identify flood triggering CPs for the three regions, the frequency of CPs that are associated with annual maximum discharges (AMAXF) was derived. Different CPs are relevant for triggering peak discharges in each region. Histograms of the flood triggering CPs were calculated for each gauge. Thereafter, mean frequencies for every region were calculated (Fig. 3.4). The differentiation into winter and summer reflects the discharge behaviour of the respective regions.

Regions West and East both show a winter dominated flood regime that is mainly influenced by only few CPs. 62% of the maximum discharges in Region West are triggered by the circulation patterns: WZ, WS, SWZ and NWZ. In Region West the dominance of WZ is more pronounced than in Region East, where the other remaining CPs play a more important role in triggering large discharges. The circulation patterns TM, TRM and TRW are important during the summer in the Regions East and South, when they are associated with large precipitation amounts that may cause floods. Note, that the importance of the CPs TM, TRM, TRW is not directly visible in Fig. 3.4, as they occur seldom.

Region South is characterized by a different seasonal flood behaviour. Summer maximum discharges dominate the AMAXF series. Winter peak discharges are triggered by the same CPs as in Region West, namely by WZ, WS and NWZ. Although summer floods have also large shares of WZ and NWZ, the circulation patterns BM, HB, TRM, NEZ and TRW play an important role for the summer flood hazard.

3.4.3 Trends in daily CP data

Daily data of CPs were analyzed for trend with the Mann-Kendall test (10% signifi-

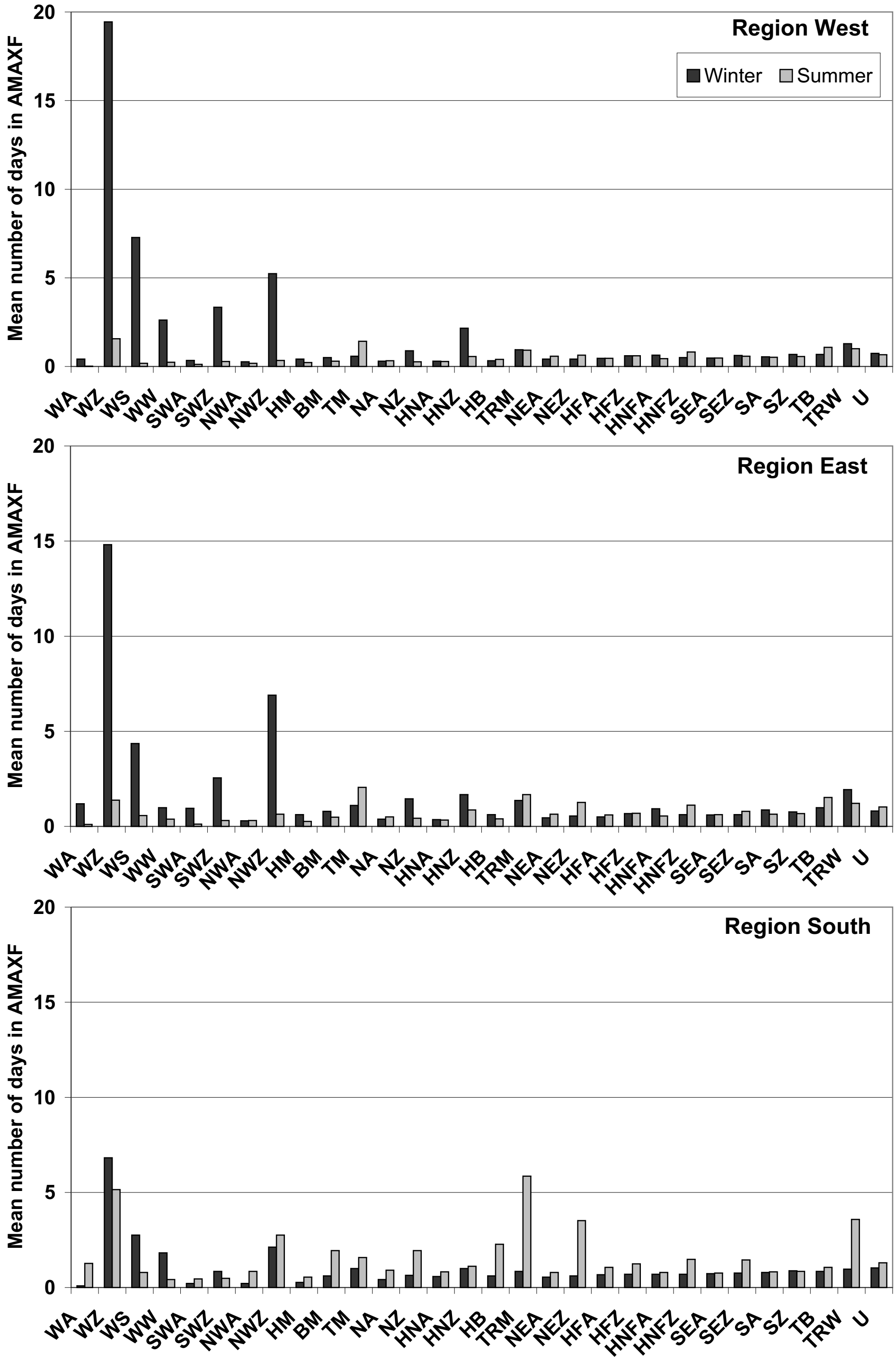

Figure 3.4: Mean frequencies of flood causing CPs in AMAXF series for the Region West, East and South

cance level). Four variables that capture the behaviour of the CPs over time were selected. These are the number of days with a certain CP per year, the number of CP events (independent of its length) and the mean and maximum durations per year. These variables were derived for the complete hydrological year and for the winter season and summer season, respectively (Table. 3.3). Since the trend results of the mean and maximum duration are very similar, Table 3.3 only shows the findings of the number of days, number of events and

		Number of days per year			Number of Events per year			Mean persistence in days per year		
CP	Name of CP	All	Wi	Su	All	Wi	Su	All	Wi	Su
1	WA	19	93	-17	0	0	0	**42**	**79**	18
2	WZ	**43**	**90**	18	0	0	0	**49**	**69**	**44**
3	WS	-31	0	0	0	0	0	0	0	0
4	WW	**-75**	-22	**-60**	**-75**	0	**-61**	0	0	0
5	SWA	50	**218**	0	0	0	0	**34**	**112**	0
6	SWZ	-13	**-45**	61	0	0	0	0	**-36**	**78**
7	NWA	72	0	0	0	0	0	**73**	0	0
8	NWZ	-16	68	**-74**	**-33**	0	**-61**	**38**	**118**	**-36**
9	HM	-29	0	**-43**	**-44**	0	**-51**	**35**	22	**31**
10	BM	**84**	**59**	**113**	21	0	0	**51**	**48**	**46**
11	TM	0	0	0	0	0	0	32	0	0
12	NA	0	0	0	0	0	0	0	0	0
13	NZ	-24	0	0	0	0	0	0	0	0
14	HNA	-19	0	0	0	0	0	0	0	0
15	HNZ	-36	0	0	0	0	0	0	0	0
16	HB	-11	**-55**	**57**	0	0	0	14	0	**163**
17	TRM	33	0	48	0	0	0	**29**	**50**	33
18	NEA	**-57**	0	0	**-75**	0	0	0	0	0
19	NEZ	**-61**	0	0	**-65**	0	0	**-39**	0	0
20	HFA	-28	0	0	**-39**	0	0	21	0	0
21	HFZ	0	0	0	0	0	0	0	0	0
22	HNFA	57	0	**260**	0	0	0	**82**	0	**384**
23	HNFZ	**-50**	0	0	0	0	0	0	0	0
24	SEA	0	0	0	0	0	0	0	0	0
25	SEZ	0	0	0	0	0	0	0	0	0
26	SA	0	0	0	0	0	0	0	0	0
27	SZ	0	0	0	0	0	0	0	0	0
28	TB	0	0	0	0	0	0	**33**	0	18
29	TRW	**58**	52	40	0	0	0	**41**	**68**	27
30	U	**-45**	0	**-44**	**-52**	0	**-50**	0	0	0

Table 3.3: Relative change within 52 years in % (bold numbers indicate trends (MK test, 10% SL); grey rows show flood relevant CPs)

the mean duration per year. Six CPs show no trend at all for all variables and the different datasets. Four CPs revealed slight changes in only one variable, which were however not significant.

3.4.3.1 Number of days

The majority of CPs shows changes in the number of days (MK test, 10% SL). However, for only eight CPs the trend is also significant for the annual dataset (column "All"). Upward trends were found for the annual dataset for the three CPs WZ, BM and TRW. It is important to note that all three CPs hold a considerable potential for floods. WZ is important throughout Germany, whereas the patterns BM and TRW only play an important role for Region South. Downward trends were detected for the patterns WW, NEA, NEZ, HNFZ, and U. Among these, only NEZ is important for the flood hazard (again only in Region South). All other changes were not significant. Figure 3.5 shows two histograms of the number of days per CP for the annual dataset (top), winter (middle) and summer (bottom), respectively. On the left side the histograms for the decade 1951–1960 are found and on the right side for the decade 1991–2000. In all three datasets, a statistically significant shift is visible towards a smaller number of CPs, which dominates the weather (Chi^2 test; 10% SL). Thus, CPs, as for instance WZ, which had already a large share of days per year even increased in the frequency, whereas less frequent CPs in general decreased. There are some exceptions that are also important for the flood hazard. For instance, the pattern TRM increased in frequency, although it rarely occurs. This is especially important for the summer flood hazard, although the changes are also detectable for the winter and the annual datasets.

For the winter and summer seasons, less trends were detected. Figure 3.6 shows results of the seasonally differentiated trends for selected CPs. These six CPs are important for at least one of the three regions. WS, a pattern that also frequently triggers floods, is not shown in the diagram because for both seasons and all three variables non-significant decreases were found. The patterns WZ, BM and TRW show for all datasets upward changes which are however not always significant. Interesting results were found for the pattern NWZ which is important throughout Germany. When testing the entire dataset for trend, no trend was detected for NWZ. A look at the seasonal time series showed, however, that during the winter a non-significant increase of 68% was found, whereas the summer time series revealed a significant downward trend of -74%. Figure 3.4 shows that the NWZ pattern is especially important for triggering winter peak discharges throughout Germany and also summer peak discharges in Region South. The SWZ pattern has the opposite development: a downward trend during the winter and a non-significant increase during the summer months.

3.4.3.2 Number of events

The analysis of the number of events with a particular CP (independent of its length) reveals less change than for the number of days (Table 3.3). Only eight CPs show changes, seven of these are trends (significant at the 10% SL). During the winter there are no changes at all, and for the

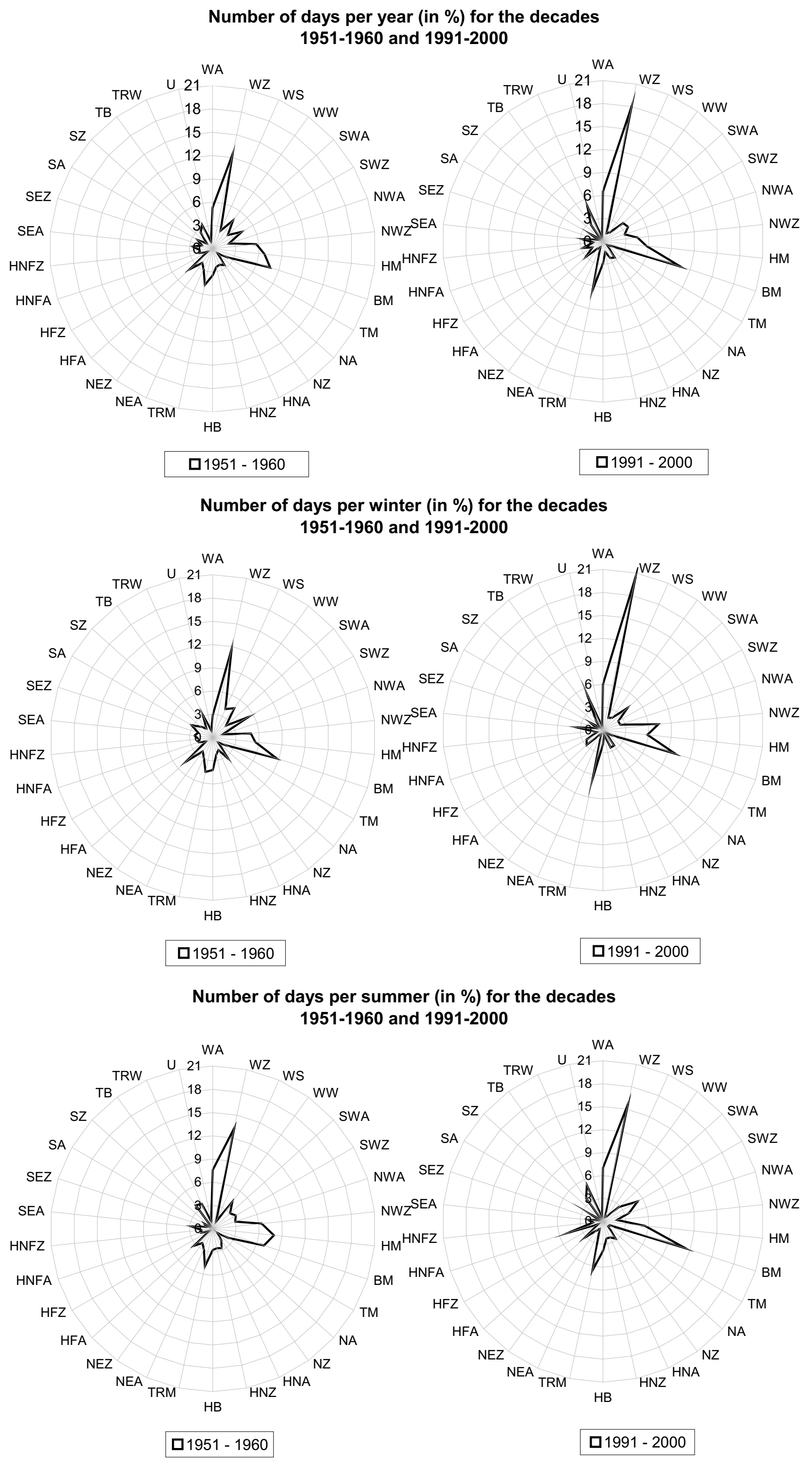

Figure 3.5: Comparison of CP frequencies for the decades 1951–1960 and 1991–2000

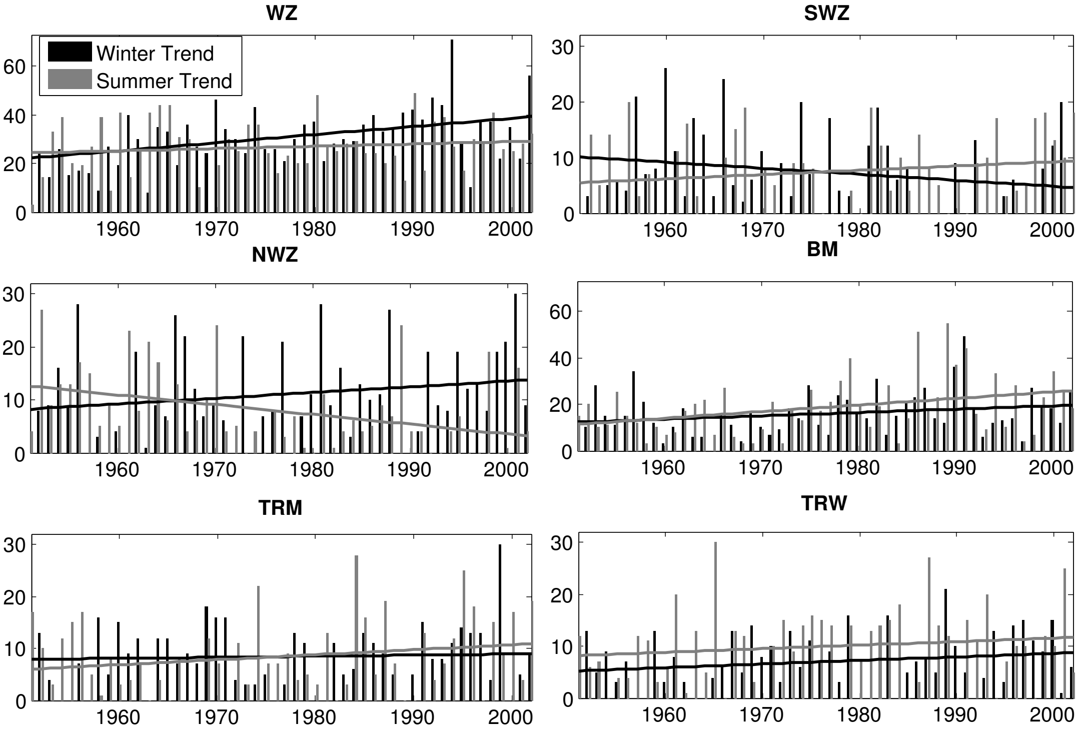

Figure 3.6: Number of days per year in selected summer and winter daily CP series

summer season there are only four trends, which are significant at the 10% SL. With the exception of one increase (for BM), which is however not significant, all other changes were downward.

