RUNOFF REGIME CHANGES IN GERMAN RIVERS DUE TO CLIMATE CHANGE

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With 11 figures and 5 tables
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Summary: The runoff regime characterises the mean seasonal runoff variations of catchments. The knowledge of the regime type therefore contains information on the average seasonal variability in runoff and the main feeding mechanisms of rivers. In the last decades, environmental change has affected the runoff regimes of German rivers. Changes in precipitation patterns, snow periods and evaporation rates have influenced the runoff regimes, same as construction of dams and river regulation measures. This study systematically analyses gauge data of large rivers in Germany in order to identify changes in the runoff regime, mainly caused by climate change since middle of the 20th century. It is shown that the general runoff regime types (such as pluvial, nival and glacial) have not changed. However, the detailed characteristics of the runoff regimes (amplitude, time of extreme values of the Pardé coefficients) were considerably affected by environmental change.

Zusammenfassung: Das Abflussregime kennzeichnet den mittleren Jahresgang des Abflusses von Einzugsgebieten. Es gibt somit Auskunft über die mittlere Variabilität des Abflusses im Jahresverlauf und über die Speisungsart der Flüsse. Der in den letzten Jahrzehnten beobachtete Wandel der Umwelt nimmt Einfluss auf das Abflussregime. Veränderte Niederschlagsmuster, Schneedeckenperioden und Verdunstungsraten bewirken genauso Veränderungen in den Abflussregimen wie die Konstruktion wasserwirtschaftlich genutzter Speicher. In diesem Beitrag wird anhand einer systematischen Analyse von Abflussdaten deutscher Flüsse die Veränderung der Abflussregime vor allem seit Mitte des 20. Jahrhunderts quantifiziert, die zu einem erheblichen Teil dem Klimawandel zugeordnet werden kann. Es zeigt sich, dass sich zwar die generellen Regimetypen (pluvial, nival, glazial) nicht verändert haben, dass aber die Ausprägung der jeweiligen Typen (Amplitude, Zeitpunkt des Eintretens der Extremwerte der Schwankungskoeffizienten) durch den Umweltwandel bereits erheblich beeinflusst wurde.

Keywords: Runoff regime, Pardé coefficient, climate change, hydrological change, German rivers

1 Introduction

One of the burning questions in contemporary hydrology is the adaptation of human life to the hydrological effects of environmental change. Therefore, knowledge of past and current changes in hydrological fluxes and the main environmental variables is required. Characteristics of interests are changes in mean behaviour, seasonality and extremes. For example, as a consequence of a changing climate, in many regions of the world hydrological change is observed. Floods as well as droughts seem to occur more frequently, and extremes seem to be more intense in general (van der Ploeg and Schweigert 2001; van der Ploeg et al. 2001).

In recent years, many studies have been carried out to identify possible trends in flood magnification based on analysing historical gauge data. For some rivers (e.g., the Rhine), significant trends in flood intensity were identified (Petrow and Merz 2009; Pinter et al. 2006; Willems and Kleeberg 2000). Yet, for the majority of available data sets of German rivers, statistically significant trends could not be detected (Mudelsee et al. 2003; Bormann et al. 2008). However, this does not prove the non-existence of trends. Radziejewski and Kundzewicz (2004) showed that the significant identification of trends in hydrological time series is extremely difficult. It depends on both, the intensity of the trend as well as on the length of the time series.

In addition to the frequency and the intensity of extreme hydrological events, such as floods and droughts, water management depends on the average hydrological behaviour of catchments (water balance) as well as on the average seasonal variability of runoff (runoff regime according to Pardé 1933). They may be affected by environmental change, as well. Water balance and runoff regime are closely related to climate and the physiographic characteristics of a catchment (e.g., topography, land use, soils, geology) and relatively easy to characterise. They are therefore often used to estimate the usable amount

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of water. The runoff regime is appropriate for an efficient characterisation of runoff characteristics of rivers (Aschwanden and Weingärtner 1985).

As a remarkable global as well as regional climate change in Germany has been detected in the last decades (IPCC 2007; Schönwiese 1999), the question arises whether German rivers already suffer a change in mean seasonal runoff behaviour. Belz et al. (2007) found a change in the runoff regime of the Rhine River as a combined reaction of climate change and anthropogenic impacts such as land use change and the construction of reservoirs. However, an assessment of changes in the runoff regime should consider that runoff regimes naturally mask enormous variabilities in runoff (Pfaundler et al. 2006). The runoff from single years may significantly deviate from the runoff regime. Additionally, Pfaundler et al. (2006) found that inter-annual deviations in the runoff regime depend on the regime type. Smallest variability was found for alpine runoff regimes compared to runoff regimes of the low mountain range. Furthermore they stated that the seasonal variability of the runoff regime exceeded the year-to-year variability of the runoff. Insofar, integration over long-term periods (e.g., 30 years when dealing with climate) generates characteristic seasonal runoff characteristics, describing the mean seasonal dynamics in a sufficient way.

Focusing on the mean annual water balance, changing climate in particular can be expected to affect the water balance of river catchments. Precipitation is the only input term into the water balance equation. Changes in precipitation therefore probably affect runoff. Increasing temperature induces an increasing evapotranspiration that, in combination with changes in the catchment precipitation, can cause changes in the water balance. A change in the temperature may also affect timing and amount of snow fall and snow melt. For most German river catchments, past trends (Schönwiese 1999) as well as future scenarios (IPCC 2007; UBA 2007) show increasing winter precipitation, decreasing summer precipitation and a temperature increase throughout the year. Independent of the likewise increasing variability in precipitation, as a consequence of regional climate change in Germany, it can be expected that winter runoff will increase and summer runoff will decrease according to the IPCC climate scenarios (e.g., Bormann 2009; Krause and Harnisch 2009). Finally, the effects of climate change are superimposed by other anthropogenic activities such as land use change and river regulation. For the Elbe River, Wechsung et al. (2006) showed that changes in low flow conditions can be related to climate change, mining activities and reservoir operation, only.

So far, a comparative analysis of gauge data of different German rivers on changes in the runoff regime has not been carried out. Only catchment specific analyses are available (e.g., Belz 2010). For this reason, runoff data of 57 gauge stations of five large German rivers are analysed in this study with respect to changes in the runoff regime since observations started. Due to data availability reasons, the main focus is set on the time period between 1930/1940 and 2005. Increase (or decrease) of the extreme values of monthly Pardé coefficients (Pardé 1933) is investigated as well as a consequential impact on the seasonal variability of runoff and a potential temporal shift of the occurrence of the extremes of monthly Pardé coefficients. This might happen due to earlier snow melt caused by regional warming. In order to account for the term "climate", 30 year time periods are investigated.

2 Material and methods

2.1 Data base

In this study, time series of daily discharges, observed at 57 gauges in the catchments of five large German rivers, are analysed (Tab. 1; Fig. 1). The minimum required length for the time series is defined to be 60 years in order to be able to detect long-term effects of environmental change. The data of the rivers Danube (11 gauges), Elbe (9 gauges), Ems (3 gauges), Rhine (16 gauges) and Weser (18 gauges) were provided by the Global Runoff Data Center (Koblenz). For the Odra River, time series of sufficient length are not available. It can however be assumed that the effects of environmental change on its runoff regime are similar to those observed for the Elbe catchment (IKSE 2005). The data were checked for completeness, outliers, changes in gauge datum and location. Specific gauge plots were generated for all gauges in order to identify discontinuities within the time series. In addition, data were pre-checked by the Global Runoff Data Centre.