3.4.3.3 Mean persistence

Conditions in the catchment prior to a flood play an important role for the flood hazard. Consecutive precipitation events due to increasing persistence of specific CPs contribute to soil saturation, leading to higher runoff, possibly even for weak precipitation events. Our analysis reveals many upward trends in CP persistence. In the entire dataset, 12 out of 30 CPs show significant changes in the mean persistence: Upward trends were detected for 11 CPs, and only one downward trend was found for NEZ (cf. Table 3.3). Eight of the 11 CPs also revealed upward trends in the maximum persistence. The only downward trend in the maximum duration was also found for NEZ. Figure 3.7 shows trends in the mean duration of selected CPs for summer and winter separately. The patterns WZ, NWZ and BM all have trends in the mean duration. WZ and BM show for all three datasets upward trends. The patterns NWZ and SWZ show again opposite trends for winter and summer. However, the trend directions are similar to those found for the frequency of days: for SWZ significant upward summer trends and for NWZ significant upward winter trends. The pattern

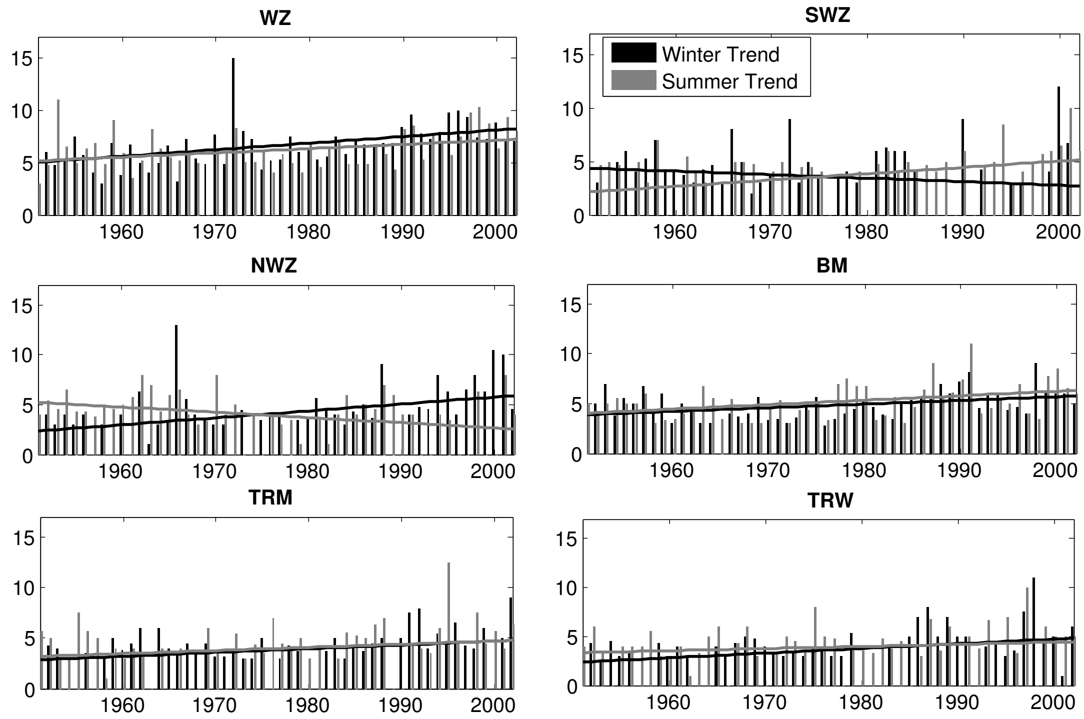

Figure 3.7: Mean duration of CPs per year in selected summer and winter daily CP series

TRM also shows increases which are however only significant for the annual dataset and the winter season.

3.4.4 Trend development of selected circulation patterns

3.4.4.1 Winter

All three flood regions are dominated during the winter season by the circulation patterns WZ, WS and NWZ (cf. Fig. 3.6). Figure 3.8 shows the significance level of trends for the number of days per winter and the mean duration matrices. Upward trends are reflected by the levels of 95 to 100, and downward trends by 5 to 0, respectively. Upward trends were detected in the number of days per winter as well as in the mean duration for WZ. NWZ also shows upward trends in frequency, especially when including the most recent years. Large changes are also visible in the mean duration of NWZ during winter, where a significant upward trend is detectable, when including the last years in the time series, no matter how long the series progresses into the past. WS does not change very much over time. The number of events of WZ and NWZ does not show a change during winter, for WS a slight decline is visible (not shown in Fig. 3.8). These results show therefore an increased flood hazard during the winter for all regions of Germany. This is espe-

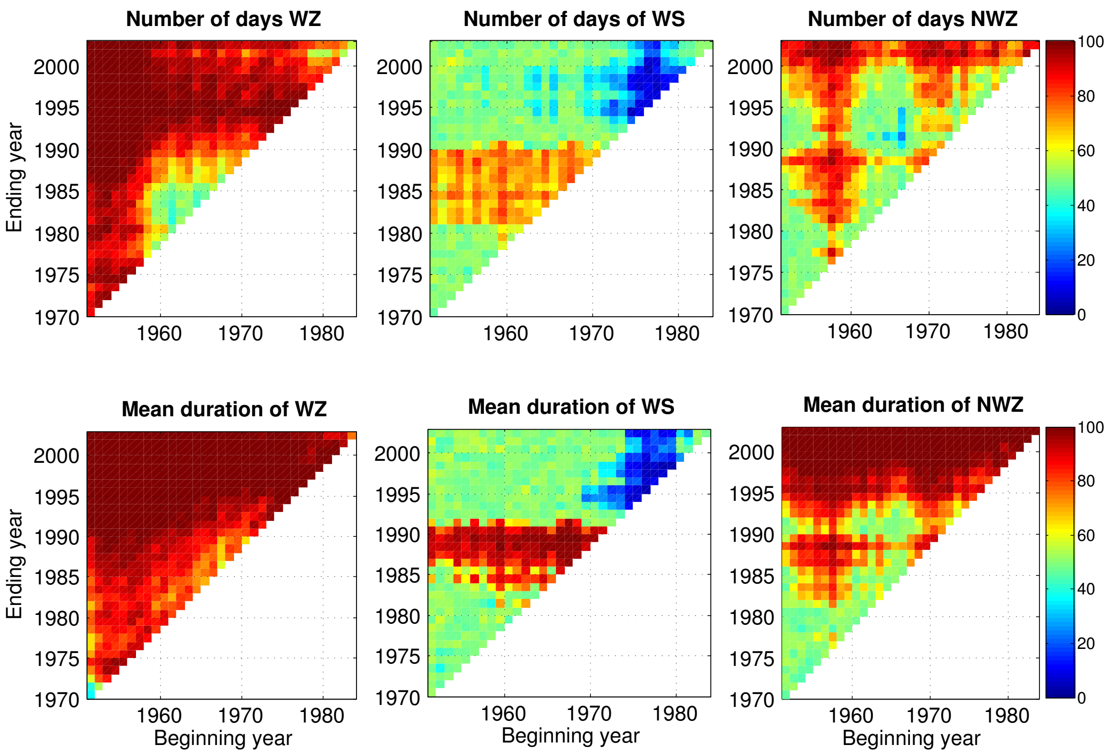

Figure 3.8: Significance level of trends in the number of days and mean duration during winter of the circulation patterns WZ, WS and NWZ. Results between 95 and 100 indicate upward trends, results between 0 and 5 downward trends.

cially important for the Regions West and East, where WZ and NWZ trigger large shares of winter peak discharges.

3.4.4.2 Summer

The trend picture for the summer season is more differentiated for all regions (Fig. 3.9). Although the percentages of WZ-triggered summer peak discharges are much lower than for winter, WZ plays an important role for the flood hazard (cf. Fig. 3.4). In Region South an increased flood hazard is visible, especially for the gauges in the Rhine catchment. Significant increases (results between 95 and 100) in the duration of WZ are evident when including the last 10 years into the dataset. No changes in number of days and number of events were detected. In contrast to the winter season, NWZ is significantly decreasing (results between 5 and 0) during summer in all three CP variables (Table 3.3). Downward changes are however only significant, when including at least 35 years into the trend test (Fig. 3.9). This decrease in the flood hazard caused by the NWZ pattern is again only relevant for Region South, since in the other two regions there are rarely NWZ-triggered summer flood events. The Vb-pattern TRM is increasing in all three variables. When in-

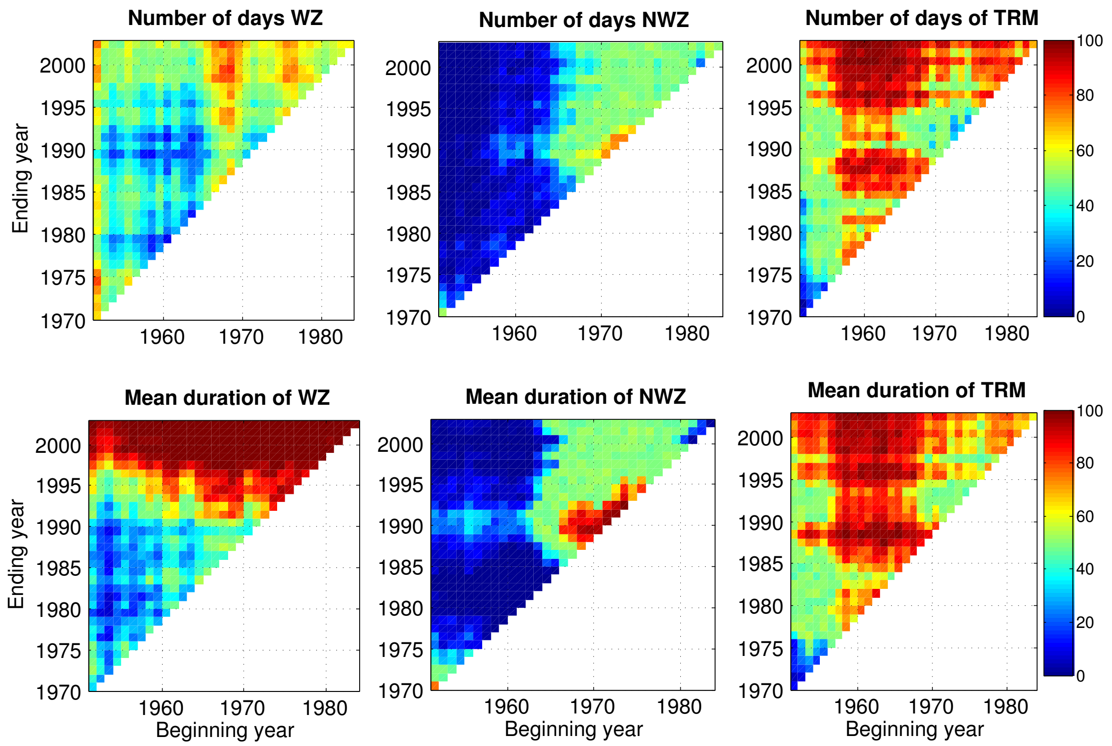

Figure 3.9: Significance level of trends in the frequency and mean duration during summer of the circulation patterns WZ, NWZ and TRM. Results between 95 and 100 indicate upward trends, results between 0 and 5 downward trends.

cluding the last decade in the trend test, the number of days and the mean duration show upward trends.

3.4.4.3 Correlation between seasonal MAXF and combinations of CP

Although there is only poor visual agreement between multiple trend test matrices of the different flood variables and individual CPs (cf. Fig. 3.3, Fig. 3.8, and Fig. 3.9), it is interesting to investigate the correlation of the time series between seasonal MAXF and combinations of CPs. The mean frequencies in Fig. 3.4 highlight the fact that a number of different CPs influences the peak discharge behaviour in all regions. We conducted therefore correlation analyses of seasonal composite MAXF and combinations of the most important and/or frequent CPs (number of days) based on the histograms in Fig. 3.4. All three regions show significant correlations (at the 10% SL) for the combinations of composite winter maximum series and the sum of days with WZ-NWZ and WZ-WS-NWZ, respectively.

Figure 3.10 exemplarily shows for Regions West (first row) and East (second row) results of four combinations of CP and seasonal discharge. These combinations were chosen based on (1) the dominance of winter peak discharges in Regions West and East, and (2) the large number of significant correlations for summer in Region East (see below). An overall good agreement of the fluctuations of seasonal MAXF and the different combinations of CPs (number of days) can be seen. The results show better agreements for both regions for the winter season (first row both diagrams and lower left diagram) than for summer. Although the coefficients of correlation are quite low (0.43–0.51) they are statistically significant. These low correlation coefficients are caused by (1) the small potential of a frequent CP to cause a flood event, and (2) the relatively poor agreement of the series during the first two decades.

For Region South, which is predominantly affected by summer floods, only non-significant correlations were found during summer, which are therefore not shown. The ASMAXF series of that region comprises many CPs, which can only be poorly represented by a small number of CPs as in Fig. 3.10. The combination with summer maxima (lower right diagram) in Region East exemplifies the complex relation during summer. Region East shows many significant correlations of the composite summer maximum series and different combinations of number of CP-days. These are WZ-TRM, TM-TRM, WZ-NWZ-TRM, and WZ-NWZ-TRM-TRW. Even the correlation between the composite ASMAXF of Region East with the number of days of TRM is statistically significant. This is an important finding since TRM only comprises about 4% of the entire CP, but regularly triggers peak discharges during summer in Regions East and South. Figure 3.10 (lower right subplot) presents therefore also a combination for summer in Region East, the one with the highest correlation. The overall agreement of fluctuations is, however, worse compared to the three subplots for winter combinations. The combination of CP days exhibits much more variability than the composite summer discharge series.

3.5 Discussion

A number of interesting trend results was found for each of the three flood regions (West, South and East Region). A link between trends in winter maximum discharges and the frequency and persistence of the CPs WZ and NWZ could be found for the Regions West and East. For summer, the link is not that obvious, however, also detectable for selected CPs and the Regions East and South. In the following, the findings of the study are discussed separately for each region.

3.5.1 Region West

Region West is dominated by winter peak discharges which are significantly increasing in magnitude. Several other studies found similar results for at least parts of the region (Caspary, 1995; Caspary and Bárdossy, 1995; Belz et al., 2007; Petrow and Merz, 2009). The study of Hennegriff et al. (2006) is in good agreement with our findings regarding the temporal dynamics of significant flood trends (cf. Fig. 3.3). They also detected at many gauges significant upward trends in AMAXF and AWMAXF for time series beginning in the 1970s.