2.2 Runoff regimes

The runoff regime describes the mean seasonality of river runoff, influenced by catchment characteristics such as climate and topography. The charac-

Fig. 1: Location of the investigated stream gauges and river catchments within Germany. The size of the gauge circles is proportional to the length of the time series of available data

Tab. 1: Time periods for which runoff data for the investigated river gauges are available

River	Gauge	Period	River	Gauge	Period
Aller	Celle	1900–2005	**Leine**	Herrenhausen	1940–2005
	Rethem	1940–2005		Schwarmstedt	1940–2005
Altmühl	Eichstädt	1940–2005	**Main**	Kemmern	1930–2006
Diemel	Helminghausen	1940–2005		Schweinfurt	1844–2005
Danube	Achleiten	1900–2005		Würzburg	1823–2005
	Hofkirchen	1900–2004	**Mosel**	Cochem	1900–2006
	Ingoldstadt	1923–2005		Trier	1930–2006
	Oberndorf	1925–2005	**Nahe**	Grolsheim	1935–2004
	Pfelling	1925–2004	**Neckar**	Plochingen	1945–2004
	Schwabelweis	1923–2004	**Rhine**	Andernach	1930–2006
Eder	Affoldern	1940–2005		Düsseldorf	1930–2004
	Schmittlotheim	1930–2005		Kaub	1930–2005
Elbe	Aken	1935–2005		Köln	1816–2000
	Barby	1899–2005		Mainz	1930–2003
	Dresden	1852–2005		Maxau	1921–2003
	Magdeburg	1930–2005		Rees	1930–2004
	Neu-Darchau	1874–2005		Rheinfelden	1930–2003
	Torgau	1935–2005		Worms	1936–2004
	Wittenberge	1899–2005	**Saale**	Calbe-Grizehne	1931–2005
Ems	Greven	1940–2003	**Salzach**	Burghausen	1900–2005
	Rheine	1930–2004	**Werra**	Allendorf	1941–2005
	Versen	1941–2005		Letzer Heller	1940–2005
Fulda	Guntershausen	1920–2005	**Weser**	Bodenwerder	1839–2005
	Rotenburg	1920–2005		Hann. Münden	1831–2005
Havel	Ketzin	1936–2005		Karlshafen	1940–2005
Iller	Kempten	1900–2005		Marklendorf	1941–2005
Inn	Passau	1920–2005		Porta	1936–2005
Isar	Landau	1925–2004		Vlotho	1831–2005
Lahn	Leun	1935–2004		Wahmbeck	1941–2005

teristic seasonal cycle described by the runoff regime exists due to the dominant feeding mechanisms of rivers: rain fall (pluvial), snow melt (nival) and ice melt (glacial). Depending on the temporal occurrence of seasonal maxima, regime types can be further distinguished with respect to climatic and topographic differences between catchments. The most famous classification system was published by Pardé (1933). He introduced the monthly Pardé coefficient (PC; relation between mean monthly (MQ_{month}) and mean annual (MQ_{year}) runoff (equation 1) in order to improve the comparability of different rivers. The Pardé coefficient therefore describes the mean monthly distribution of runoff over the year:

$$PC_{month} = \frac{MQ_{month}}{MQ_{year}} \qquad 1$$

Depending on the number of maxima of the monthly Pardé coefficients over the year, Pardé (1933) distinguished between unimodal (one maximum) and complex (more than one maximum, e.g., bimodal) runoff regimes. In addition, he differentiated between pluvial, nival and glacial runoff regimes depending on the dominant feeding mechanism. In case of complex runoff regimes, combinations of two or three feeding mechanisms are assumed. The difference between the maximum (PC_{max}) and the minimum (PC_{min}) values of monthly Pardé coefficients is called amplitude (A; equation 2). It characterises the inter-annual variability of mean monthly flow:

$$A = PC_{max} - PC_{min} \qquad 2$$

To identify temporal changes of the runoff regime due to climate change, 30-year periods are investigated in this study (e.g., 1941–1970 vs. 1971–2000). In order to detect gradual changes since mid of the 20th century, 30-year averages are calculated for each 10-year time step (e.g., 1951–1980 vs. 1961–1990 vs. 1971–2000). Additionally, the data of the most recent available 30 year period are analysed, as well (e.g., 1976–2005). In comparison to this approach, Belz et al. (2007) investigated time periods of 25 years (e.g. 1951–1975 vs. 1976–2000) to get insight into the long-term dynamics of the runoff regime.

Furthermore, a linear trend analysis is carried out, analysing trends in monthly Pardé coefficients over the last 60 years. Algebraic sign and slope of the trends are compared to the changes identified for the 30-year averages, shifted in 10-year time steps. For that purpose, the slope coefficient α (equation 3) is determined for all months of a year:

$$PC_{month} = \alpha \cdot year + \beta \qquad (3)$$

In summary, changes in the runoff regimes are analysed based on the following criteria:

1. Change in seasonal behaviour of monthly Pardé coefficients,
2. Change in extreme values of monthly Pardé coefficients (min, max), resulting in an increase or decrease of the seasonal variability of runoff (= change in amplitude),
3. Change in the timing of extreme values of monthly Pardé coefficients, indicating an inter-annual shift of dominant hydrological processes,
4. Uniformity of trends of the monthly Pardé coefficients within river catchments.

Finally, for all available time series, linear trends in the mean annual runoff (MQ) are computed for the same time periods that were used in analysing changes in the runoff regime (most recent 60 years of available data).

2.3 Observed climate change

Based on climate observations of the German Weather Service (DWD) from six German weather stations, a trend analysis is performed in order to confirm the climate trends found in the literature. The weather stations Hamburg, Bremen, Potsdam, Karlsruhe, Hohenpeißenberg and Zugspitze, representing different climatic regions in Germany (Northern German lowland, East German basins, Rhine valley, Alps), are selected due to their long-term data series (>100 years). Linear trends are derived from annual and seasonal (summer vs. winter) values of temperature and precipitation. In addition, as compared to the investigation on the runoff regime, 30 years moving averages are investigated. As the signal of anthropogenic climate change has been proven for the second half of the 20th century (Schönwiese 1999), the trend analysis is performed for the last 60 years' annual averages (1947–2006) and the last 30 moving averages over 30 years (1948–1977 to 1977–2006).

2.4 Correlation between climate change and hydrological change

Correlation between climate change and hydrological change is investigated by two different analyses. Both analyses focus on the correlation of changes in precipitation and runoff. Firstly, trend in average specific discharge (Mq), identified for the time period 1950 to 2000, is correlated with mean annual catchment precipitation. Catchment precipitation is derived from GPCC (Global Precipitation Climate Centre) data set of the Deutscher Wetterdienst (Schneider et al. 2008) which globally provides monthly data for a 0.5° grid. In order to consider seasonal correlation between climate change and hydrological change, the runoff trends identified for the monthly Pardé coefficients are compared to respective trends in Pardé coefficients for monthly catchment precipitation.

2.5 Land use change and river engineering

Climate change is not the only change that can be observed. The river catchments analysed in this study have been intensively used by people for centuries. It can be assumed that – in addition to climate change – change in land cover, river engineering, construction of reservoirs and mining activities had an impact on the hydrological behaviour of the catchments, as well. Many of those changes occurred before runoff observations started (Buck et al. 1993). Therefore, a qualitative literature study is carried out to judge the importance of anthropogenic changes in land use and river engineering activities in German river catchments since 1945 in general.

3 Results

In this section, environmental and anthropogenic changes are described first, followed by changes regarding the runoff regime. Thus, the presentation of identified changes in the runoff regime is based on the knowledge of observed environmental change.

3.1 Climate change

The linear trend analysis of temperature observations revealed uniform trends. For all weather stations, trends in annual as well as seasonal (summer, winter) averages are positive. However, the relation of summer to winter warming rate is different for different stations (Tab. 2). While for the northern German stations (Bremen, Hamburg, Potsdam) warming in winter was stronger than in summer, in southern Germany (Karlsruhe, Hohenpeißenberg, Zugspitze) regional warming in summer was stronger. The trends, calculated from 30-year moving averages show slightly higher values compared to the trends based on annual averages (Tab. 2). All trends in temperature, calculated from annual values of moving averages, are statistically significant. The results confirm direction and regional differences in the trends published by Schönwiese (1999) while the warming trends are stronger. This is due to the shorter and more recent time period used in this analysis (1947–2006) compared to Schönwiese (1891–1990) causing stronger trends due to the acceleration of global warming in the second half of the 20th century (IPCC 2007).

The trends identified for precipitation show larger differences between stations and regions (Tab. 3). Potsdam station, representing a continental climate, shows a negative trend in summer in particular, while at stations representing a humid climate (e.g., Hamburg, Karlsruhe, Zugspitze) precipitation increases particularly in winter. Trends calculated from annual values and from moving averages mostly show similar directions, but partly show remarkable differences in the slope of the trend. Except for the climate station Zugspitze, precipitation trends based on annual data are not statistically significant, while the trends based on moving averages predominantly are (Tab. 3). In contrast to the trends published by Schönwiese (1999) for the period 1961–1990 who described a winterly increase and a summerly decrease in precipitation for all of Germany, the values of selected weather stations deviate slightly from average behaviour. In summary, the identified trends are consistent with the literature on regional climate change in Germany.

3.2 Correlation between climate change and hydrological change

The comparison of catchment precipitation and annual specific runoff, calculated for the data from 1950 to 2000 for all catchments, results in a clear linear correlation ($\Delta Mq = 0.89\ \Delta Precip - 0.16$; $r^2 = 0.66$; see Fig. 2). With an increasing trend in annual catchment precipitation, the trend in annual specific runoff increases, as well, while the offset is close to zero. The magnitude of the trend is catchment specific. Moreover, the variability within the catchments is on the same order of magnitude as the trend differences among the catchments. Regional trend analyses were performed for the Rhine (Belz 2010; Belz et al. 2007) as well as for the Elbe (Wechsung et al. 2006) catchments. Their results are consistent with the results presented here.

Long-term trends in monthly Pardé coefficients of precipitation and runoff are closely correlated for pluvial regimes, as well. For the pluvial Weser River, a polynomial correlation yields an $r^2=0.46$ (Fig. 3), where snow storage and snow melt only play a minor role. Increasing trends in monthly precipitation in winter (except February) are mainly correlated with increasing trends in monthly runoff (e.g., January, March), while decreasing precipitation trends in summer mainly are followed by decreasing trends in runoff (e.g., July, August). There is no considerable lag time between precipitation and runoff. For the

Tab. 2: Changes in temperature (ΔT) [°C] related to a 100-year period at six climate stations in Germany; linear trends in the last thirty 30-years moving averages (1948–1977 to 1977–2006) and for comparison in the annual values of the last 60 years (1947–2006)

	ΔT annual [°C/100a]		ΔT summer [°C/100a]		ΔT winter [°C/100a]	
	Moving average	Annual average	Moving average	Half year average	Moving average	Half year average
Hamburg	2.7	2.36	2.3	2.1	3.1	2.62
Bremen	1.3	1.19	0.59	0.7	2.01	1.68
Potsdam	1.9	1.53	1.24	1.09	2.56	2.97
Karlsruhe	2.85	2.66	2.91	2.86	2.79	2.46
Hohenpeißenberg	2.44	1.72	2.42	1.93	2.46	1.51
Zugspitze	1.26	0.74	1.39	1.02	1.13	0.46

Tab. 3: Changes in annual precipitation (ΔP) [mm/a] related to a 100-year period at six climate stations in Germany; linear trends in the last thirty 30-years moving averages (1948–1977 to 1977–2006) and for comparison in the annual values of the last 60 years (1947–2006). **significant at 1% level; *significant at 5% level

Climate station (mean annual precipitation [mm] 1977–2006)	ΔP annual [mm/100a]		ΔP summer [mm/100a]		ΔP winter [mm/100a]	
	Moving average	Annual average	Moving average	Half year average	Moving average	Half year average
Hamburg (791)	195**	102	-5	4	200**	98
Bremen (694)	-106**	-73	-95**	-33	-11	-40
Potsdam (562)	-180**	-104	-162**	-69	-18*	-35
Karlsruhe (785)	173**	111	44**	71	129**	40
Hohenpeißenberg (1204)	70*	130	40	97	30*	33
Zugspitze (2090)	454**	762*	20	257*	434**	505*

Elbe catchment, similar trends (r^2=0.46 for polynomial regression) are identified while an effect of climate change on snow storage is already visible: In February, runoff increases despite decreasing precipitation, while in March runoff remains constant despite increasing precipitation trends (Fig. 3). In the Rhine and Danube catchments, nival influence is more important. There is still mainly a correlation between decreasing Pardé coefficients of precipitation and runoff in summer as well as increasing Pardé coefficients in winter, but in spring and autumn, trends in precipitation and runoff differ remarkably. In spring time, decreasing precipitation trends partly go along with increasing Pardé coefficients of runoff while the trends in autumn are vice versa.

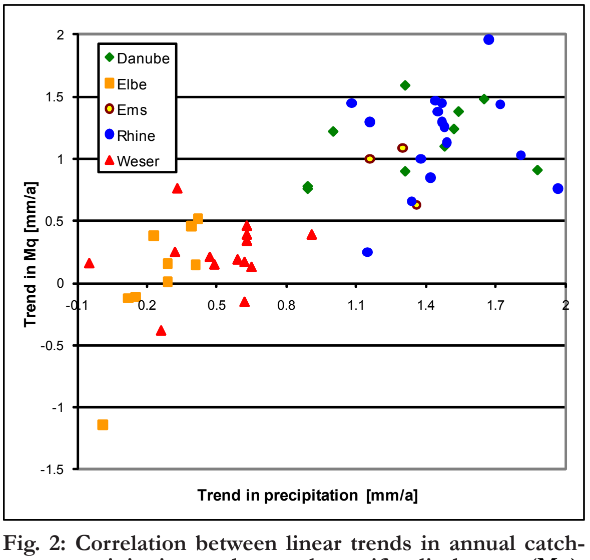

Fig. 2: Correlation between linear trends in annual catchment precipitation and annual specific discharges (Mq). Regression equation: ΔMq = 0.89 ΔPrecip – 0.16; R² = 0.66 (determined for all river catchments)

3.3 Land use change and river engineering

In Germany, land use has remarkably changed since 1945. Data from the Federal Statistical Office show that from 1951 to 1989, the agricultural area decreased from 57.8% to 53.7% while forest areas remained almost constant and impervious areas increased from 7.4% to 12.3%. This trend continued after the German reunification. As a consequence of increasing sealed surfaces, an increase in runoff generation and a decrease in groundwater recharge can be expected. Additionally, Van der Ploeg et al. (2001) assumed that land consolidation and intense agriculture led to a magnification of flood events. Although Bronstert et al. (2004) showed that effects of land use change on flood generation are small on the regional scale, an impact on the runoff regime is possible.

In addition to land use change, drainage of open-cast mines or rather recently closing mines and phasing down drainage can have a significant impact on river low flows. Wechsung et al. (2006) showed that during the 1970s and 1980s, the release of water from lignite mines increased continuously while after the German reunification the closure of lignite mines led to a decrease in water drained to the Saale River (by 20 m^3/s). During low flow situations, this water deficit aggravates low flows and can have an impact on the runoff regime of rivers affected by mining activities.

In addition to the anthropogenic activities, in the last 200 years, all large German rivers have been affected by river engineering to improve navigability of rivers, to produce energy and to protect against floods (e.g., Buck et al. 1993; Busch et al. 1989; Faist and Trabant 1996; Schenk 2001; Steinhauser 1962;