The overwhelming part of peak discharges in Region West is triggered by

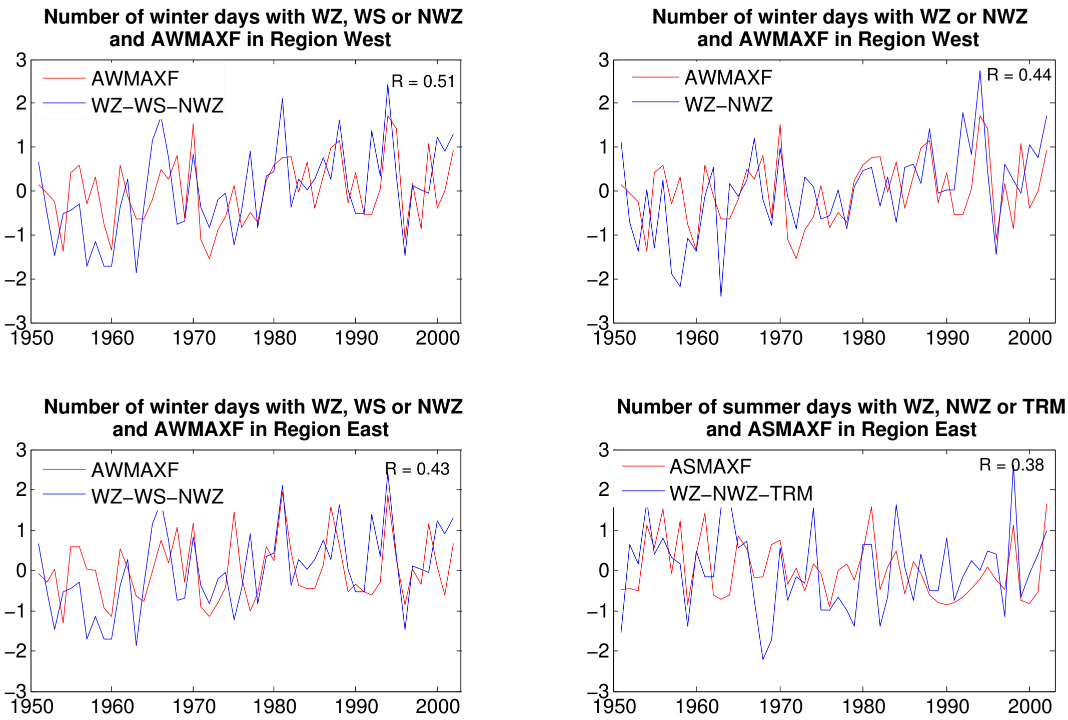

Figure 3.10: Comparison of seasonal MAXF data and combinations of CPs (number of days) for Region West (first row) and Region East (second row)

westerly winds of varying direction: WZ, WS, SWZ and NWZ. Although no major trends were detected for WS, the other CPs revealed significant changes, which affect the flood hazard in that region. With only slight changes in the number of events, the increasing number of days and persistence of WZ and NWZ cause the flood hazard to rise. Belz et al. (2007) also detected increasing trends of discharge and WZ for the winter season in the Rhine catchment. Gerstengarbe and Werner (2005) found for the winter season increasing trends of westerly atmospheric circulation types, too. 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 causing flood events but may be increasingly hazardous due to a longer duration. Long-lasting westerly atmospheric circulation types cause eventually large-scale soil saturation, leading to higher runoff coefficients. 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.

3.5.2 Region East

Region East is characterized by a similar winter discharge and CP regime as in Region West. The dominating patterns WZ and NWZ increase in frequency and persistence and will therefore intensify the flood hazard during the winter season. Mudelsee et al. (2006) also found an increase in the winter flood hazard during the last decades for parts of the region. Gerstengarbe and Werner (2005) found decreasing percentages of easterly circulation patterns during the winter, which cause cold and dry winters especially in Region East. At the same time, the number of days with precipitation tripled during winter in combination with increases in the frequency and duration of the patterns WZ and NWZ (Werner et al., 2008). These findings fit to our results of upward trends in the winter maximum discharges in Region East which are caused by more rain induced flood events due to milder winters and an intensified zonal circulation (Gerstengarbe and Werner, 2005).

Summer floods play a more important role than in Region West, especially floods triggered by TM and TRM (Petrow et al., 2007). We found decreasing trends in summer maximum discharges in Region East (cf. Table 3.2). A decrease in the flood hazard would be expected to be also visible in a decrease in flood-prone CPs during summer. The most frequent pattern WZ shows an upward trend in the duration. However, this pattern usually does not cause large floods in the region. In contrast the pattern TRM is better known to trigger large floods in the area. Although increases in the number of days and in the persistence of TRM were detected, these are not significant. Thus, a decreasing flood hazard based on the trends found in the discharge data of Region East is possible, despite these non-significant increases in the duration of flood-prone CPs.

3.5.3 Region South

Region South is dominated by summer maximum discharges. Also for this region, an increasing flood hazard can be found due to increasing trends in the patterns WZ, SWZ, TRM and TRW which play an important role for AMAXF discharges in the region. Our results show an upward trend in the persistence of SWZ during summer. This pattern is prone to triggering heavy convective rainfall during summer, which regularly causes local flood events. Also, Gerstengarbe and Werner (2005) found for summer large upward trends in the frequency of SWZ (tripled frequency with a step change in the 1940s).

3.6 Conclusions

Analyses of trends in flood hazard and in flood-triggering CPs show a regionally and seasonally differentiated picture for Germany. We investigated flood time series of 122 meso-scale catchments in Germany and their triggering circulation patterns. Our analysis detected discharge trends (at the 10% SL) for a large number of catchments, as well as in the frequency and persistence of flood-favouring circulation patterns. Of particular interest is a significant increase in (1) the flood relevant CPs, as well as in (2) the very frequent CPs. Significant correlation (at the 10% SL) between the frequency of CPs and seasonal flood time series was detected.

We found a trend (significant at 10% SL) towards a reduced diversity of CPs, causing fewer patterns with longer persistence to dominate the weather over Europe (cf. Fig. 3.7). This indicates changes in the dynamics of atmospheric circulations which are of direct relevance to the flood hazard. Longer persistence of CPs may lead to consecutive precipitation events. Although the single events may have rather low precipitation amounts, the succession of several events may lead to saturated catchment conditions. This is particularly important for winter peak discharge, which are in many cases triggered by WZ or NWZ patterns. Both are weather patterns that do not favour extreme precipitation. However, very wet preconditions may cause large runoff coefficients paving the way for flooding. Rapp and Schönwiese (1996) found upward trends in winter precipitation in the period 1891–1990 for large parts of south-western and western Germany. These results are in agreement with our findings and other studies for the Rhine catchment, which show significant increases in precipitation extremes and in the flood hazard during winter (e.g. Caspary and Bárdossy, 1995; Hundecha and Bárdossy, 2005; Belz et al., 2007; Petrow and Merz, 2009).

The investigated time span of 52 years in our study is relatively short compared to low-frequency climate variability. There are well organized modes of climate variability at different time scales and this variability may have a significant impact on the occurrence and magnitude of floods by changed atmospheric moisture transport (Hirschboeck, 1988). For example, Llasat et al. (2005) compiled a catalogue of floods for three basins in north–east Spain since the 14th century and found episodes of 20 to 40 years with markedly increased occurrence of catastrophic floods. Sturm et al. (2001) compiled a catalogue with floods in Central Europe from 1500 until today. Basins in Central Europe show clustering of floods. Given low–frequency climate variations, a much longer time period would have been favourable. However, a compromise between data availability and spatial coverage had to be found, when conducting a countrywide study. Although long series would capture a broader picture of the variability, a good spatial coverage with shorter time series was favoured over a long period of more than 100 years at only few stations. Further, long flood time series covering 100 or more years, are often associated with considerable uncertainty. For example, Glaser and Stangl (2004) stress that the direct comparison is problematic between reconstructed historical floods and measured data due to the different derivation of the datasets. For Finally, the considered time period is particularly interesting, since global warming is supposed to be of minor effect before the second half of the 20th century.

The presented results have implications for the flood risk management, especially for flood design measures. Petrow et al. (2008) compared a stationary and an instationary flood frequency analysis approach. They showed for the period of 1951–2002 that the stationary estimation (which assumes no trend in the data) may underestimate discharges of extreme events. Owing to the many detected flood trends in our study, a revised estimation of extreme events, which incorporates the instationarity inherent in the data, seems appropriate for the affected catchments.

Acknowledgements

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4 Aspects of seasonality and flood generating circulation patterns in a mountainous catchment in south-eastern Germany

Abstract

Analyses of discharge series, precipitation fields and flood producing atmospheric circulation patterns reveal that two governing flood regimes exist in the Mulde catchment in south-eastern Germany: frequent floods during the winter and less frequent but sometimes extreme floods during the summer. Differences in the statistical parameters of the discharge data can be found within the catchment from west to east. The discharges are compared to a number of landscape parameters that influence the discharge in the subcatchments. Triggering circulation patterns were assigned to all events of the annual maximum discharge series in order to evaluate which circulation patterns are likely to produce large floods. It can be shown that the cyclone Vb-weather regime (TM, TRM) generates the most extreme flood events in the Mulde catchment, whereas westerly winds produce frequently small floods. The Vb-weather pattern is a very slowly moving low pressure field over the Gulf of Genoa, which can bring large amounts of rainfall to the study area. It could also be shown that even with the two flood regimes estimates with the annual maximum series provide a safer flood protection with a larger safety margin than using summer maximum discharge series for extreme summer floods only. In view of climate change it is necessary to integrate knowledge about catchment characteristics, the prevailing flood regime or the trends of weather patterns in the estimation of extreme events.

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4.1 Introduction

Limited data on extreme and thus rare flood events complicate the accurate estimation of design discharges (e.g. Francés et al., 2001; Benito et al., 2004; Merz and Thieken, 2005). Numerous approaches have been developed for flood estimation, which include statistical approaches such as flood frequency analysis (FFA), the use of envelope curves as well as rainfall-runoff modelling with hydrological models. The focus in this study is set on the FFA.

The most common methods for FFA use annual maximum series (AMS) and peak over threshold series (POT) (Institute of Hydrology, 1999). The AMS and POT series can also be extracted for summer or winter seasons, when, for instance, one flood process type (e.g. floods triggered by snow melting) is of special interest. Several distribution functions such as the Gumbel, Weibull, Generalized Extreme Value, or the Pearson type III can be fitted to the data (Hosking and Wallis, 1997; Institute of Hydrology, 1999). Although these functions and possibilities exist as to which data to integrate, large uncertainties still remain when estimating extreme events. There is much debate about the length of the data series. Short series may not capture the entire flood variability and very long series may not reflect stationary conditions (e.g. Bárdossy and Pakosch, 2005; Khaliq et al., 2006)). Moreover, it is questionable whether or not an AMS is stationary when the discharges reflect different flood producing processes. Independence, homogeneity and stationarity are required characteristics of the data to legitimate flood frequency analysis (Stedinger, 2000; Kundzewicz and Robson, 2004). However, often these criteria are not satisfied due to climatic change and/or anthropogenic influence (Webb and Betancourt, 1992; Klemĕs, 1993; Jain and Lall, 2000; Sivapalan et al., 2005; Svensson et al., 2005; Khaliq et al., 2006). Independence is almost always given, when analyzing annual maximum series, whereas partial series have to be carefully examined in order to avoid miscounting one flood event as two. Usually, a threshold of several days is included in the extraction of the data, which defines the minimal time between two floods to ensure independence of the events. This threshold can comprise up to 30 days depending on the catchment area and discharge conditions. Stationary conditions seldom exist due to changes in climate, land-use or in the vulnerability of the study area, although these are often assumed (Merz, 2006). Moreover, the dynamics of atmospheric processes and flood generation have to be taken into account in the study of stationarity and independence and further in the FFA (Merz and Blöschl, 2003; Sivapalan et al., 2005).

The relationship between climate and flood generation has been of growing interest and study (Webb and Betancourt, 1992; Kästner, 1997; Jain and Lall, 2000; Bárdossy and Filiz, 2005; Steinbrich et al., 2005; St. George, 2007). Steinbrich et al. (2005) analyze the correlation between circulation patterns (CP) and heavy rain for the south-western part of Germany (Baden-Wuerttemberg). Kästner (1997) found that only five out of thirty different weather patterns are susceptible to produce flood events in Bavaria. Three catchments in southern Germany (Bavaria), which have different discharge characteristics and are differently influenced by snow melting, were studied. Kästner (1997) found the Vb-weather regime to be most susceptible for the generation of large floods. This weather system is a low pressure system that moves very slowly from the Gulf of Genoa northwards. It can accumulate large amounts of moist and warm air over the Mediterranean Sea, which is transformed into large precipitation amounts that fall along the northern slopes of the Alps and mountain ranges in Central and Eastern Europe. It is therefore interesting to analyze the relationship of circulation patterns and flood generation in the study area.

More information about flood generating processes can be gained when extending the study from one gauge station to the hydrological behaviour of sub-catchments and neighbouring regions (Harlin and Kung, 1992; Merz et al., 2006; Ouarda et al., 2006). Harlin and Kung (1992) extract for each sub-catchment the most extreme measured events and simulate the simultaneous occurrence of the floods which has not been observed yet. Of special interest for the flood hazard estimation of ungauged areas is also the regional FFA which incorporates flood process information from neighbouring catchments (e.g. Stedinger, 1983; Hosking and Wallis, 1997; Institute of Hydrology, 1999)). Regionally valid distribution functions are fitted to data of preferably independent gauges within a region, which exhibit, in general, better fits (Merz, 2006).

In this paper the flood discharge characteristics of the Mulde catchment in south-eastern Germany are analyzed according to stationarity, their spatial distribution of the statistical moments and the relationship between landscape characteristics and flood peaks. Additionally, the relationship between the dominating weather pattern in Europe and the flood generation in this catchment is discussed. The following questions will be answered based on this analysis: Which landscape components (geology, soil, groundwater flow, land-use, precipitation) contribute to the flood discharge regime? Can seasonal or spatial differences be distinguished? Do specific circulation patterns exist which trigger large events? And finally, are the requirements for the flood frequency analysis with AMS for this catchment fulfilled?

4.2 Study area and data

4.2.1 Study area

The Mulde catchment is a sub-catchment of the Elbe River basin in south-eastern Germany. The southern boundary is marked by the mountain ranges of the Erzgebirge, which coincides with the Czech-German border. The catchment has a total area of 6171 km^2 (at the gauge Bad Düben) and has three large sub-catchments (Zwickauer Mulde, Zschopau, Freiberger Mulde), which drain the upper, mountainous part of the catchment (Fig. 4.1). Within only 20 km, the tributaries Zschopau and Freiberger Mulde disembogue near the gauge Erlln (gauge 13, Fig. 4.1) into the Zwickauer Mulde and form the Vereinigte Mulde ("Joined Mulde"), which disembogues near the city of Dessau into the Elbe River.

The elevation ranges from 52 m to 1213 m a.s.l. with approx. 2/3 of the area being lowlands and 1/3 mountains (500–1213 m a.s.l.) (Fig. 4.1). The mountain ranges in the south cause fast runoff responses to rainfall events in the tributaries, whereas in the major part of the catchment slower runoff responses dominate. The annual precipitation ranges from 500 mm in the lowlands to 1100 mm in the mountain ranges.

The landscape characteristics of the catchment such as geology, soil, hydrogeology and land-use parameters were evaluated to gain information about the variability of the discharge behaviour. Therefore, the catchment was split into three zones, which correspond to the three large subcatchments (Fig. 4.1).

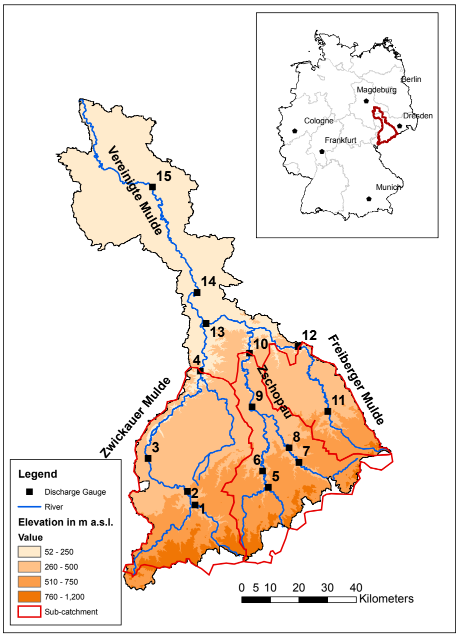

Figure 4.1: Study area Mulde catchment: left: discharge gauge locations (numbered according to Tab.4.1) and the digital elevation model; right: geographical location in Germany

The region has a long history of large flood events. First written documents about floods, the corresponding water levels and damage can be found from the 9th century onward and more detailed documents starting from the 14th century (Pohl, 2004). It is noteworthy that large winter floods with ice blockage as well as summer floods from torrential storms or long lasting frontal rains caused high damages on infrastructure and agriculture, often with fatalities.

During the last 100 years, three extreme flood events occurred in the study area, namely in July 1954, July 1958 and August 2002. These events will be analyzed in more detail in this paper. All of them were caused by large torrential storms. The floods in 1954 and 2002 were triggered by Vb-weather systems. Both flood events in the fifties caused high damage in different parts of the catchment, whereas in 2002 the entire catchment was affected. This flood caused a damage of 11.6 Billion € in Germany alone (DKKV, 2004; Thieken et al., 2006). As a consequence of the flood history, flood defence measures play an important role and have been extended until the present day (DKKV, 2004). Numerous flood retention basins and dams were constructed, which are mainly located in the upper part of the catchment, and significantly influence the discharge downstream.