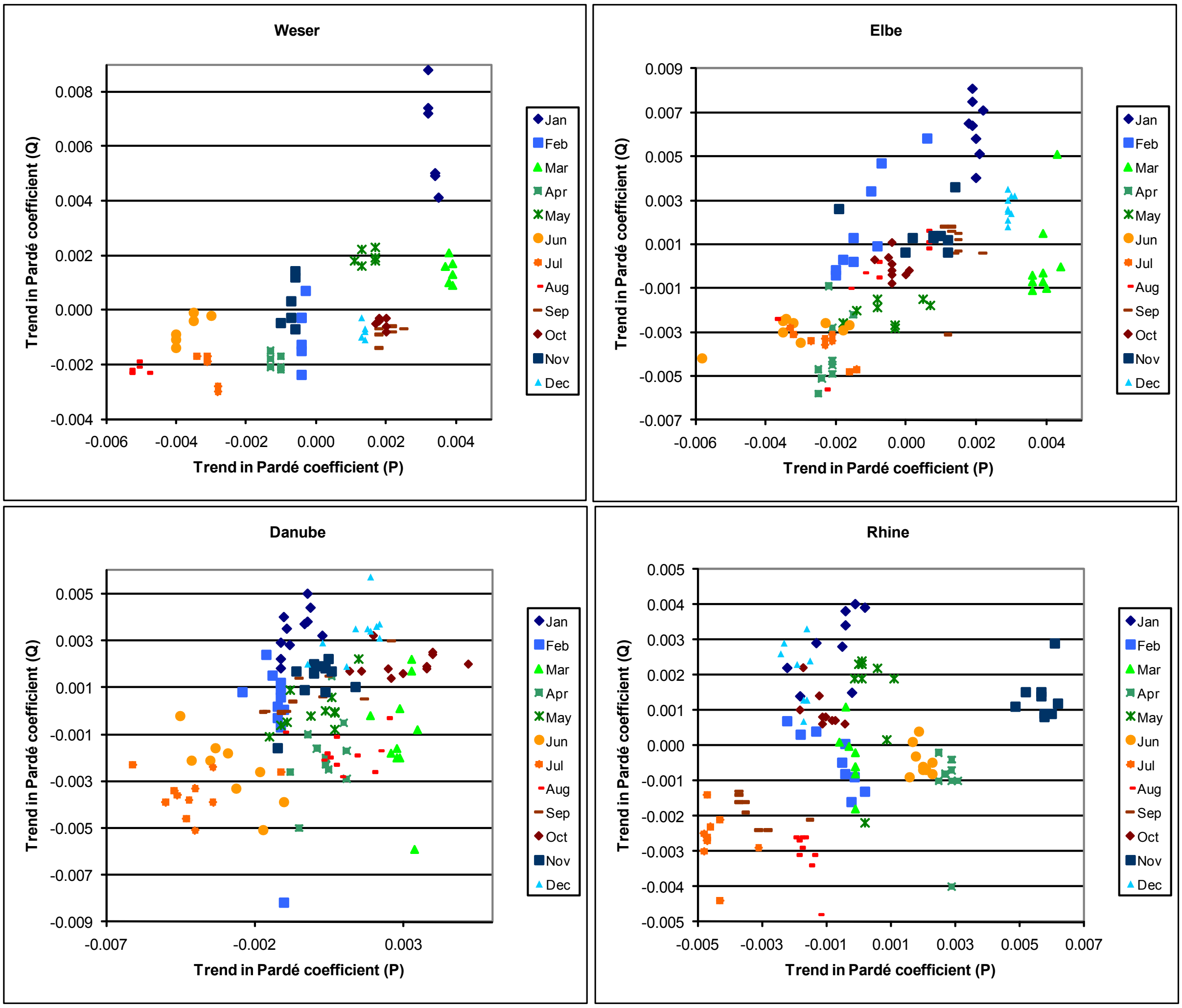

Fig. 3: Relation between linear trends in Pardé coefficients with respect to discharge (Q) and precipitation (P) for gauges of four river basins: Weser, Elbe, Danube and Rhine. Coefficients of determination: Weser (r^2 = 0.46, polynomial), Elbe (r^2 = 0.46, polynomial), Danube (r^2 = 0.16, linear), Rhine (r^2= 0.16, linear)

WECHSUNG et al. 2006). Dikes were constructed, rivers deepened, water levels controlled by weirs and erosion was controlled by groins and ground sills. Reservoirs were built for different purposes such as flood protection, drinking water supply and raising low flows. Most of river engineering activities were finalised prior to the investigation period of this study, but since the middle of the 20th century, further projects have been realised (for examples see Tab. 4).

It can be assumed that most river engineering activities (except dike constructions) aim at balancing river runoff regimes. While reservoirs mostly retain water in wet periods, they release water in dry periods. Thus, maximum runoff decreases while minimum runoff increases. River power plants work most efficiently under steady flow conditions, requiring adequate flow control. The river engineering activities discussed above induce reduced runoff variability. Similarly, BELZ et al. (2007), IKSE (2005) and FINKE et al. (1998) suppose a balancing effect of reservoir operation in mountainous areas.

3.4 Change in runoff regimes

Those gauges with time series longer than 60 to 80 years predominantly show an indifferent behaviour in the past with respect to changes in the runoff regime (monthly Pardé coefficients). Possible reasons are the natural climate variability over time but also the superposition of land use change, river engineer-

Tab. 4: Exemplary river engineering activities since 1945 along large German rivers

River	Year / period	River engineering
Rhine	1954–1977	Construction of nine reaches and river power plants along the upper Rhine (e.g., Birsfelden, Breisach Strasburg, Gambsheim, Iffezheim) (Buck et al. 1993)
Neckar	1945–1988	Construction of 60 reservoirs (Buck et al. 1993)
Main	1962	Canalisation completed until Bamberg
	1982–1984	Construction of river power plants, e.g., Offenbach
Moselle	1951–1964	Construction of twelve barrages (Buck et al. 1993)
Lahn	1954 – 1985	Construction of river power plants, weirs and locks (Schönefeld 1986)
Saar	1975–1988	Construction of seven barrages (Buck et al. 1993)
Elbe	1956–1975	Construction of reservoirs in Czech republic (Wechsung et al. 2006; Finke et al. 1998)
Weser	1953–1960	Completion of five weirs and locks (Busch et al. 1989)
Inn	1951–1998	Construction of 16 river power plants
Isar	1949	Redirection of the River Riß into the Walchensee
	1954–1959	Construction of the Sylvenstein reservoir
	1994–2001	Heightening of the Sylvenstein dam by 3 m
Iller	1950, 1994	Construction of the river power plants Aitrach and Mooshausener weirs

ing and reservoir construction (see also Belz et al. 2007). However, since global warming obviously accelerated in the middle of the 19th century (IPCC 2007; Schönwiese 1999), runoff regimes show noticeable trends. Three examples are analysed in detail for the last 100 to 180 years, whereas in the following sub-chapters, only trends of the last 60–80 years will be discussed.

Time series longer than 100 years are available for the gauges Hofkirchen (Danube), Cologne (Rhine) und Hannoversch Münden (Weser). The rivers are characterised by pluvio-nival regimes for the upper Danube and the lower Rhine and a pluvial regime for the Weser. All three rivers show considerable variations in the runoff regimes over the 30 year time periods (Fig. 4). Obviously, the variability in Pardé coefficients depends on the season. At Hofkirchen (Danube), variability in Pardé coefficients is high especially in winter (December, January) and summer (June, July), at Cologne (Rhine) in winter (February), late summer (September) and autumn (November) and at Hannoversch Münden (Weser) in early spring (March), summer (July) and winter (December, January).

The general regime types of the three rivers remained unchanged (pluvial and pluvio-nival regimes, as mentioned above), whereas the seasonal trends are regime specific. The analysis of typical months for each season and gauge station (e.g., those months showing minimum and maximum flows) reveals remarkable changes in the Pardé coefficients (Fig. 5). The changes identified since the middle of the 20th century are mostly within the variability observed previously. However, the gauges predominantly show trends in Pardé coefficients after 1950 for the selected summer and winter months shown in figure 5. At gauge Hofkirchen (Danube), Pardé coefficients decreased in the early 20th century in winter, spring and summer. Afterwards they increased in spring and summer. In the end of the 20th century, Pardé coefficients increased in autumn and winter and decreased in spring and summer. At gauge Cologne (Rhine), the variability in Pardé coefficients in the 19th century was small compared to the 20th century. Pardé coefficients decreased in winter, remained constant in May and September and increased in spring. Only in the second half of the 20th century did remarkable changes occur. While Pardé coefficients significantly increased during winter and spring, they decreased in summer and autumn. At gauge Hannoversch Münden (Weser), variability in Pardé coefficients was very high in the end of the 19th century. In contrast to the other gauges, Pardé coefficients increased during summer and autumn until the middle of the 20th century. Afterwards, they decreased again. Contrarily, Pardé coefficients in late winter decreased after 1950.

In summary, since the middle of the 20th century, similar trends have been observed for the three rivers: An increase in Pardé coefficients in winter (except Weser River in December, Cologne in February) and a decrease in summer. In contrast, the observations at the end of the 19th and early 20th century show different changes. Therefore, it can be assumed that in the 19th and in the first half of the 20th century, regional environmental changes such as land use change and river engineering affected regionally different changes in river flow while in the