4.2.2 Data

4.2.2.1 Discharge data

Over 60 discharge and water level gauges exist in the Mulde catchment. The earliest measurements at regular intervals began in 1910 at two gauges. In order to evaluate the influence of a dam before including data from the downstream discharge gauge into the dataset, daily differences of inflow

Number	Gauge	Basin area [km^2]	Elevation [m.a.s.l.]	Period of Measurements	Mean max. annual flood discharge [m^3/s]	Highest value of observation period
1	Aue 1	362	349	1928–2002	66	315
2	Niederschlema*	759	314	1928–2002	111	585
3	Zwickau-Poelbitz*	1030	255	1928–2002	128	683
4	Wechselburg 1	2107	160	1910–2002	213	1000
5	Streckewalde	206	410	1921–2002	30	145
6	Hopfgarten*	529	357	1911–2002	81	420
7	Pockau 1	385	397	1921–2002	69	449
8	Borstendorf	644	356	1929–2002	91	540
9	Lichtenwalde	1575	253	1910–2002	218	1250
10	Kriebstein UP	1757	183	1933–2002	231	1350
11	Berthelsdorf	244	377	1936–2002	35	360
12	Nossen 1	585	204	1926–2002	69	690
13	Erlln	2983	133	1961–2002	329	1550
14	Golzern 1*	5442	118	1911–2002	517	2600
15	Bad Düben 1	6171	82	1961–2002	474	1760

Table 4.1: Analyzed discharge gauges in the study area (stations with one year of missing values)*

versus outflow of five large dams for the period 1991–2002 were compared. More information from the dam authorities was not available. Inflow and outflow flood peaks were compared and the downstream stations were excluded from the dataset if the flood peak differences were greater than 10%, and if there were at least five affected flood events during this 10 year period. Additionally, daily time series of discharge gauges that are in the immediate vicinity of a dam were compared to daily discharge data from neighbouring gauges at other tributaries. Time series of discharge gauges that did not reflect the hydrograph at the compared gauge station were excluded from the dataset. AMS (hydrological year from November to October) were extracted from daily maximum discharges.

A subset of discharge gauges was selected for this analysis which met the following criteria:

- the time series must have a length of at least 40 years,
- the sub-catchment area is larger than 100 km^2,
- the flood AMS exhibits no trend,
- the discharge gauges are distributed across the catchment and have a distance of at least 3 km between each other.

15 discharge gauges meet these criteria; they are listed in Fig. 4.1 and Table 4.1. For better readability, the gauge stations are listed in all tables in the same order beginning with those located in the southwest (Zwickauer Mulde), then progressing

north and east (Zschopau, Freiberg Mulde) and ending with gauges located in the Vereinigte Mulde (cf. Fig. 4.1).

4.2.2.2 Precipitation Data

Precipitation data were available from the German Weather Service (DWD) at 49 stations in and around the Mulde catchment (see Fig. 4.2). The data cover the time period between 1952 and 2002 on a daily basis. Daily areal precipitation was calculated based on cubic interpolation for each of the 15 sub-catchments (corresponding to the discharge stations) for the comparison of precipitation and discharge.

4.2.2.3 Atmospheric circulation patterns

Information about the predominant European circulation pattern for each day was available from the "Catalogue of Großwetterlagen in Europe 1881–2004" (Gerstengarbe and Werner, 2005). The catalogue distinguishes three large circulations, which are divided into 30 different circulation patterns (one is classified to be a "transition class") (Tab. 4.2). The Vb-weather system is represented by the patterns TM (low Middle Europe) and TRM (Trough Middle Europe).

The circulation patterns comprise the zonal circulation form, the mixed circulation form as well as the meridional circulation form. For every day a circulation pattern is assigned to be the dominant one for Europe. Through the specific distribution of lows and highs over Europe, it may therefore be possible that the dominant circulation pattern of a particular day is not necessarily representative for the Mulde catchment. This is for instance the case, if the Mulde catchment is still under the influence of a weakened low, which is however already situated above Eastern Europe, whereas the dominating European circulation pattern is above Western Europe. However, other than this catalogue, more detailed meteorological data for the study area were not available.

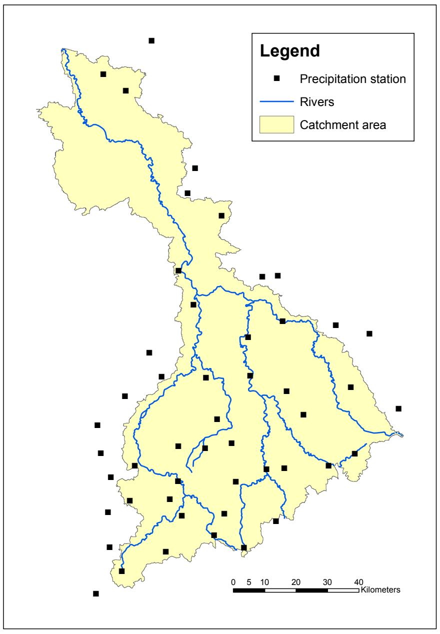

Figure 4.2: Locations of the 49 precipitation stations in and around the study area

4.3 Methodology

4.3.1 Flood frequency analysis

The distribution-free and non-parametric Mann-Kendall test for Trend (one-sided test; significance level: $\alpha = 0.05$) was used for the detection of trends in the data.

Form of Circulation	No.	Circulation pattern name	Abbr.
Zonal Circulation	1	West wind, anti-cyclone	WA*
	2	West wind, cyclone	WZ*
	3	Southern west wind	WS*
	4	Angular west wind	WW*
Mixed circulation	5	South-west wind, anti-cyclone	SWA*
	6	South-west wind, cyclone	SWZ*
	7	North-west wind, anti-cyclone	NWA*
	8	North-west wind, cyclone	NWZ*
	9	High pressure system, middle Europe	HM*
	10	High pressure circuit over middle Europe	BM*
	11	Low pressure system, middle Europe	TM*
Meridional circulation	12	North wind, anti-cyclone	NA
	13	North wind, cyclone	NZ
	14	High pressure Iceland, anti-cyclone	HNA
	15	High pressure Iceland, cyclone	HNZ*
	16	High pressure, British Isles	HB*
	17	Trough Middle Europe	TRM*
	18	North-east wind, anti-cyclone	NEA
	19	North-east wind, cyclone	NEZ*
	20	High pressure Fennoscandia, anti-cyclone	HFA*
	21	High pressure Fennoscandia, cyclone	HFZ
	22	High pressure Norwegian Sea-Fennoscandia, anti-cyclone	HNFA
	23	High pressure Norwegian Sea-Fennoscandia, cyclone	HNFZ
	24	South-east wind, anti-cyclone	SEA
	25	South-east wind, cyclone	SEZ*
	26	South wind, anti-cyclone	SA
	27	South wind, cyclone	SZ
	28	Low Pressure, British Isles	TB*
	29	Trough, Western Europe	TRW*
	30	Transition, no classification	U

Table 4.2: Classification of the form of circulation and its specific pattern (indicates circulation patterns which are relevant for AMS discharges in the Mulde catchment)*

Since small trends in the data may not be detectable, for instance by the Mann-Kendall test (Bárdossy and Pakosch, 2005), a regional test of stationarity was conducted with all 15 data sets (Lindström and Bergström, 2004). To this end, several data series from the same region, that cover the same period of measurements, are tested jointly (also with the Mann-Kendall test). For comparison, the discharge data were divided by the MAF (mean maximum annual flood discharge) of the respective series. AMS of 13 gauge stations with data from 1936 to 2002 and of two gauges with data from 1961 to 2002 were included.

Independence of the data was ensured by using AMS data, which were also checked for possible dependent values around the turn of a hydrological year. For this, a threshold time of 7 days between two AMS floods was included, which guarantees the independence of two close-by flood events, since the time of concentration for this basin is smaller than 7 days.

Flood frequency analyses were performed with seven different distribution functions (Gumbel, Weibull, 2-parametric LogNormal, Generalized Extreme Value (GEV), General Logistics (GL), 3-parametric LogNormal, and Pearson type III) with both the Method of Moments and with the L-Moments (Hosking and Wallis, 1997; Institute of Hydrology, 1999). The GEV and GL distribution functions (both with L-Moments) revealed the best fits based on the Kolmogorov-Smirnov test and visual examination relative to the empirical probabilities (Test hypothesis: $F(x) = CDF$ for all x with $\alpha = 0.05$). Emerging consensus can be found in many studies worldwide that the GEV distribution reveals the best fits (Pearson, 1991; Onoz and Bayazit, 1995; Vogel and Wilson, 1996; Douglas and Vogel, 2006). The Institute of Hydrology (1999) also describes the "theoretical and historical importance" of the GEV. Hence, subsequent analyses were performed using the GEV.

4.3.2 Spatial distribution of flood characteristics

The spatial distributions of the statistical moments of the AMS, such as skewness and coefficient of variation, were analyzed to detect possible differences among sub-catchments. The spatial extent and distribution of the three most extreme flood events (July 1954, July 1958, August 2002) were analyzed in more detail. For every event and gauge station, return periods (GEV, L-Moments) were calculated. These estimates were then assigned to each river segment upstream of the 15 gauge stations in order to analyze the flood characteristics in a spatially explicit manner.

Moreover, the AMS of 11 gauge stations with data from 1929 to 2002 (74 years) were studied with respect to the spatial distribution and magnitude of flood events. To this end, the number of different flood events per year in the catchment was analyzed. If all 11 gauges have their highest discharge of a certain year on the same day (+/- 1 day), the number of flood events for that year will be one. The other extreme is that all gauges have their highest peak at another time of the year. In that case, the number of flood events for that year is 11.

4.3.3 Relationship between precipitation maxima and discharge maxima

The relationship between precipitation maxima and discharge maxima was studied in more detail. Areal precipitation was calculated for the three large sub-catchments (Zwickauer Mulde: gauge Wechselburg; Zschopau: gauge Lichtenwalde; Freiberger Mulde: gauge Nossen) and the Vereinigte Mulde at the gauge Golzern. Precipitation sums of 24 h, 48 h and 72 h of the flood events were compared to discharge maxima. The four discharge stations are distributed over the entire catchment and represent the large sub-catchments. Rainfall AMS were extracted from the precipitation data and then compared on a seasonal basis to the discharge AMS to determine, how many large precipitation events are reflected in the discharge AMS.

4.3.4 Circulation pattern and flood generation

Daily data of circulation patterns between 1911 and 2002 were analyzed in order to obtain an overview about the seasonal distribution and frequency of the circulation patterns in Europe. Additionally, the circulation patterns, which are triggering the AMS discharges, were assigned to the AMS flood data of the gauge Golzern. The gauge at Golzern is representative for the entire catchment, because it comprises 88% of the catchment area. As the first gauge at the Vereinigte Mulde it represents the influence of the two large sub-catchments. Moreover it has a long time series (1911–2002) compared to nearby gauges such as Bad Düben or Erlln (both 43 years).

From the AMS data, empirical probabilities were assigned to the flood events and then combined with the circulation pattern data. With this information, it is possible to estimate the potential of a circulation pattern to generate a flood of a certain return period.

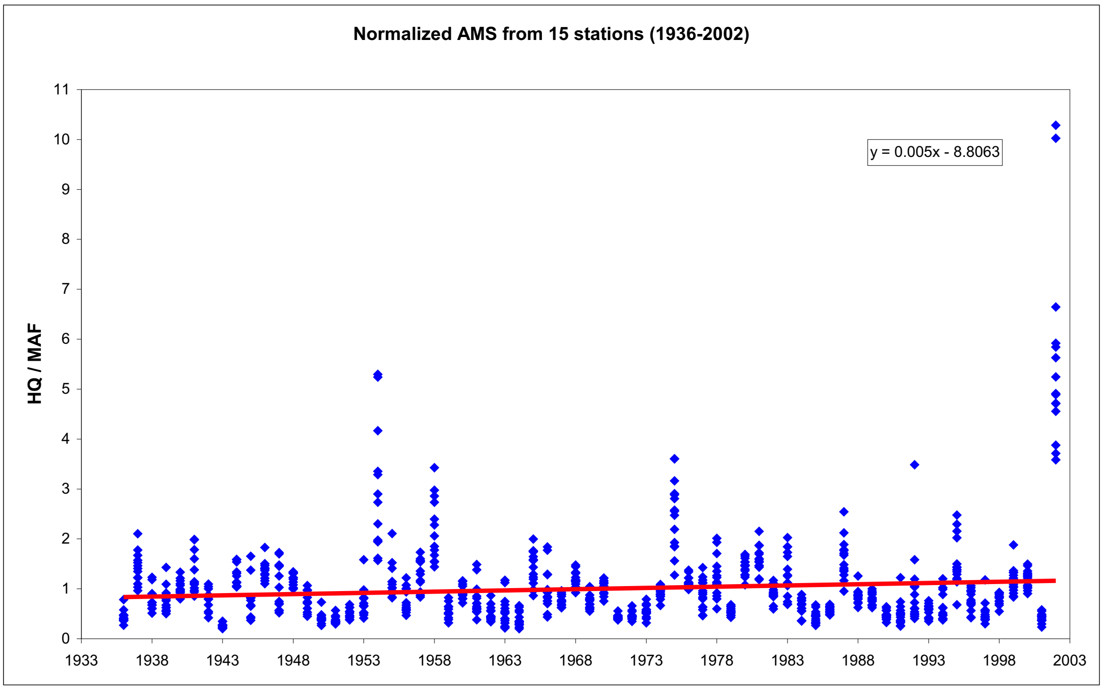

Figure 4.3: Regional trend test based on discharge data of 15 stations.

4.4 Results

4.4.1 Testing for trends in the flood AMS

The one-sided Mann-Kendall test for increasing trend (significance level $\alpha = 0.05$) revealed no trends for all 15 gauge stations. The trend test for regional stationarity was performed with the normalized AMS of the 15 gauge stations. As Fig. 4.3 shows, the data exhibit a very small positive trend in the regional trend analysis. When the flood event from August 2002 was excluded from the data, the slightly positive trend became slightly negative. The Mann-Kendall test showed no trend (significance level $\alpha = 0.05$). Therefore the data were used for flood frequency analysis.

4.4.2 Seasonal occurrence and magnitude of floods

Two dominant flood process types in the Mulde catchment can be extracted from the data. During March and April, a first peak in the discharge AMS occurs during snow melt and "rain on snow" flood events. The second peak occurs in July and August, when large torrential storms traverse the area (Table 4.3). At all 15 discharge stations winter floods (November-April) comprise a larger part of the AMS than summer floods. In the upper western part of the Erzgebirge (corresponding to the gauges at Aue, Niederschlema, Zwickau), the percentage of summer and winter floods in the AMS is almost equal (e.g. Aue: 46% summer floods; 54% winter floods), whereas in the eastern part of the catchment winter floods have larger percentage (59%–69%).