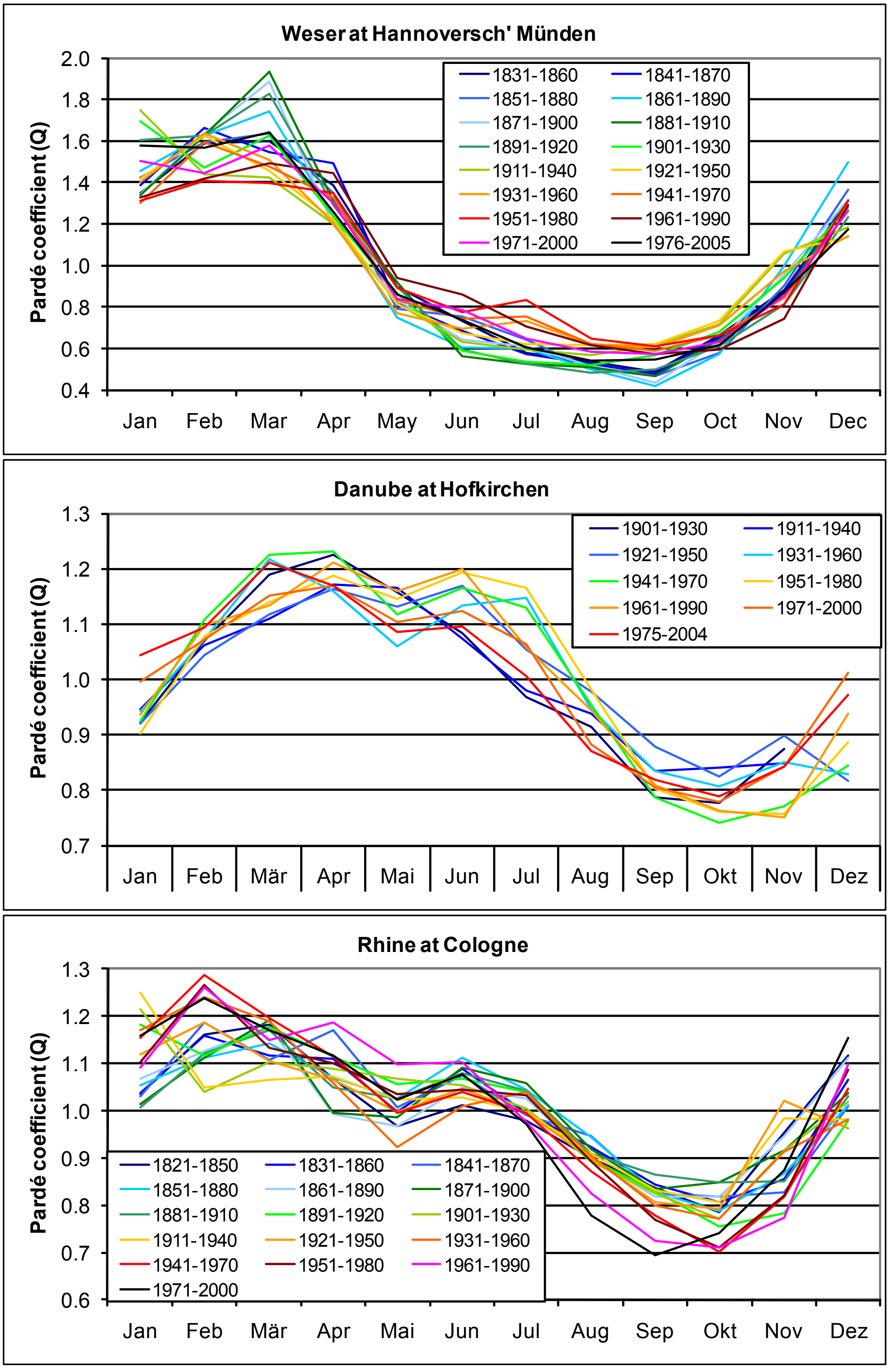

Fig. 4: Change in Pardé coefficient, describing variability in runoff regime of the Weser, Danube and Rhine rivers over time (30-year averages)

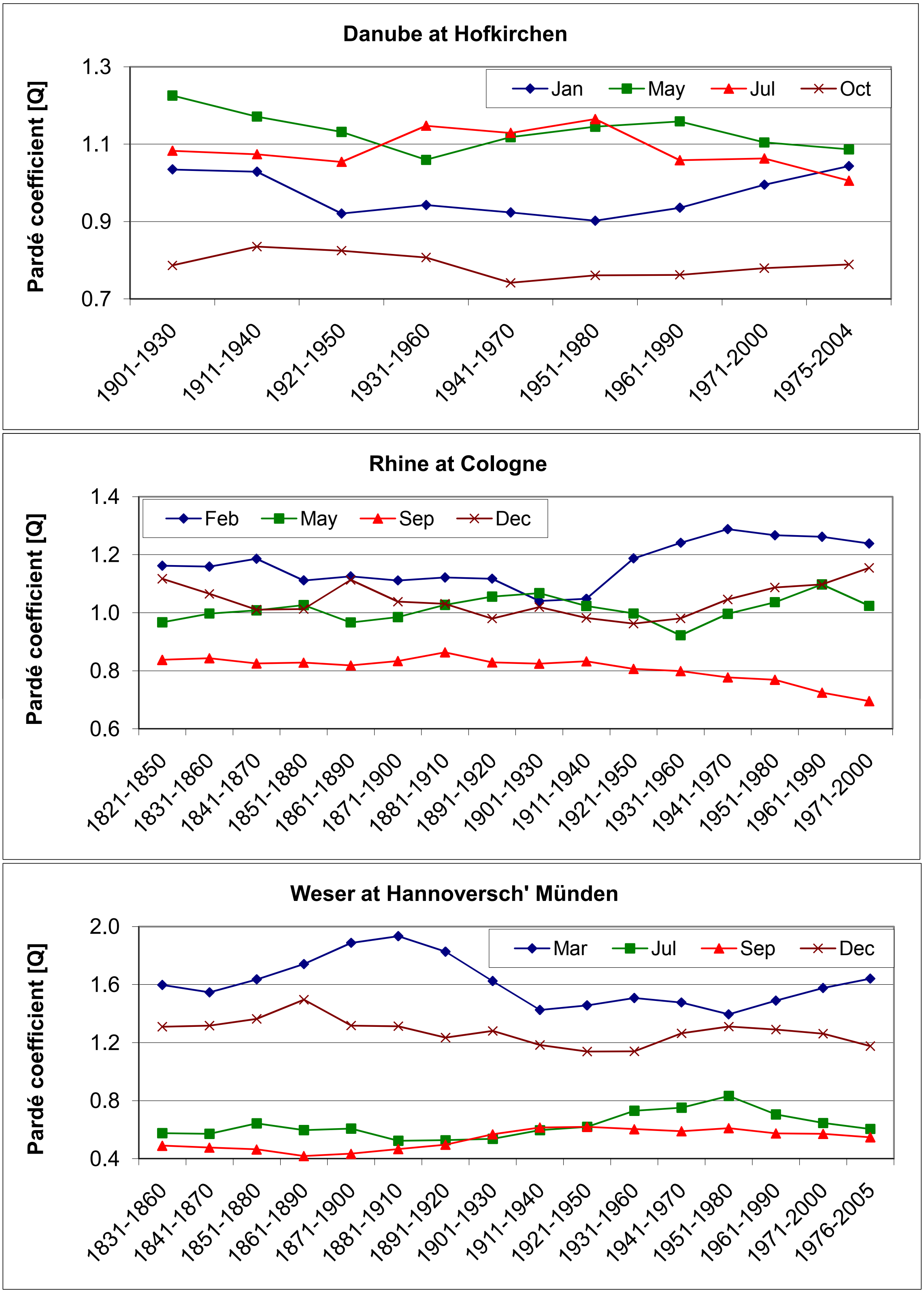

Fig. 5: Change in the 30-year Pardé coefficient over time for the stream gauges Hofkirchen (Danube), Cologne (Rhine) and Hannoversch Münden (Weser)

second half of the 20th century, a change across the catchments (probably climate change) dominated change in river flow. Changes in timing and amplitude of Pardé coefficients will be discussed in the river specific subsections.

3.4.1 Rhine River

The runoff regime of the Rhine changes considerably along the river. In Germany, the nival regime type at the upper Rhine passes over into a nivo-pluvial type. While the flow regimes of the alpine and upper Rhine are dominated by melting snow and ice, resulting in a unimodal regime (minimum in winter, maximum in summer), pluvial influence dominates downstream. Rainfall dominated tributaries such as Neckar and Main contribute to a bimodal runoff regime of the Rhine, generating a second maximum in winter. Further downstream (middle and lower Rhine), the winterly runoff maximum dominates the summer maximum, changing the runoff regime into a pluvio-nival type (Fig. 6; Belz 2010; Belz et al. 2007; HAD 2003). The runoff regimes of the inves-