The winter floods are usually small events with a low return period. They constitute at all 15 gauges only 8–21% of the 20% of the largest floods. Summer flood events, on the other hand, are less frequent, but cover a larger proportion of extreme events (26–39%). In Fig. 4.4 the data of Table 4.3 are summed up for all 15 gauges. Additionally, the monthly distribution of

Gauge	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Aue	8	4	9	24	8	5	15	8	7	4	3	5
Niederschlema	5	5	12	23	8	8	15	7	4	4	1	7
Zwickau	4	5	11	20	8	9	16	7	4	4	3	8
Wechselburg	12	8	13	9	5	8	17	9	1	2	5	12
Streckewalde	11	9	16	17	5	7	17	9	0	4	1	5
Hopfgarten	13	10	14	11	7	8	12	7	1	5	1	11
Pockau	11	11	17	10	10	6	12	7	2	4	2	7
Borstendorf	8	9	20	14	9	5	11	7	1	4	3	8
Lichtenwalde	13	14	19	10	6	5	9	9	1	2	1	11
Kriebstein	9	11	19	14	7	7	10	7	1	3	1	10
Berthelsdorf	7	13	24	7	9	3	10	7	1	1	1	13
Nossen	10	16	23	5	6	4	9	6	3	3	3	12
Erlln	10	12	26	10	7	2	7	12	2	2	0	10
Golzern	14	12	16	9	5	7	11	9	2	3	3	8
Bad Düben	10	10	26	12	7	2	10	10	2	2	0	10

Table 4.3: Monthly relative frequency of discharge AMS (in percent)

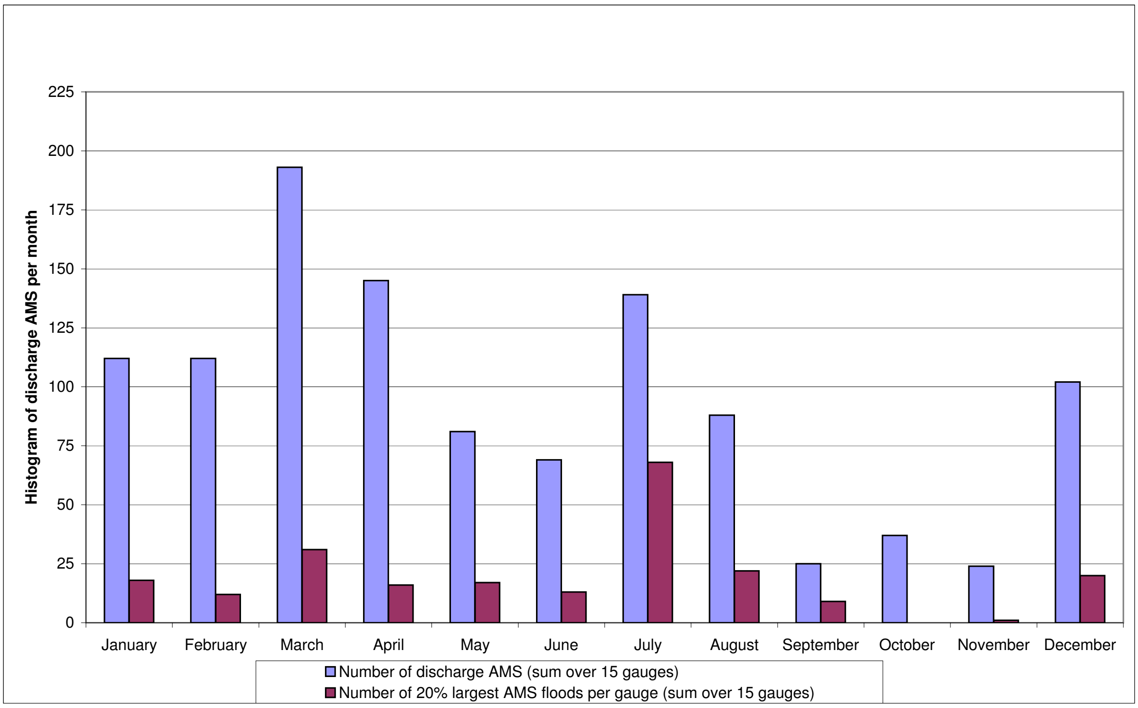

Figure 4.4: Monthly distribution of the number of discharge AMS, summed up over the 15 gauges for all AMS floods and for the 20% largest events

the 20% largest flood events is shown. Again, it is visible that winter floods have a large percentage of the AMS, but the most extreme events occur during the summer. From these analyses we could conclude that summer flood events play a more important role for the flood hazard estimation of extreme events, which would necessitate the usage of Summer Maximum Series (SMS) instead of AMS. A comparison of return periods estimated with AMS and SMS for the three extreme flood events showed however that estimated return periods up to 270 years are at all 15 gauges much lower with AMS. As an example return periods (GEV) for the gauge Aue are shown for the three floods 1954: 48 (AMS), 65 (SMS); 1958: 7 (AMS), 10 (SMS); 2002: 115 (AMS), 143 (SMS). Thus, a larger discharge would be needed to estimate the same return period, e.g. a design discharge of 100 years when using AMS compared to SMS. Estimates for return periods larger than 270 years show, however lower values with SMS. Therefore, flood protection measures designed on the basis of AMS estimated return periods provide safety margins, even for extreme summer events up to 250 years.

4.4.3 Spatial distribution of flood characteristics

The AMS of 11 gauge stations with data from 1929 to 2002 (74 years) were studied with respect to the spatial distribution

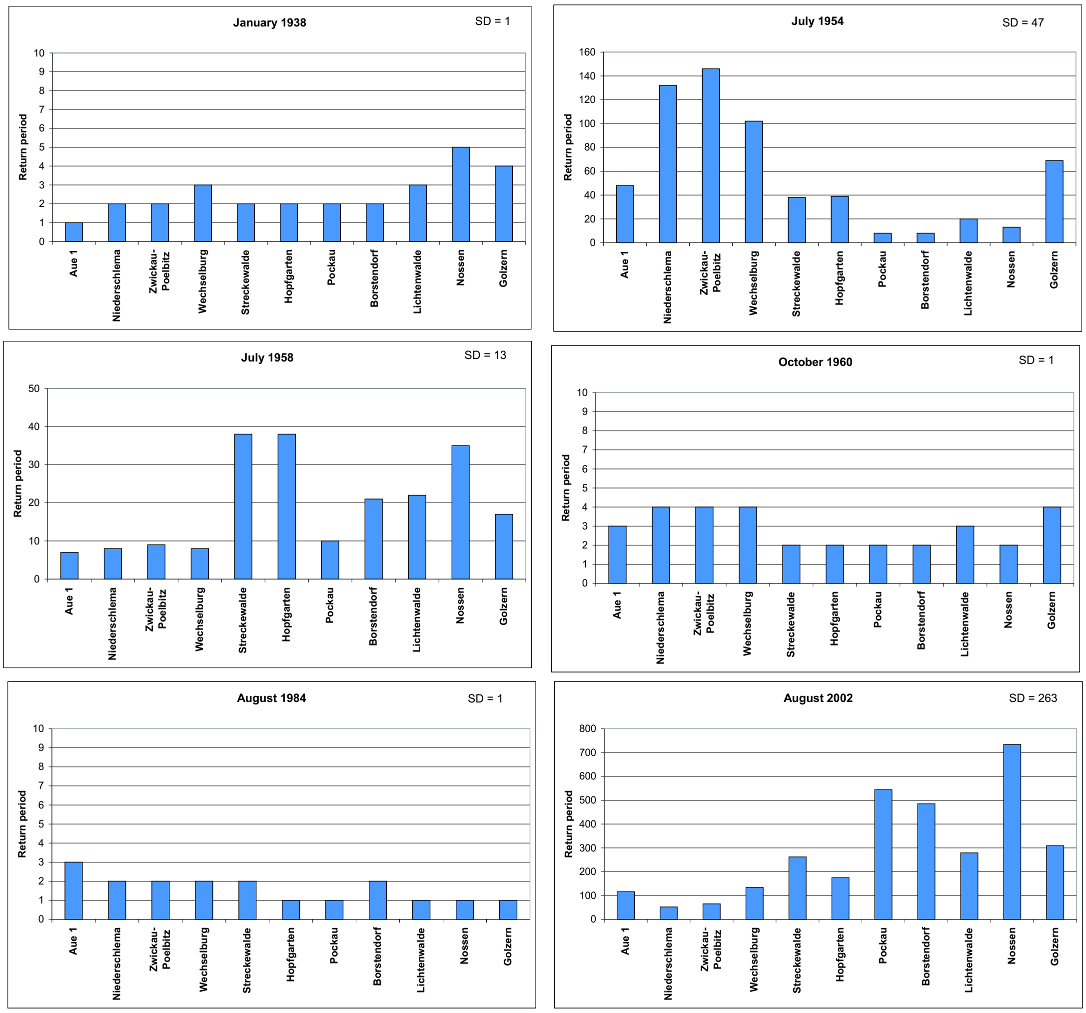

Figure 4.5: Variation of return periods for six different floods (SD = standard deviation)

and magnitude of flood events. To this end, the number of different flood events per year in the catchment was analyzed. In 13 years of the 74-year period, one flood event occurred that affected all 11 sub-basins, whereas in 18 years no dominant flood event (i.e. four to seven flood events per year) could be identified. These are summer and winter events. In most years (27) three different flood events are related to AMS discharges.

In Fig. 4.5 six different flood events at the 11 analyzed gauges and their respective return periods are shown. The return periods were estimated with the GEV (L-Moments). The six flood events comprise the three largest events in the catchment (1954, 1958, 2002) and three small catchmentwide events. Events with discharges that correspond up to a 10-year peak discharge are mostly homogenously distributed across the catchment. They

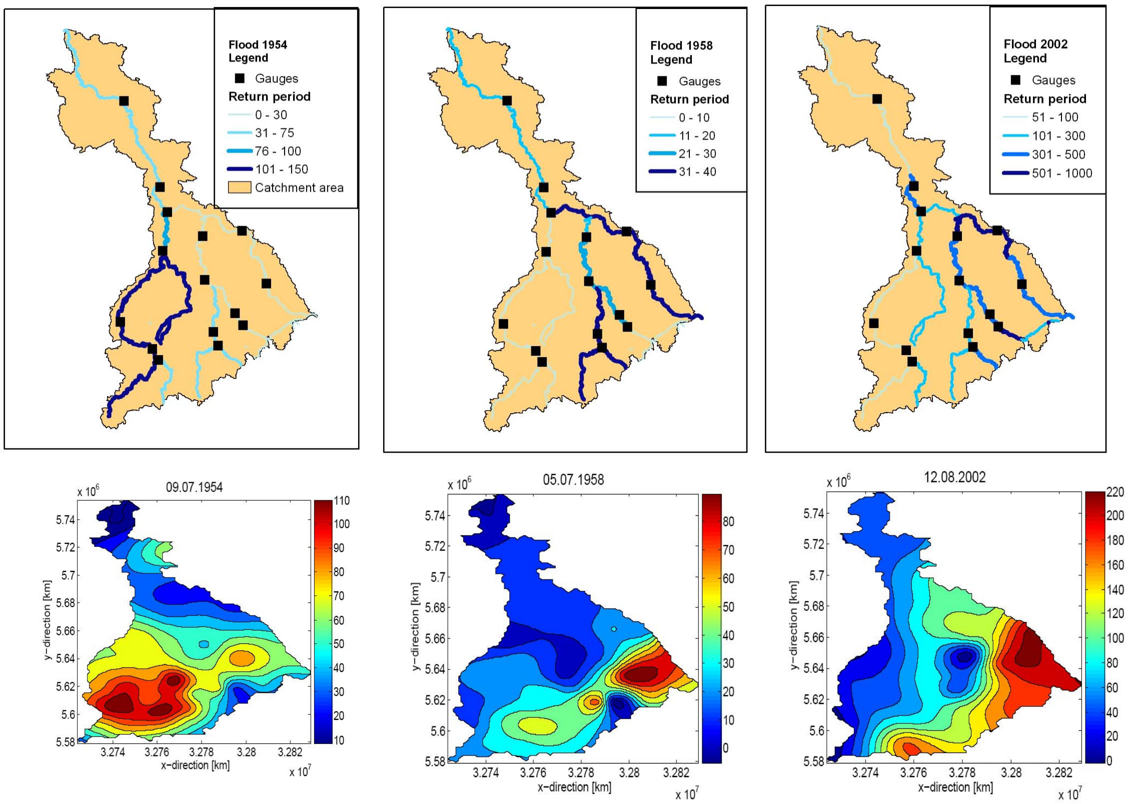

Figure 4.6: Estimated return periods (GEV, L-Moments) for the floods in 1954, 1958, 2002 (period 1929–2002 (above)) and the corresponding precipitation fields (below). Note that for a better illustration of the spatial distribution the classes of discharge return periods and precipitation amounts differ

have similar return periods at all gauges and exhibit a standard deviation of 1. This is shown for the floods in January 1938, October 1960 and August 1984. Events with discharges larger than a 10-year peak exhibit increasing spatial distinctions as well as increasing standard deviations. This is illustrated by the floods in 1954, 1958 and 2002. Depending on the location of the precipitation field, one or the other subcatchment is more affected during a large flood event. Figure 4.6 shows the spatial distribution of the return periods that were calculated for the observed discharges of the three most extreme flood events (1954, 1958, 2002) in the Mulde catchment (upper part) and the corresponding areal precipitation events (lower part). The return period calculated for a certain gauge was assigned to the river segment upstream of the gauge. A marked spatial distribution can be seen. For the flood event in 1954, high return periods were calculated for the western part of the catchment. This is explained by the rainfall event that had its centre in the western part. The floods in 1958 and 2002 were caused by precipitation events with their centres east of, or in the eastern part of the study area. Figure 4.6 illustrates the direct relationship between the location of

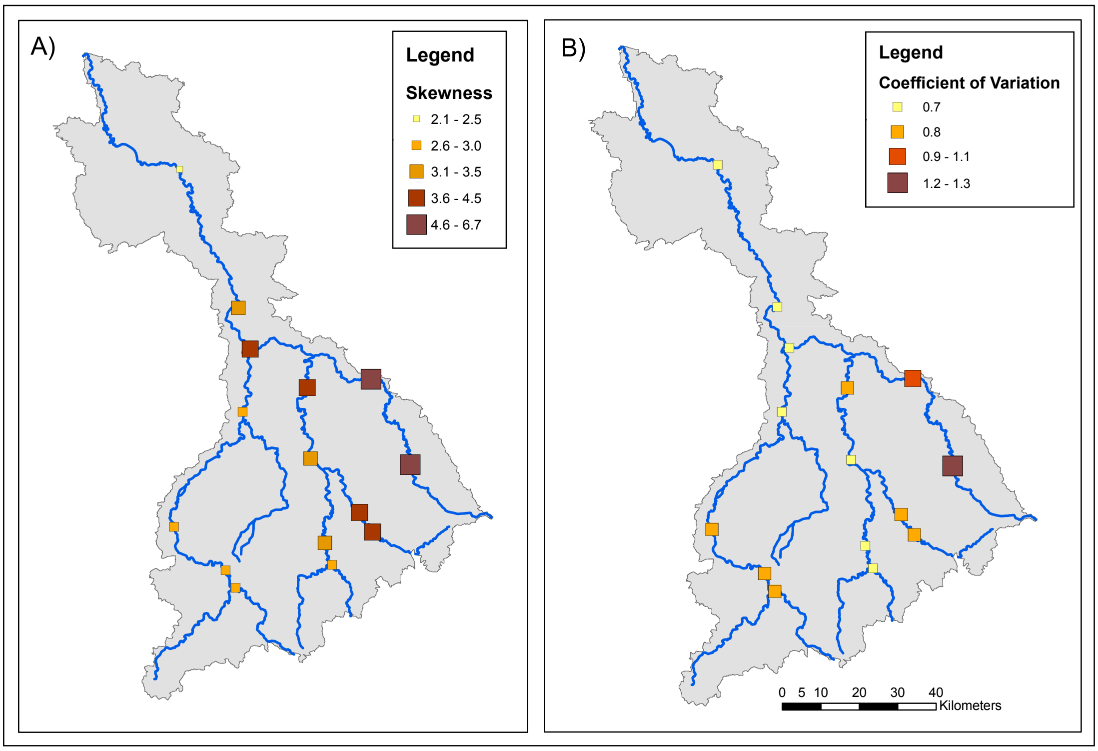

Figure 4.7: Skewness (A) and coefficient of variation (B) of the discharge AMS for the 15 gauges

		Zwickauer Mulde	Zschopau	Freiberger Mulde
Landuse	Urban Areas	12%	7%	7%
	Agricultural Land	52 %	60%	70%
	Forest	32%	33%	18%
Soil	Cambisols and Planosols	88%	94%	90%
Hydrogeology	no or small local groundwater reservoirs	94%	99%	99%
Geology	Metamorphic or plutonic rocks	66%	91%	85%

Table 4.4: Percentages of the dominating landscape characteristics

the precipitation field and the flood return period for the three events.

More similar statistical moments were found along the tributary rivers rather than according to the elevation of the gauge locations. In the beginning the assumption was made that the gauges in the mountains of the Erzgebirge can be grouped together to exhibit similar statistical moments as well as the gauges in the lowlands. However, increasing values of the statistical moments occur from west to east that corresponds to the division of the subcatchments. Figure 4.7 shows the spa-

Gauge	24 h Summer	Winter	48 h Summer	Winter	72 h Summer	Winter
Wechselburg	65%	7%	61%	7%	70%	10%
Lichtenwalde	88%	20%	88%	7%	71%	14%
Nossen	78%	15%	89%	26%	83%	26%
Golzern	59%	20%	68%	17%	68%	20%

Table 4.5: Percentages of agreement between precipitation AMS (precipitation sums of 24h, 48h and 72h) and discharge AMS

tial distribution of the skewness (A) and the coefficient of variation (B) for the 15 gauges. The subcatchment of the Zwickauer Mulde and the western part of the Zschopau (gauges 1–6 in Table 4.1) are more homogeneous and differ significantly (CI 95%) in its statistical moments from the eastern part of the catchment. These results suggest a different distribution of the precipitation in the subcatchments which in turn leads to differences in the discharge behaviour. Another possibility is that the landscape characteristics are largely responsible for these differences, which is discussed in the following section.

4.4.4 Landscape characteristics

The land-use is dominated forest covered mountains and intensively used agricultural lowland. The proportion of agriculturally-used areas increases from west to east and south to north, whereas the percentage of forest decreases. Urban areas only play a role in the sub-catchment Zwickauer Mulde with two larger cities (Zwickau, Chemnitz). Meadows and pastures are homogenously distributed across the area with a slightly larger area in the upper middle Erzgebirge.

Table 4.4 shows the main percentages of the analyzed landscape characteristics. It can be seen that no major differences in soil (type of soil with information on soil depth, texture, conductivity, etc.), bedrock, groundwater flow and land-use can be distinguished among the three large subcatchments. As we can see landscape characteristics, such as soil and hydro-geology, do not vary much between the subcatchments. Although there are slight differences in the land-use, there is much evidence in the literature that during extreme events the land-use only plays a minor role (e.g. DKKV, 2004). Thus, the dominant influence seems to be exerted by precipitation and weather characteristics, which is discussed in the following two sections.

4.4.5 Relationship between precipitation AMS and discharge AMS

AMS of precipitation and discharge were therefore compared to determine how well precipitation and discharge AMS coincide. Different precipitation AMS were extracted from sums of one, two and three days. A time lag of two days between the precipitation event and the discharge peak was allowed. Table 4.5 shows exemplarily for four discharge stations the percentages of agreement for summer and winter sepa-

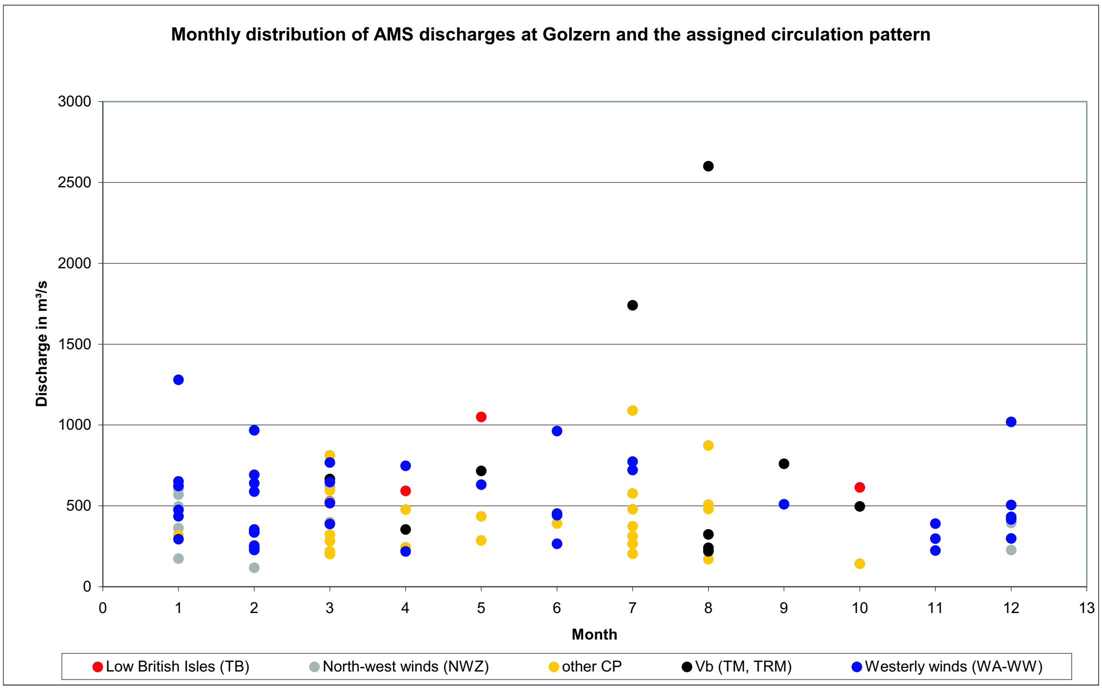

Figure 4.8: Monthly distribution of AMS discharges at Golzern and the assigned circulation pattern

rately. During the winter, the precipitation events are not so clearly and directly reflected in the discharge data (agreement 7–26%). One reason for this can be found in the topography of the catchment.

During the winter time, large amounts of the precipitation can fall as snow in the Erzgebirge and the water is stored in the snowpack. The discharge generation is delayed until melting starts. Therefore, the triggering circulation pattern,which may have brought a major snow cover, cannot be directly related to the corresponding discharge peak. On the contrary, a direct connection between a large summer rain event and a large discharge can be found in the summer throughout the catchment (agreement 59–89%). Based on these findings the question was posed if large summer flood events can also be related to a specific circulation pattern. This question will be answered in the following section.

4.4.6 Circulation pattern and flood generation

First of all, daily information about the dominating European circulation pattern between 1911 and 2002 were analyzed. For the entire period, westerly winds (WA-WW) cover about 25% of the total circulation patterns; high pressure weather regimes (all circulation patterns beginning with the letter "H") cover about 27%. The proportion of the Vb-weather regime (TM and TRM) is relatively low with 6.5%.

The analysis of the discharge AMS at the gauge Golzern shows that approx. 60%

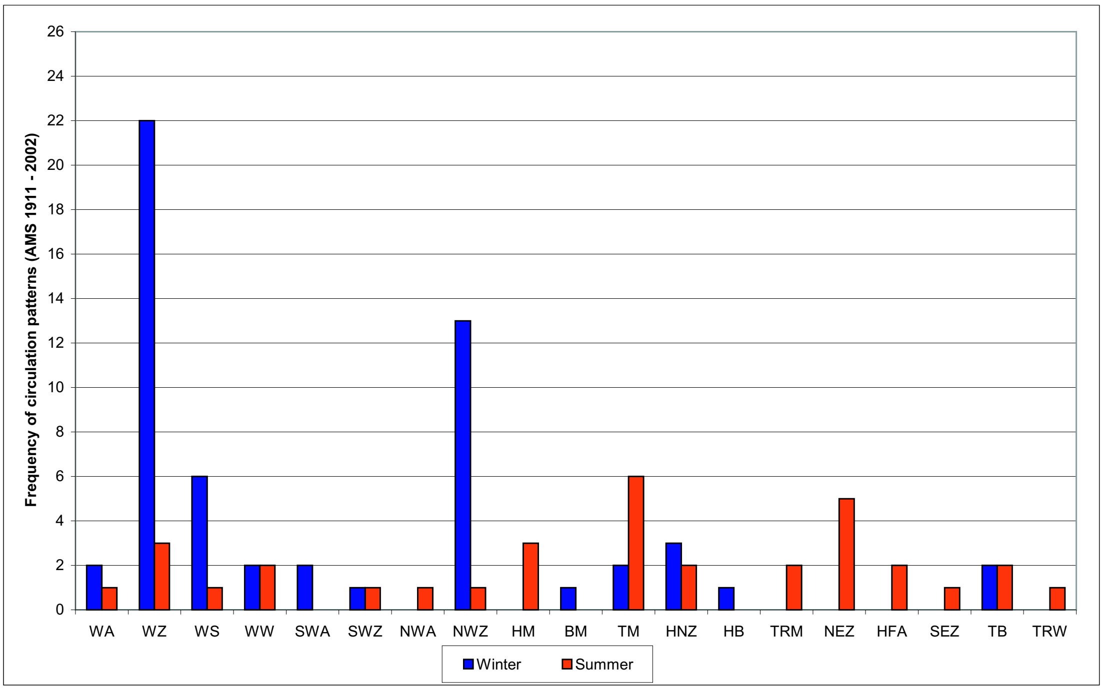

Figure 4.9: Histogram of the circulation patterns at the gauge Golzern that generated AMS discharges between 1911 and 2002 (abbr. see Table 4.2)

occur during the winter time and 40% during the summer time. Only 19 out of the 30 circulation patterns (cf. Table 4.2) play a role in creating AMS discharges in the Mulde catchment. Thus, 11 out of 30 CPs have not created an AMS discharge within the 92 years. In the winter (November-April), the cyclonal western and northwestern patterns (WA-WW; NWZ) play the dominant role in flood generation, because they account for 84% of the AMS winter discharges and 100% for the floods from November until February (see Fig. 4.8). The summer AMS discharges are generated by several different CPs, though mainly by westerly cyclones (WA-WW), north-east cyclones (NEZ) and the troughs over central Europe (TM, TRM). Figure 4.9 illustrates the distribution separately for summer and winter.

To answer the question, which circulation pattern is likely to generate large floods in the Mulde catchment, the flood potential was calculated as the probability for a flood quantile HQT , given a certain CP: $P(HQT|CPX) = \frac{nHQ_T}{nCP_X}$ where nHQ_T is the number of flood events larger than HQ_T (e.g. the 10-year flood) that have been triggered by a certain circulation pattern CPX, whereas nCPX is the number of days with the corresponding circulation pattern. It is important to note that already for small return periods (5 years) the Vb-weather regime (TM, TRM) has the highest flood potential (Fig. 4.10). These circulation patterns occur seldom, however they are associated with high discharge peaks. Their flood potential is even more pronounced for floods of larger return periods. Weather patterns, such as the westerly and north-western cyclones, which are responsible for most of the winter AMS discharges, play only an important role for return periods of max. 10 years.

There exist also Vb-weather regimes that generated floods with low return periods at the gauge Golzern. However, they often caused high damage in other catchments in Europe and had their precipitation centre outside the Mulde catchment. This is for example the case for the flood in April 1930 in Bavaria, the August 1984 flood in Switzerland, and the flood in July 1997 in the Odra catchment, when the Czech Republic and Poland were heavily affected (Grünewald et al., 1998; Wasserwirtschaftsamt Bayreuth, 2006).

Analyses of the other gauge stations as well as historical records of large floods in the Mulde catchment show similar results with the highest floods being generated by Vb-weather regimes. From this analysis we can conclude that although Vb-weather pattern do not occur often in the European weather regime they carry a large flood risk in the Mulde catchment.

4.5 Conclusions

Analyses of discharge series, precipitation fields and flood producing atmospheric

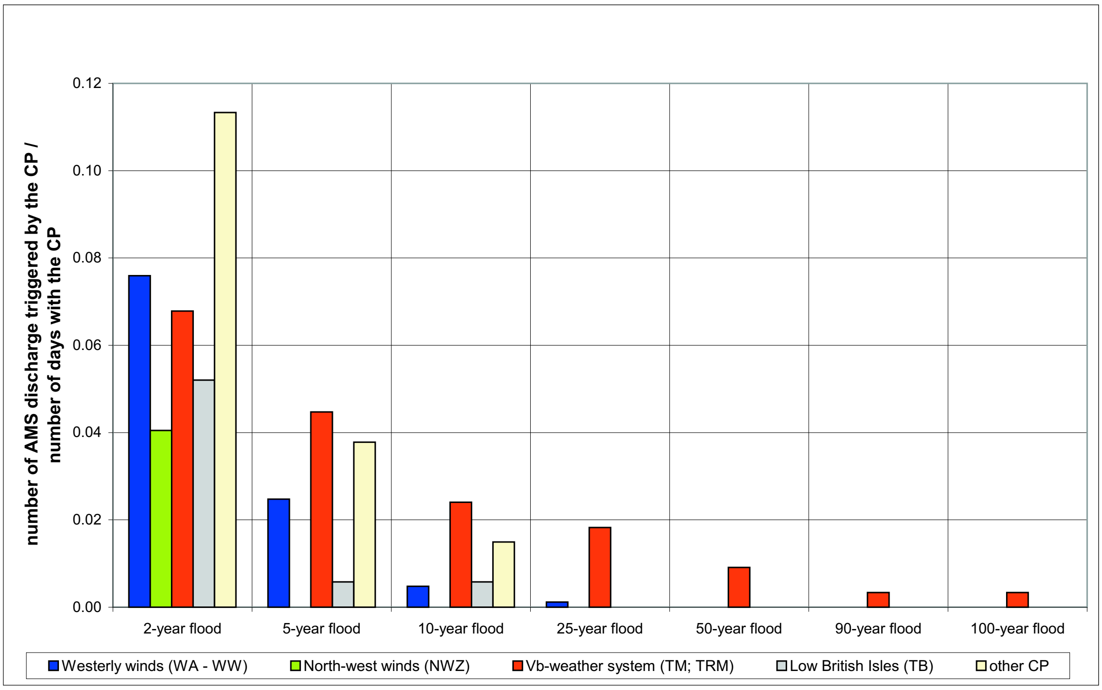

Figure 4.10: Flood potential of different circulation patterns to cause a flood of a certain return period

circulation patterns revealed two governing flood regimes in the Mulde catchment in south-eastern Germany: (1) frequent floods during the winter with generally low return periods and (2) less frequent floods during the summer, which can reach remarkable flood peaks. Differences in the statistical parameters of the discharge data are found in the catchment from west to east, which are however not reflected in the landscape characteristics such as soil, elevation or land-use. It is suspected that the location and the duration of the precipitation field are the most influencing factors for the discharge.

The usage of SMS could seem appropriate for extreme events in this catchment. However, return periods based on SMS revealed underestimations of extreme discharges up to a return period of 270 years. Estimates for even larger events showed underestimations with the AMS. Thus, flood protection measures for design floods up to 250 years based on estimations from AMS are still recommended. From these analyses we can conclude that for catchments with two or more flood regimes it is not always necessary to separate these from the AMS given that the extreme events are well represented by the AMS and thus flood protection measures are designed with safety margins. However, a thorough analysis of the flood characteristics of a catchment as well as flood producing weather regimes is of great importance for reliable flood estimates. In view of the climate change it is necessary to gain information about weather regimes that trigger large flood events in the region of interest and possible trends of these. With the combined information of catchment characteristics, flood behaviour and weather patterns, the uncertainty in the estimation of extreme events can be reduced.

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.

5 Summary and Conclusions

For the period 1951–2002, 145 discharge series across Germany were analyzed for flood trends using eight different flood indicators. These comprised annual and seasonal maximum series (AMAXF, AWMAXF, ASMAXF) as well as peak-over-threshold series of flood magnitude (POTxM) and frequency (POTxF). Seasonally differentiated series were studied to better distinguish changes in the flood hazard for both seasons (winter and summer).

Data from the gauge Golzern in the Mulde catchment were investigated in more detail for aspects of flood seasonality and the relationship between CPs and flood peaks. The analysis of CP data was conducted based on daily data from the "Catalogue of Großwetterlagen in Europe 1881–2004" by Hess and Brezowsky (1952). Four indicators were derived from these CP data, which capture different aspects of the frequency and persistence. These are the number of days and events a CP was detected in each year, and the mean and maximum durations of each CP per year. Trend tests were performed for varying time periods. Finally, CP and flood data were correlated.

In the introduction, research questions were posed concerning the existence of flood trends in Germany as well as the influence of atmospheric circulation patterns on discharge series. In this Chapter, these questions are discussed based on the results in Chapters 2 to 4. Consequences for flood hazard estimation are outlined by using the example of flood frequency analysis. Furthermore, data constraints, which became apparent during the thesis, are discussed in the context of data availability and uncertainty. Finally, an outlook indicates further research directions.

5.1 Main findings

In the following, the research questions will be answered briefly, highlighting the main findings of the work.

Can significant flood trends be detected in Germany?

Significant trends were detected at 64% of the gauges in at least one of the eight flood indicators. Regional differences emerge: in the Elbe catchment only 50% of the sites show trends in at least one flood indicator. In contrast, 60% - 76% of the gauges of Rhine, Weser and Danube show trends in at least one flood indicator. Trends in at least two indicators were detected at 47% of the Danube sites, 49% of the Rhine gauges and 33% of the Weser. In summary, sites in the Rhine, Weser and Danube catchments revealed more trends than sites in the Elbe basin. Spatial clusters with significant upward or downward trends were identified. Partly, they appear to be field significant, i.e. they are representative for the entire region. Thus, no ubiquitous increase in the flood magnitude and frequency emerges for the entire country. In the following, the trend results are separately summarized for each of the four large river basins.