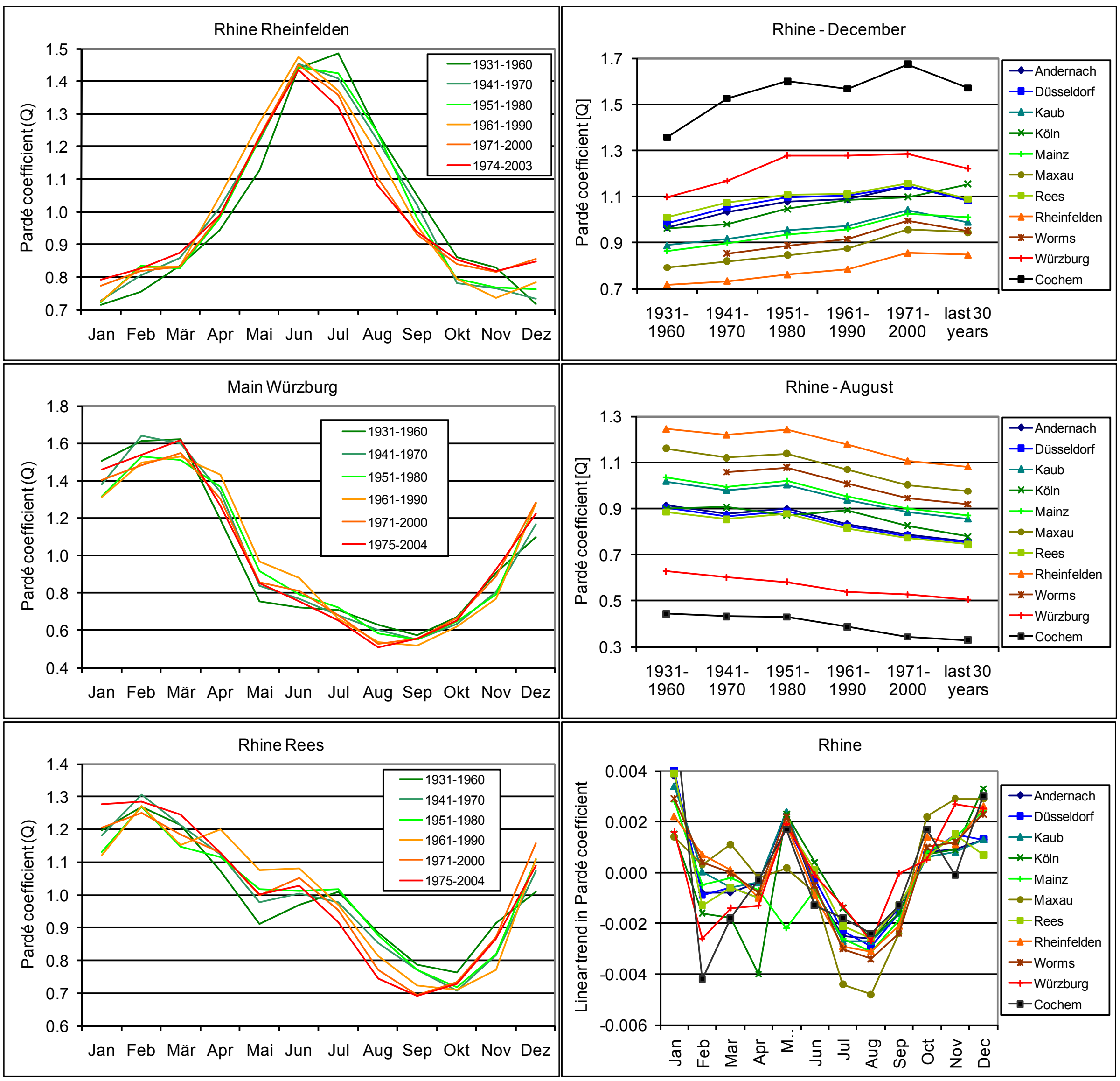

Fig. 6: Change in the shape of the runoff regime of the Rhine River and its tributaries since the middle of the 20th century (left). Greenish colours represent the first half, reddish colours the second half of the analysed time period. Right: Change in the Pardé coefficients for exemplary summer and winter months, and monthly, linear trends of the Pardé coefficient within the Rhine catchment since 1945

tigated tributaries (e.g., Lahn, Main, Moselle, Nahe, Neckar) are without exception of a pluvial type.

Along the entire German reach of the Rhine, since the middle of the 20th century, winter Pardé coefficients have increased while the values for summer and autumn have decreased. Minima recently occur one month earlier. Comparable to the Rhine, its tributaries show decreasing Pardé coefficients during summer (Fig. 6), minima occur earlier (e.g., Main at gauge Würzburg), and winterly Pardé coefficients increase (e.g., Nahe, Lahn, Moselle). Partly, Pardé coefficients in spring increase as well (Main, Lahn, Nahe). The trends in monthly Pardé coefficients confirm the findings based on 30-year averages (Fig. 6).

With respect to average discharge (MQ), all Rhine gauges have shown positive trends since 1950. These rising trends increase from upper Rhine (increase of about 200 m^3/s in 100 years) up to 500 m^3/s in 100 years at the lower Rhine (Cologne, Düsseldorf, Rees), while the tributaries do not show a uniform trend.

The identified changes go along with the findings of Belz (2010) and Belz et al. (2007), stating an increasing mean discharge in the northern part of the Rhine catchment, which is attributed to an increasing winterly discharge. They agree, that the amplitude decreased in the southern part (snow melt dominated) while it increased in the northern part of the river catchment (rainfall dominated). Scherrer et al. (2004) and Günther and Matthäus (2005) assume an increasing percentage of rain instead of snow in winter time as well as an earlier snow melt in spring time to be the main reasons. Reservoir operation contributes to this trend, as well. In addition to changing precipitation patterns (Schönwiese 1999), the increasing amplitude of the pluvial regime type is amplified by an increase in evapotranspiration in summer, resulting in higher discharges in winter and reduced discharges in summer.

3.4.2 Danube River

Comparable to the Rhine, the runoff regime of the Danube considerably changes along the German river reach. Due to the tributaries of the rivers Iller and Lech, the pluvial runoff regime at the gauge Berg (Belz et al. 2004) passes over into a nival regime at gauge Ingoldstadt. Rainfall dominated tributaries such as Altmühl, Naab and Regen modulate the nival into a nivo-pluvial runoff regime (gauges Oberndorf, Pfelling and Schwabelweis). Downstream of the tributary Inn, the regime changes back to a nival type (gauge Achleiten; Fig. 7; Belz et al. 2004; HAD 2003). The runoff regime is therefore mainly dominated by the runoff regimes of the large tributaries from southern (nival) or northern (pluvial) directions. While the river Altmühl, as an example for the tributaries from the northern lower mountain range, has a rainfall dominated runoff regime with a maximum Pardé coefficient in winter, the southern tributaries from the Alps show a nival regime with a maximum Pardé coefficient in summer. With increasing distance from the Danube's spring, the seasonal variation of Pardé coefficients is smoothened: The amplitude decreases (Belz et al. 2004).

Due to the large contribution of the tributaries to the discharge of the Danube, changes in its runoff regime depend on changes in the tributaries as well. While the tributaries from the lower mountain range in the north show decreasing Pardé coefficients in summer and late winter (e.g., gauge Eichstätt, Altmühl), Pardé coefficients in autumn and early winter increase. The tributaries from the Alps show a decrease in the summer Pardé coefficients, while in winter there is an increase in Pardé coefficients. As a consequence, the seasonal variability in runoff decreases (Fig. 7). The linear trend analysis of monthly Pardé coefficients confirms the findings based on the 30 year moving averages.

The discharge behaviour of the Danube follows the behaviour of the Alpine tributaries, which deliver most of the discharge into the Danube. At all available gauges of the Danube, Pardé coefficients increase in winter (December, January). While in spring a systematic change cannot be identified, Pardé coefficients decrease in summer. In autumn, Pardé coefficients increase (October in particular), which is confirmed by Belz et al. (2004). Similarly to the upper Rhine, seasonal variability of runoff (= amplitude) decreases (Fig. 7). Main reasons for the increase in winter Pardé coefficients are an increase of rainfall in winter and shorter duration of the snow cover. Snow melts earlier in the year, and smaller snow depths reduce the flow maxima in summer. It can be assumed that management of reservoir and river power plants reduces the seasonal variability additionally. This is confirmed by Belz et al. (2004), reporting on an increasing trend with respect to low flows, while there are no significant trends with respect to floods.

Average discharge has increased at all Danube gauges since 1950. This positive trend increases from the Danube spring to the gauge Schwabelweis (71 m^3/s in 100 years) and then decreases slightly to

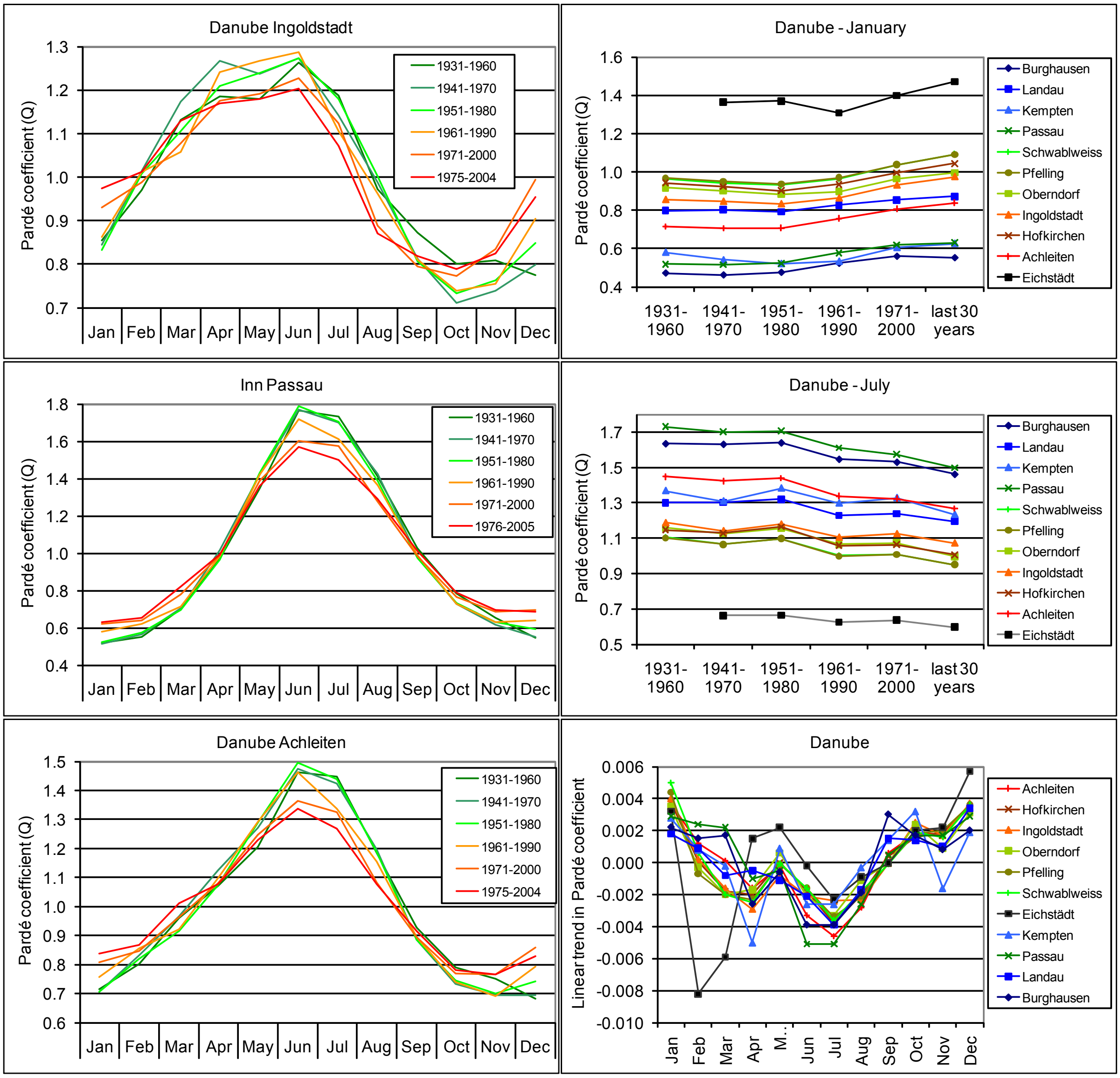

Fig. 7: Change in the shape of the runoff regime of the Danube River and its tributaries since the middle of the 20th century (left). Greenish colours represent the first half, reddish colours the second half of the time period analysed. Right: Change in the Pardé coefficients for exemplary summer and winter months, and monthly, linear trends of the Pardé coefficient within the Danube catchment since 1945

the Austrian border (40 m³/s in 100 years at gauge Achleiten). Insofar, except for the Iller, most of the Danube tributaries (e.g., Altmühl, Inn, Isar, Salzach) show increasing trends in mean discharge as well (between 5 and 21 m³/s in 100 years).

3.4.3 Elbe River

Due to the topography of the Elbe catchment (mainly lower mountain range and lowlands), the Elbe River has a pluvio-nival runoff regime (Finke et al. 1998; HAD 2003; IKSE 2005). Only the source areas of Elbe and Vltava show a runoff regime dominated by snow melt as compared to rainfall. Those tributaries flowing from the lower mountain range into the Elbe show a pluvio-nival regime as well (e.g., Eger, Mulde, Schwarze Elster). Highest Pardé coefficients occur in late winter and early spring (March, April). Maximum runoff at the middle Elbe is generated by snow melt from the Giant Mountains and the Bohemian Forest and by rainfall from the German lower mountain range. The largest tributaries in Germany (Saale, Elster) have pluvial runoff regimes

(Fig. 8). Downstream of Geesthacht, the Elbe is tidally influenced by the North Sea. Therefore, continuous discharge measurements are not available.

The change in the runoff regime is uniform for all available gauges of the Elbe River in Germany. In winter, the high Pardé coefficients further increase (November to March), while in spring and early summer (May to July) the small Pardé coefficients further decrease. Recently, the maximum Pardé coefficients have occurred one month earlier (March), as compared to the middle of the 20th century (April), indicating an earlier snow melt due to rising temperature. The amplitude (=seasonal variability in Pardé coefficients) increases (Fig. 8). The changes in the runoff regimes of the main tributaries Saale and Havel are similar: Winter maxima of the Pardé coefficients increase (December–March) while summer minima decrease (June–September), inducing an increasing amplitude, as well. The minimum Pardé coefficients during summer show the tendency to occur one month earlier, as well (Fig. 8).

In contrast to climate change induced impacts (Wechsung et al. 2006), which correspond well to

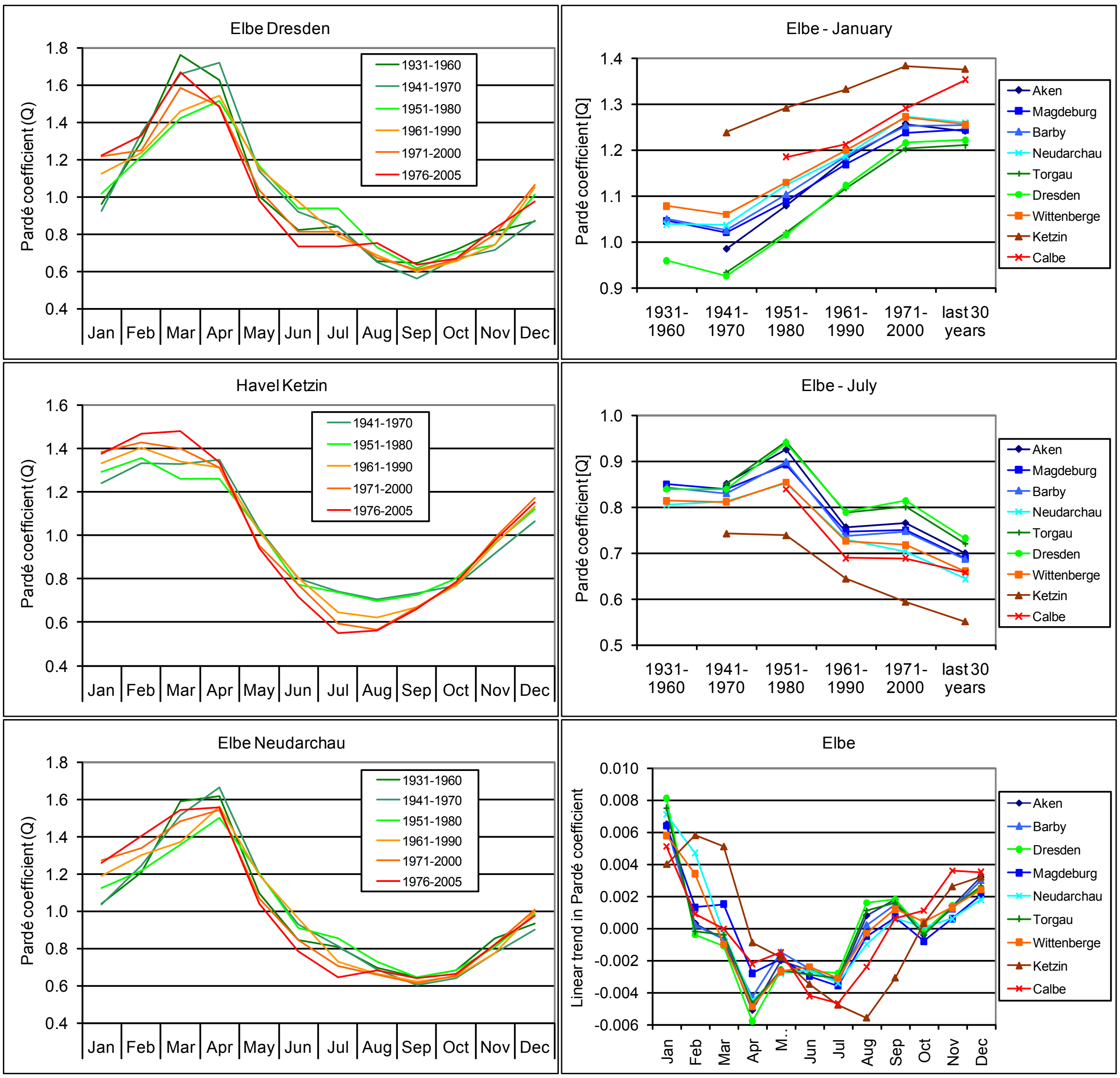

Fig. 8: Change in the shape of the runoff regime of the Elbe River and its tributaries since the middle of the 20th century (left). Greenish colours represent the first half, reddish colours the second half of the time period analysed. Right: Change in the Pardé coefficients for exemplary summer and winter months, and monthly, linear trends of the Pardé coefficient within the Elbe catchment since 1945

the average trends of temperature increase, summer rainfall decrease and winter precipitation increase in Germany (Schönwiese 1999), reservoir operation in the lower mountain range is expected to have a modulating impact on the runoff regime. According to (Finke et al. 1998), 165 reservoirs are operated in the Elbe catchment. In addition, water drainage from lignite mining has significantly increased discharge, for example of the Saale river in the 1970s and 1980s, raising low flows during summer in particular (Finke et al. 1998; IKSE 2005; Wechsung et al. 2006). After the German reunification, release of drainage water decreased again. Despite the influence of reservoir operation and lignite mining, the seasonal variability in Pardé coefficients has increased since the middle of the 20th century. Therefore, it can be assumed that climate change has the dominant impact on the change in runoff regime. As for the Rhine and Danube rivers, results from linear trend analysis and 30 year moving averages show consistent tendencies.