The Rhine catchment is characterized by many upward trends. More than 40% of the gauges show significant increases in annual maximum series as well as in the frequency of floods (POT3F, cf. Fig. 2.9). All sites located along the main river of the Rhine between Mainz and Düsseldorf show significant trends in AMAXF. The majority of increases in the frequency of floods (POT3) and in the annual maxima are attributed to upward trends in winter floods.

Besides the Rhine basin, the Danube river basin is most affected by changes in flood discharge behaviour. In contrast to the Rhine, the sites in the Danube catchment are much more dominated by summer floods. Accordingly, upward trends in annual maxima are mainly attributed to upward trends in summer floods. More than 1/3 of the series show significant increases in the annual maxima, and more than 40% of the sites upward trends in the frequency of floods (POT3F). Gauges along the main river of the Danube are especially affected by these trends: 89% of these gauges had significant increases in POT3F.

The Elbe river basin shows a trend pattern that significantly differs from the ones of Rhine and Danube. At only 6% of the sites were significant trends detected in the annual maximum series. On the contrary, similar shares (21–25%) of upward trends in winter (AWMAXF) and downward trends in summer (ASMAXF) were detected. 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. This sub-catchment shows a trend pattern that is similar to the one in the neighbouring Weser catchment. Downward trends were detected at 1/4 of the gauges. Although these trends are field significant, the particular sites where these occur are rather randomly distributed in space.

The Weser represents a transitional zone between the western and eastern flood regimes. This is visible in two points: (1) upward trends in the annual and the winter maximum series were detected at 1/3 of the gauges, which are all located in the south-western and southern parts of the catchment, and (2) significant downward trends in summer maximum series were detected at 1/5 of the sites, which are all located in the south-eastern and north-eastern parts of the catchment. This clear spatial distinction of trends was therefore also considered in the determination of the three regions in Chapter 3.

In summary, a surprisingly large number of sites show significant trends in one or more of the eight flood indicators. Most changes were detected for sites in western, southern and central Germany, with partly spatial clusters. Trends in winter floods are larger compared to the ones in summer floods.

Is there a link between trends in CPs and trends in flood discharges?

After summarizing the main results on flood trends in the previous section, the results on CP trends are now briefly outlined and the possible link between both aspects is discussed. In the following, findings for the three regions, which were defined in Chapter 3, are summarized.

Floods in Region West (parts of the Rhine, Weser, Ems and Danube catchments) are predominantly triggered by the patterns WZ and NWZ (for abbreviations see Tab. 3.1). Figure 3.4 illustrates well the dominance of winter floods in the annual maximum discharges in this region. Often these are triggered by the two patterns WZ and NWZ. An increase in the flood hazard in Region West is attributed to significant upward trends in the frequency and persistence of both CPs.

Region East (parts of the Elbe and Weser catchments) is mostly affected by the same development of these two flood relevant CPs during winter as Region West. Therefore, also Region East is affected by an increasing winter flood hazard. Gerstengarbe and Werner (2005) found that the number of days with precipitation tripled during winter and the frequencies and duration of the patterns WZ and NWZ increased (Werner et al., 2008), while easterly CPs, which cause cold and dry winters especially in Region East, decrease at the same time. Both studies fit the results of this thesis well. An increase in rain-induced flood events can therefore be expected, due to milder winters and an intensified zonal circulation.

In Region East, summer floods play a more important role than in Region West, through rare but extreme events. However, decreasing trends were detected in summer maximum discharges (cf. Table 3.2). These decreases would be expected to result in a decrease in flood-prone CPs during summer. Interestingly, the most frequent pattern WZ shows an upward trend in the duration. This pattern usually does not cause large floods in the region. In contrast, the pattern TRM, better known to trigger large floods in the area, does not allow for definite conclusions. For the Mulde catchment, it was possible to show that TRM is of great importance for the summer flood hazard. The flood potential was estimated for different return periods at Golzern gauge in order to capture the entire range from frequent to rare flood events. Even for small return periods, the pattern TRM appeared to dominate. Although increases in the number of days per year and the mean persistence of TRM were visually observed in Chapter 3, these, however, are not significant at the 10% SL. A clear picture for the future flood hazard cannot be drawn based on these findings of field-significant decreases in discharges on the one hand, and a slight increase in the CP that triggers extreme floods in the area on the other.

Region South is dominated by maximum discharges during summer. An increasing flood hazard was found due to increasing trends in the patterns WZ, SWZ, TRM and TRW, which play an important role for AMAXF series in the region (cf. Fig. 3.4). An upward trend in the persistence of SWZ during summer may lead to an increase in local thunderstorm-induced flash floods. This is in agreement with Gerstengarbe and Werner (2005), who detected a tripled frequency of SWZ during summer.

Moreover, a significantly smaller variety of CPs was detected for the 1990s compared to the 1950s (cf. Chapter 3, Fig. 3.5). This is of direct relevance for the flood hazard as fewer patterns with longer persistence now dominate the weather across

Europe. Longer persistence of CPs may lead to consecutive precipitation events, whereby single events may have rather low precipitation amounts. This succession of precipitation may lead to saturated catchment conditions. This finding is particularly important for winter floods. In many cases these are triggered by WZ or NWZ patterns. Both patterns usually do not favour large storms. However, very wet pre-conditions may cause large runoff coefficients, which in turn may lead to flood events.

In summary, a link between CPs and the flood hazard was identified for large parts of Germany. A distinct number of CPs dominate the weather pattern in Germany. A subset of these CP could be shown to trigger large floods. Statistically significant correlations between composite maximum discharge series and combinations of frequent CPs were found for many combinations and regions, which supports the hypothesis of a supposed link between circulation patterns and flood peaks.

5.2 Consequences for the flood hazard estimation

For the study in the Mulde catchment, only discharge series without a significant trend were included in the analysis. A comparison of annual and seasonal maximum series revealed large deviations in the estimation of return periods. The use of annual discharge data provided larger safety margins for flood protection measures of up to 250 years return period than summer series. Around return periods of 250 years a change occurred leading to a larger safety margin for more extreme events when using summer maximum series. The use of both seasonal and annual maximum series is recommended for flood hazard assessment and consequently, for flood design measures against the background of a possible poor reflection of the seasonality in annual maxima. This was shown for instance for the Weser catchment (cf. Chapter 2).

The results of Chapter 2 show that the assumption of stationarity for the purpose of flood estimation cannot be held any more for 64% of the gauges, due to significant trends in at least one flood indicator. An instationary flood frequency analysis that considers trends is therefore recommended for flood estimation purposes for these catchments (see also Zhang et al., 2004; Coles, 2001).

In a complementary study, trend results based on the Mann-Kendall test (cf. Chapter 2) were compared with trend results estimated with an instationary GEV model (Petrow et al., 2008). The study revealed a similar trend pattern for both approaches (MK and GEV) at the large scale. However, flood protection measures are usually performed on the local scale, which necessitates the examination of trends for the area of interest. The Rockenau gauge, which is situated along the Neckar river (Rhine basin), serves as an example. Figure 5.1 shows the annual maximum series of this Rockenau gauge (1951–2002) with the fitted trend line of the instationary GEV model (top diagram). The trend is significant at the 10% significance level. The lower part of Fig. 5.1 presents different flood frequency functions for the stationary and instationary GEV models. Contrary to the stationary model, the flood frequency changes with time when using the instationary model. Both curves from the instationary model show larger discharge amounts for a flood with 100 years return period compared to the stationary one. When comparing both curves of the instationary model, the increase in the flood hazard becomes even more evident due to the larger discharge estimate for 2020 compared to 2002.

Starting from this gauge-specific analysis, stationary and instationary approaches were also applied to all 145 discharge series (annual and seasonal maximum series) studied in Chapter 2. The stationary GEV model reveals lower discharge estimates for a flood of 100 years return period for at least 75% of the gauges compared to the instationary model. The results for winter and annual series show significant trends at many sites. Summer series do not show clear tendencies.

These findings underline again the importance of incorporating different approaches into the flood frequency estimation. These could comprise the use of instationary models for the estimation of rare events, but also the use of model chains, which enables the consideration of the several aspects of the flood risk. However, the latter approach goes beyond the scope of the thesis and has to be accomplished in another study.

5.3 Data constraints

In this section, some of the main contraints that arose during data analysis, are discussed. The first part covers aspects of the uncertainty caused by different lengths of the time series and the grade of accuracy of the investigated discharge data. The second part focuses on aspects related to the flood triggering CPs, namely the assignment of the flood triggering CP as well as the uncertainty in the results due to the influence of snow.

5.3.1 Flood data

Inherently, data on extreme flood events contain a large amount of uncertainty. When regular flood measurements began, estimates of the water level were obtained during a flood event and later converted into discharge estimates. Nowadays, several methods for discharge recordings are available, which yield more accurate results for mean discharges. Nevertheless, the accurate estimation of flood peaks has not yet been achieved during large flood events such as one in 2002 in Saxony or the ones in 2005 in Switzerland and Austria.

For the estimation of flood design measures, preferably long time series are needed. A careful analysis of the data provided is needed, if flood indicators such as annual maximum series are to be investigated. For this study, discharge data with varying information were obtained from the water authorities: daily mean discharges from all stations were provided. Some water authorities provided additional information such as daily maximum discharges or monthly maximum discharges. It could be shown for the Mulde catchment that deviations of up to 28% occur between the daily mean and maximum discharges. Table 5.1 presents such deviations for selected flood events measured at the Golzern 1 gauge (Mulde catchment).

These deviations have an influence on

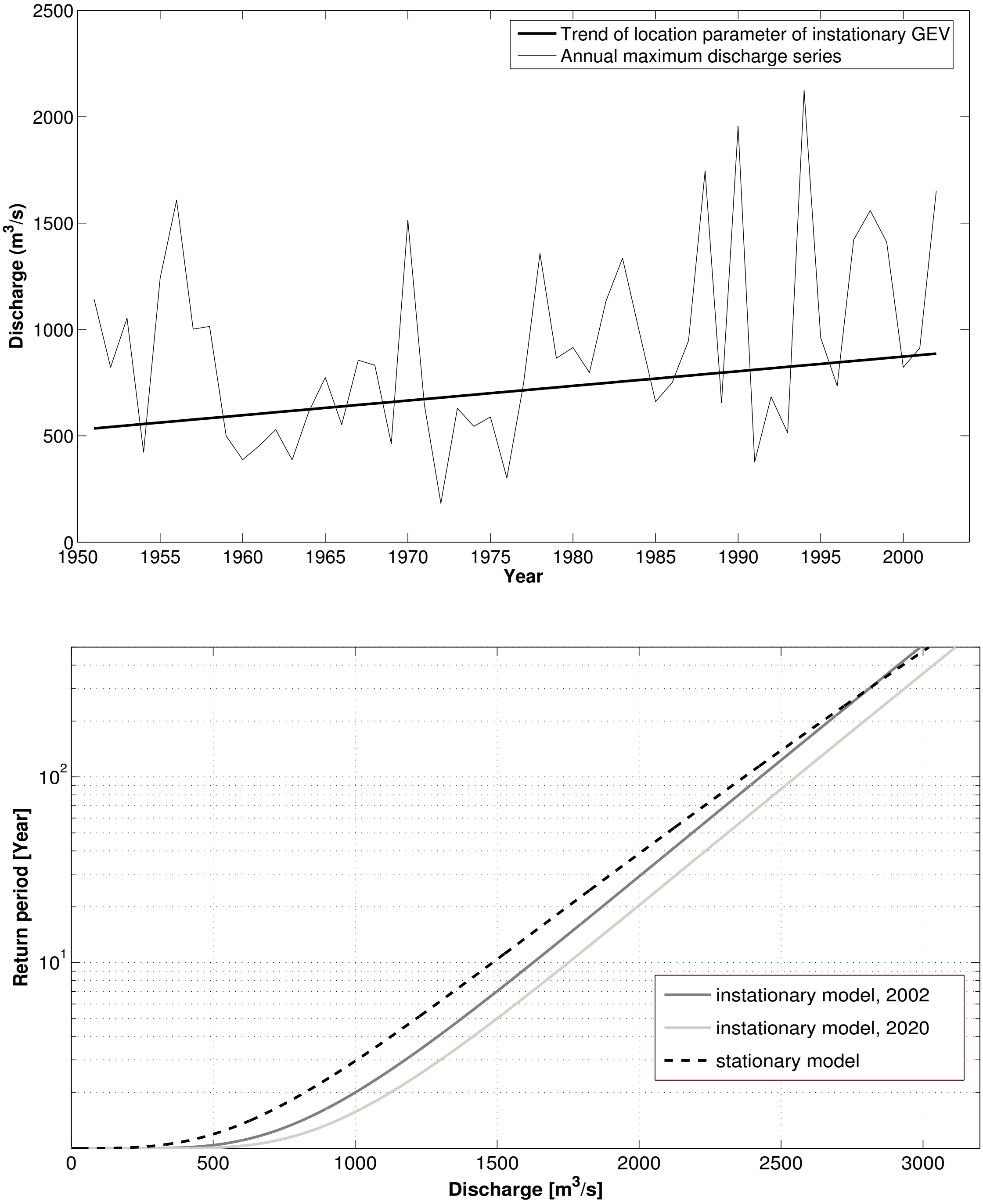

Figure 5.1: Annual maximum discharge series of gauge Rockenau/Neckar catchment (top) and flood frequency functions for the stationary and instationary GEV model (bottom)

date of flood	daily mean discharge [m^3/s]	daily maximum discharge [m^3/s]	deviation in %
11 July 1954	1310	1740	25
31 July 1955	523	577	10
6 July 1958	875	1090	20
18 October 1960	544	615	12
9 December 1974	970	1020	5
13 August 2002	1880	2600	28

Table 5.1: Deviation of mean and maximum daily discharges for selected flood events at gauge Golzern (Mulde catchment)

the results of flood data analysis. Therefore, the most accurate data, representing the flood peaks, were used. In Chapter 4, flood data based on daily maximum discharges were studied. This was particularly important for the flood frequency analysis since the magnitude of floods determines the discharge estimated for the considered return period. In Chapters 2 and 3 analyses were performed with daily mean discharge data, since not all water authorities provided daily maximum data. This may have a slight influence on the trend results of flood magnitude indicators such as maximum series or POTM series.

5.3.2 Data on circulation patterns

Data on the dominant atmospheric circulation pattern over Europe were available for every day of the studied period. The coarse scale of information causes some uncertainty associated with the data. For each day, only one CP over Europe is determined. Atmospheric features of smaller scale, such as shortwave troughs and ridges, are not included. Therefore, in some occasions, a pattern different from the dominant one may cause a local flood event. For example, a local flash flood in southern Germany might be caused by a south-westerly flow component, while the dominant pattern over Europe is determined to be WZ. Since more detailed information was not available, it is difficult to quantify the associated error.

The assignment of the triggering CPs was an important procedure of the study, which however bears much uncertainty. For the assessment of a possible link between CPs and flood peaks, the flood triggering CP was automatically assigned to the flood data depending on the size of the respective catchment. The concentration on meso-scale catchments was attributed to the complex assignment of the flood triggering circulation patterns in large catchments with different sub-catchments. For example, flood peaks at the Cologne gauge at the Rhine River can have its source in different upstream regions. These are, for instance, the Upper Rhine in Switzerland, or one or more sub-catchments like Mosel, Neckar or Main. Depending on the location of the flood triggering precipitation field and the distance to the Cologne gauge, a time lag of 2 to 6 days would have to be assigned. Since the meso-scale catchments analyzed here cover most of the country, a model for large nested catchments was not developed.

Another issue in the assignment of a triggering CP is seasonality. Winter precipitation is often accumulated as snow for several days or weeks. This applies to a large number of German catchments in the middle mountain ranges. During the snow melting season it is difficult to estimate which of the past circulation patterns can be designated as the one that triggers a spring flood event. It is questionable whether these events should be investigated separatly. Some studies like Duckstein et al. (1993) or Bárdossy and Filiz (2005) have chosen catchments that are not affected by snow. However, most parts of Germany are dominated by winter flood events, which are partly influenced by snow melting. Therefore, it was not reasonable to exclude winter data from the analysis. The assessment of the uncertainty associated with the assignment of CPs during winter would require more information of the affect of the snow on each catchment. A possible solution is to perform a flood typology according to Merz and Blöschl (2003) to separate catchments with and without snow influence. Thereafter, a revised assignment of the flood triggering CP to annual and winter discharge maxima can be performed, which enables the quantification of the uncertainty. Unfortunately, the time frame of the project did not allow conducting these analyses during the project.

Although there is a large amount of uncertainty associated with the CP data, the results presented in Chapters 3 and 4 are in lines with those presented in Kästner (1997); Pfister et al. (2004a); Grünewald (2006); KLIWA (2007).

5.4 Influence of the selected time period

The time period used in this study is an important factor influencing the results of trend detection studies. Chapters 2 and 3 examine a time period (1951–2002) that covers significant changes at many gauges. Several studies have already documented changes of hydrological variables during the 1970s (e.g. Franks, 2002; McCabe and Wolock, 2002). Moreover, it is a period in which there was a significant increase in greenhouse gases (Solomon et al., 2007).

It was a declared goal of the study to have a good temporal and spatial coverage with nearly no gaps in the discharge data. Consequently, a compromise between time length and data availability had to be found. Currently, discharge data representing more than 1000 sites are available in Germany. However, A large number of gauge data could not be included in the study due to gaps of more than one year or short time lengths. Especially eastern Germany is poorly represented. For instance, 29 meso-scale catchments in the Elbe basin did not fit the criteria of our study due to short time series lengths. Thus, only 32 out of 61 meso-scale catchments in the area could be investigated. In the end, 145 gauge stations with data between 1951 and 2002 provided us with a good spatial and temporal coverage with the exception of eastern Germany. With the help of field significance tests, conclusions for entire regions could be drawn (for details see Chapter 2). In the study presented in Chapter 4 (Mulde catchment), all available data were used without defining a common period for all gauges. Consequently, discharge series with lengths of 43 to 91 years were investigated.

When focusing only on the Mulde catchment (Chapter 4), the comparison of the results gained in Chapters 3 and 4 reveals an interesting point. Although seven gauges were analyzed in both studies, the prevalent patterns vary for the different time periods. Especially results of very long series of up to 91 years are not directly comparable to the study covering 52 years. This is the case, for instance, with the prevailing weather pattern at the Golzern gauge. For the period of 1951–2002 the most frequent CP associated with the annual maximum series was found to be NWZ (cyclonic north-western pattern), whereas during the period 1911–2002 it was the WZ pattern (cyclonic western pattern). However, the frequency of both patterns was almost equal (12 WZ vs. 11 NWZ). Despite these deviations, it is important to note that the main findings of both studies in Chapters 3 and 4 for this region coincide well.

5.5 Future research prospects

Despite the findings summarized above, a number of research directions remain for the future. One research focus should be set on the analysis of catchments smaller than 500 km^2. These catchments are often heavily influenced by flood protection measures and land-use changes. Thus, it would be of particular interest to perform analogue flood trend analyses with discharge series of these catchments. With such results, a validation of the conceptional model by Blöschl et al. (2007) would then be possible. According to Blöschl et al. (2007) the impact of land-use is a function of the catchment size. In contrast, the impact of climate variability on floods does not change with catchment size.

Another aspect of interest regarding small catchments would be the analysis of flood-triggering CPs, since small mountainous catchments are mainly affected by flash floods, which often occur during spring and summer. A shift in the importance and frequency of flood relevant CPs is to be expected, especially in prealpine catchments. For instance, the southwesterly pattern SWZ is known for causing intense thunderstorms during summer in southern and central Germany, regularly triggering local floods. These may not be detectable on the meso-scale.

The coupling of flood data with NAO or other atmospheric pressure indices should also be applied in future research. The NAO index represents the difference in normalized sea-level pressure anomalies between the Azores and Iceland and is estimated through automated procedures. Similar to Bouwer et al. (2008), a comparison of different atmospheric indicators and their reflection in the flood data could be performed.

The findings of this PhD thesis emphasize again the importance of incorporating instationary approaches into flood hazard estimation. The use of these models for the estimation of rare events has to be implemented on a large scale, but complemented by the use of model chains. In that way, a more holistic picture of the flood hazard is gained, which enables more appropriate and precise flood management measures.

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Appendix

Overview of used discharge data and the providing water authority.

Gauge	River basin	Basin area [km^2]	Period of measurements	Water authority
Achleiten	Donau	76653	1900–2002	WSA Regensburg
Affoldern	Weser	1452	1940–2004	BfG Koblenz
Aken	Elbe	69849	1935–2003	BfG Koblenz
Allendorf	Weser	5166	1941–2004	BfG Koblenz
Altena	Rhein	1190	1950–2005	LUA Essen
Andernach	Rhein	139549	1930–2006	WSD Südwest (Mainz)
Aue 1	Elbe	362	1928–2002	StuFa Plauen
Bad Düben	Elbe	6171	1961–2002	LfUG Dresden
Bad Kissingen	Rhein	1587	1929–2003	LFW München
Bad Mergentheim	Rhein	1018	1929–2004	LFU Karlsruhe
Barby	Elbe	94060	1899–2003	BfG Koblenz
Berthelsdorf	Elbe	244	1936–2002	StuFa Chemnitz
Beuerberg	Donau	954	1950–2002	LFW München
Birnbach	Donau	865	1930–2003	LFW München
Bodenwerder	Weser	15924	1940–2005	WSD Mitte
Borstendorf	Elbe	644	1929–2003	StuFa Chemnitz
Brenneckenbrück	Weser	1638	1945–2002	NLÖ Hildesheim
Burghausen	Donau	6649	1900–2003	LFW München
Calbe-Grizehne	Elbe	23719	1931–2003	BfG Koblenz
Calvörde	Elbe	732	1951–2003	LHW Sachsen-Anhalt
Camburg-Stöben	Elbe	3977	1931–2003	TLUG Jena
Celle	Weser	4374	1901–2004	BfG Koblenz
Chamerau	Donau	1356	1930–2003	LFW München
Cochem	Rhein	27088	1900–2006	WSD Südwest (Mainz)
Dillingen	Donau	11315	1923–2003	WWA Krumbach
Donauwörth	Donau	15037	1923–2003	LFW München
Dörzbach	Rhein	1029	1923–2003	RP Stuttgart
Dresden	Elbe	53096	1852–2003	BfG Koblenz
Düsseldorf	Rhein	147680	1930–2006	WSD West
Eichstätt	Donau	1400	1929–2003	LFW München
Eisenhüttenstadt	Oder	52033	1920–2004	WSA Eberswalde
Erfurt	Elbe	843	1930–2003	TLUG Jena
Erlln	Elbe	2983	1961–2002	LfUG Dresden
Eschelbach	Donau	1335	1930–2002	LFW München

Gauge	River basin	Basin area [km^2]	Period of measurements	Water authority
Frankenroda	Weser	4214	1935–2004	TLUG Jena
Freising	Donau	3088	1950–2003	LFW München
Fürstenfeldbruck	Donau	1235	1920–2003	LFW München
Gera	Elbe	2186	1950–2003	TLUG Jena
Gerstungen	Weser	3039	1931–2004	TLUG Jena
Golzern 1	Elbe	5442	1910–2003	LfUG Dresden
Göritzhain	Elbe	532	1910–2003	StuFa Chemnitz
Grafenmühle	Donau	1436	1939–2003	LFW München
Grebenau	Weser	2975	1950–2004	BfG Koblenz
Greene	Weser	2916	1940–2002	NLÖ Hildesheim
Greiz	Elbe	1255	1924–2003	TLUG Jena
Greven	Ems	2842	1940–2004	BfG Koblenz
Große Schwülper	Weser	1734	1925–2002	NLÖ Hildesheim
Guntershausen	Weser	6366	1920–2004	BfG Koblenz
Hadmersleben	Elbe	2758	1931–2003	LHW Sachsen-Anhalt
Haltern	Rhein	4273	1950–2005	LUA Essen
Hann-Münden	Weser	12442	1931–2005	WSD Mitte
Harburg	Donau	1578	1939–2003	LFW München
Havelberg	Elbe	24037	1945–2003	BfG Koblenz
Heitzenhofen	Donau	5426	1920–2003	WWA Regensburg
Heldra	Weser	4302	1950–2004	BfG Koblenz
Herrenhausen	Weser	5304	1941–2005	WSD Mitte
Herzlake	Ems	2226	1937–2002	NLÖ Hildesheim
Hofkirchen	Donau	47496	1900–2004	WSA Regensburg
Hof	Elbe	521	1920–2003	WWA Hof
Hohensaaten	Oder	109564	1920–2004	WSA Eberswalde
Hopfgarten	Elbe	529	1911–2003	StuFa Chemnitz
Horb/Neckar	Rhein	1113	1931–2004	WWA Hof
Hundersingen	Donau	2639	1929–2004	LFU Karlsruhe
Ingolstadt	Donau	20001	1923–2003	LFW München
Inkofen	Donau	3043	1926–2006	LFW München
Intschede	Weser	37720	1940–2005	WSD Mitte
Kalkofen	Rhein	5304	1935–2006	WSD Südwest (Mainz)
Kalteneck	Donau	762	1920–2003	LFW München
Karlshafen	Weser	14794	1940–2005	WSD Mitte
Kaub	Rhein	103488	1930–2006	WSD Südwest (Mainz)
Kelheim	Donau	22950	1923–2003	WWA Landshut
Kempten	Donau	955	1919–2003	LFW München
Köln	Rhein	144232	1845–2004	BfG Koblenz
Kriebstein UP	Elbe	1757	1910–2002	LfUG Dresden
Landau	Donau	8467	1925–2003	LFW München
Landsberg	Donau	2287	1900–2003	WWA Weilheim

Gauge	River basin	Basin area [km^2]	Period of measurements	Water authority
Laufermühle	Rhein	954	1926–2003	LFW München
Lauffen	Rhein	7916	1948–2006	WSD Südwest (Mainz)
Lechbruck	Donau	1714	1950–2003	WWA Weilheim
Letzter Heller	Weser	5487	1940–2004	BfG Koblenz
Leun	Rhein	3571	1935–2006	WSD Südwest (Mainz)
Lichtenwalde	Elbe	1575	1910–2003	StuFa Chemnitz
Magdeburg	Elbe	94942	1930–2003	BfG Koblenz
Mainz	Rhein	98206	1930–2006	WSD Südwest (Mainz)
Marklendorf	Weser	7209	1941–2005	WSD Mitte
Maxau	Rhein	50196	1921–2006	WSD Südwest (Mainz)
Meinigen	Weser	1170	1918–2004	TLUG Jena
Mellingen	Elbe	627	1922–2003	TLUG Jena
Münchshofen	Donau	4014	1929–2003	LFW München
Nägelstedt	Elbe	716	1936–2003	TLUG Jena
Neu Darchau	Elbe	131950	1900–2004	BfG Koblenz
Neubrück	Rhein	1595	1950–2006	StUA Krefeld
Neuhausen	Rhein	11887	1930–2004	BfG Koblenz
Niederschlema	Elbe	759	1928–2002	StuFa Plauen
Niedertrebra	Elbe	894	1922–2003	TLUG Jena
Nossen 1	Elbe	585	1925–2003	LfUG Dresden
Nürnberg	Rhein	1192	1910–2003	LFW München
Oberaudorf	Donau	9712	1900–2003	WWA Rosenheim
Oberndorf	Donau	26448	1925–2003	LFW München
Oberstein	Rhein	558	1937–2003	LFW Mainz
Offingen	Donau	951	1940–2003	LFW München
Ohrum	Weser	813	1925–2002	NLÖ Hildesheim
Oldisleben	Elbe	4174	1922–2003	TLUG Jena
Opladen	Rhein	606	1951–2006	LUA Essen
Passau	Donau	26084	1920–2003	LFW München
Pettstadt	Rhein	7005	1922–2003	LFW München
Pforzheim/Enz	Rhein	1479	1931–2004	LFU Karlsruhe
Plattling	Donau	8839	1925–2003	WWA Deggendorf
Plochingen	Rhein	3995	1918–2006	WSD Südwest (Mainz)
Pockau 1	Elbe	385	1921–2002	StuFa Chemnitz
Porta	Weser	19162	1935–2005	WSD Mitte
Rees	Rhein	159300	1931–2006	WSD West
Regenstauf	Donau	2660	1900–2002	WWA Regensburg
Rekingen	Rhein	14718	1920–2004	BfG Koblenz
Rethem	Weser	14730	1940–2005	WSD Mitte
Rheine	Ems	3740	1930–2004	BfG Koblenz
Rockenau	Rhein	12710	1950–2006	WSD Südwest (Mainz)
Rönkhausen	Rhein	884	1950–2005	StUA Siegen

Gauge	River basin	Basin area [km^2]	Period of measurements	Water authority
Rotenburg	Weser	2523	1920–2004	BfG Koblenz
Rottersdorf	Donau	720	1939–2003	LFW München
Rudolstadt	Elbe	2678	1942–2003	TLUG Jena
Schmittlotheim	Weser	1202	1930–2004	BfG Koblenz
Schwabelweis	Donau	35399	1930–2002	WSA Regensburg
Schwarmstedt	Weser	6443	1941–2005	WSD Mitte
Schweinfurt	Rhein	12715	1844–2006	WSA Schweinfurt
Schwürbitz	Rhein	2424	1940–2003	LFW München
Seebruck	Donau	1399	1930–2003	LFW München
Speyer	Rhein	53131	1950–2006	WSD Südwest (Mainz)
Staudach	Donau	952	1920–2003	LFW München
Stegen	Donau	993	1930–2003	LFW München
Streckewalde	Elbe	206	1921–2002	StuFa Chemnitz
Sylvenstein	Donau	1138	1949–2003	LFW München
Torgau	Elbe	55211	1935–2003	WSA Dresden
Treuchtlingen	Donau	982	1940–2003	WWA Ansbach
Trier	Rhein	23857	1931–2006	WSD Südwest (Mainz)
Türkheim	Donau	671	1950–2003	WWA Krumbach
Unterjettenberg	Donau	940	1900–2003	LFW München
Unterköblitz	Donau	2004	1940–2003	WWA Amberg
Unterlangenstadt	Rhein	713	1931–2002	WWA Hof
Vacha	Weser	2246	1921–2004	TLUG Jena
Versen	Ems	8369	1941–2004	BfG Koblenz
Villigst	Rhein	2009	1950–2005	LUA Essen
Wahmbeck	Weser	12996	1941–2005	WSD Mitte
Warnbach	Donau	821	1940–2003	LFW München
Wechselburg	Elbe	2107	1910–2003	StuFa Chemnitz
Wegeleben	Elbe	1215	1894–2003	LHW Sachsen-Anhalt
Wildenau	Donau	712	1940–2003	LFW München
Wittenberg	Elbe	61879	1950–2003	BfG Koblenz
Wittenberge	Elbe	123532	1899–2003	BfG Koblenz
Wolfsmünster	Rhein	2131	1930–2003	LFW München
Wolmirstedt	Elbe	1503	1951–2003	LHW Sachsen-Anhalt
Worms	Rhein	68827	1936–2006	WSD Südwest (Mainz)
Zwickau-Pölbitz	Elbe	1030	1928–2003	StuFa Plauen

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2004 – 2009	Scientific Staff (PhD student) at GFZ German Research Centre for Geosciences, Section Hydrology
2006 – 2007	Teaching at the University of Potsdam, Institute of Geoecology
2003 – 2004	Scientific Staff at GFZ German Research Centre for Geosciences, Section Engineering Hydrology
2001	Practical work at ETH Zurich, Chair of Forest Ecology
2000	Practical work at Credit Valley Conservation in cooperation with the University of Guelph (Canada)
1995 – 1996	Voluntary Ecological Year (FÖJ) at the Foundation for Nature Conservation Berlin

Education

1996 – 2003	Studies of Geoecology at the University of Potsdam, Graduation with honors as Dipl.-Geoecologist
2002	Diploma thesis at ETH Zurich „Modelling snow cover in a pre-alpine valley with remotely sensed data“, supported by DAAD
1999 – 2000	Studies of Environmental Sciences at the University of Guelph, Canada
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List of Publications

Kreibich, H., Petrow, T., Thieken, A., Müller, M., and Merz, B. (2005a). Consequences of the extreme flood event of August 2002 in the city of Dresden (Germany). In M. Savic D. A.and Marino, H. Savenije, and J. Bertoni (editors), *Sustainable Water Management Solutions for Large Cities*, *IAHS Publications*, volume 293, pp. 164–173. International Association of Hydrological Sciences.

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Author’s declaration

I have prepared this dissertation without illegal assistance. The work is original except where indicated by special reference in the text and no part of the dissertation has been submitted for any other degree. This dissertation has not been presented to any other University for examination.

Theresia Petrow
Potsdam, June 2009