In contrast to the Rhine and Danube rivers, the trend in average discharge at most of the Elbe gauges is negative (decreasing from -13 m³/s in 100 years at gauge Aken down to -109 m³/s in 100 years at gauge Neudarchau). Due to the predominantly continental climate, positive trends in winter precipitation are overcompensated by decreasing summer precipitation and an increasing evapotranspiration throughout the year, including increasing evaporation from reservoirs.

3.4.4 Weser River

The springs of both headwaters of the Weser River, the Fulda and the Werra, are located in the lower mountain range. Therefore, both rivers as well as the Weser have unimodal, pluvio-nival runoff regimes. Discharge maximum is in late winter (March), discharge minimum in late summer (HAD 2003). The lower part of the Weser is tidally influenced of the North Sea; downstream of Bremen, discharge data are not available.

All gauges in the upper and middle Weser have shown increasing Pardé coefficients in winter (December to March) and decreasing Pardé coefficients in summer (June to September) since the middle of the 20th century, inducing an increase in seasonal variability of discharge. As snow plays only a minor role in the Weser catchment, this is mainly due to the change in precipitation (increase in winter, decrease in summer; Schönwiese 1999). All investigated tributaries show identical trends from analysis of annual Pardé coefficients as well as from 30 year moving averages. For all gauges, amplitude and therefore seasonal variability in discharge have increased (Fig. 9), despite the increasing storage volume of reservoirs and discharge control for shipping industry, reported by Busch et al. (1989). Therefore, comparable to the Elbe catchment, climate change can be assumed to be the dominant change in the catchment affecting the runoff regime.

As regards mean discharge (MQ), all gauges except gauge Marklendorf at the upper Weser show an increase in MQ of 10 to 20 m³/s in 100 years. Similarly, all tributaries except Werra River (gauge Letzter Heller) show slightly increasing MQ values as well (e.g., Fulda, Leine, Aller).

3.4.5 Ems River

The largest part of the Ems catchment belongs to the Northern German lowland. The Ems shows a unimodal pluvial runoff regime (HAD 2003), whose amplitude is significantly larger compared to other rivers in Northern Germany (e.g., Elbe, Saale, Weser). Snow melt is not important, in contrast to the geology (sandy sediments), which induces a dominant contribution of baseflow to river discharge.

Since the middle of the 20th century, the Pardé coefficients of the Ems have slightly increased in winter (December to March), while they have slightly decreased in summer (April to September; Fig. 10), inducing an increasing seasonal variability in discharge. Climate change is the main driver of changes in the runoff regime, similar to the Weser River. Mean annual discharge (MQ) has increased since the middle of the 20th century from 10 (gauge Rheine) to 19m³/s in 100 years (gauge Versen).

4 Discussion

The results show that, despite environmental and anthropogenic changes, the general runoff regime types of German rivers have not changed in terms of the dominating feeding mechanism since observations started. Nevertheless, the characteristics of the regime types have changed. Maximum monthly Pardé coefficients have consistently increased for pluvial flow regimes and decreased for nival flow regimes. In addition, the timing of the extremes in monthly Pardé coefficients as well as the amplitude changed at many gauge stations. The amplitude decreased for nival and increased for plu-

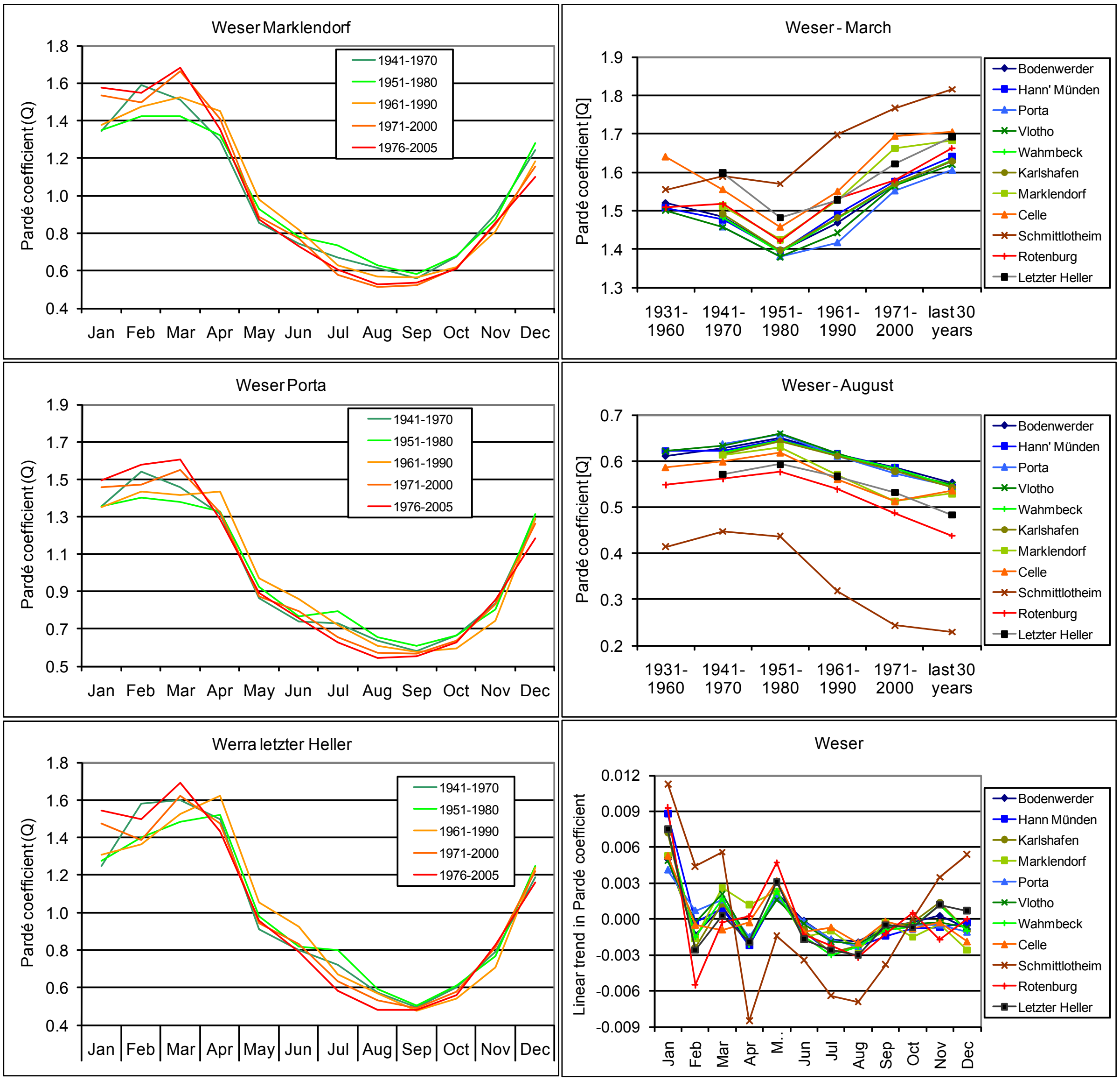

Fig. 9: Change in the shape of the runoff regime of the Weser River and its tributaries since the middle of the 20th century (left). Greenish colours represent the first half, reddish colours the second half of the time period analysed. Right: Change in the Pardé coefficients for exemplary summer and winter months, and monthly, linear trends of the Pardé coefficient within the Weser catchment since 1945

vial flow regimes. Therefore, the changing environment, dominantly climate change, affected the runoff regimes. Table 5 provides an overview over the changes identified for the investigated German rivers. For the different river catchments similar trends were identified.

For almost all gauges at all rivers and for all runoff regime types, Pardé coefficients have increased in winter and decreased in summer since the middle of the 20th century. Although linear trends in monthly Pardé coefficients are not statistically significant, trends in moving averages show considerable tendencies. Similarly, mean discharges show positive trends at most of the river gauges. While increasing discharge can be generated by changing climate as well as by changing land use (e.g., increase of sealed surfaces, as reported by Van der Ploeg et al. 2001), a dominance of climate impact is likely to produce the homogenous pattern of seasonal trends in Pardé coefficients.

For nival and nivo-pluvial runoff regimes, additionally, a change in the timing was observed. Recently, at several gauge stations the discharge maximum in summer occurred one month earlier

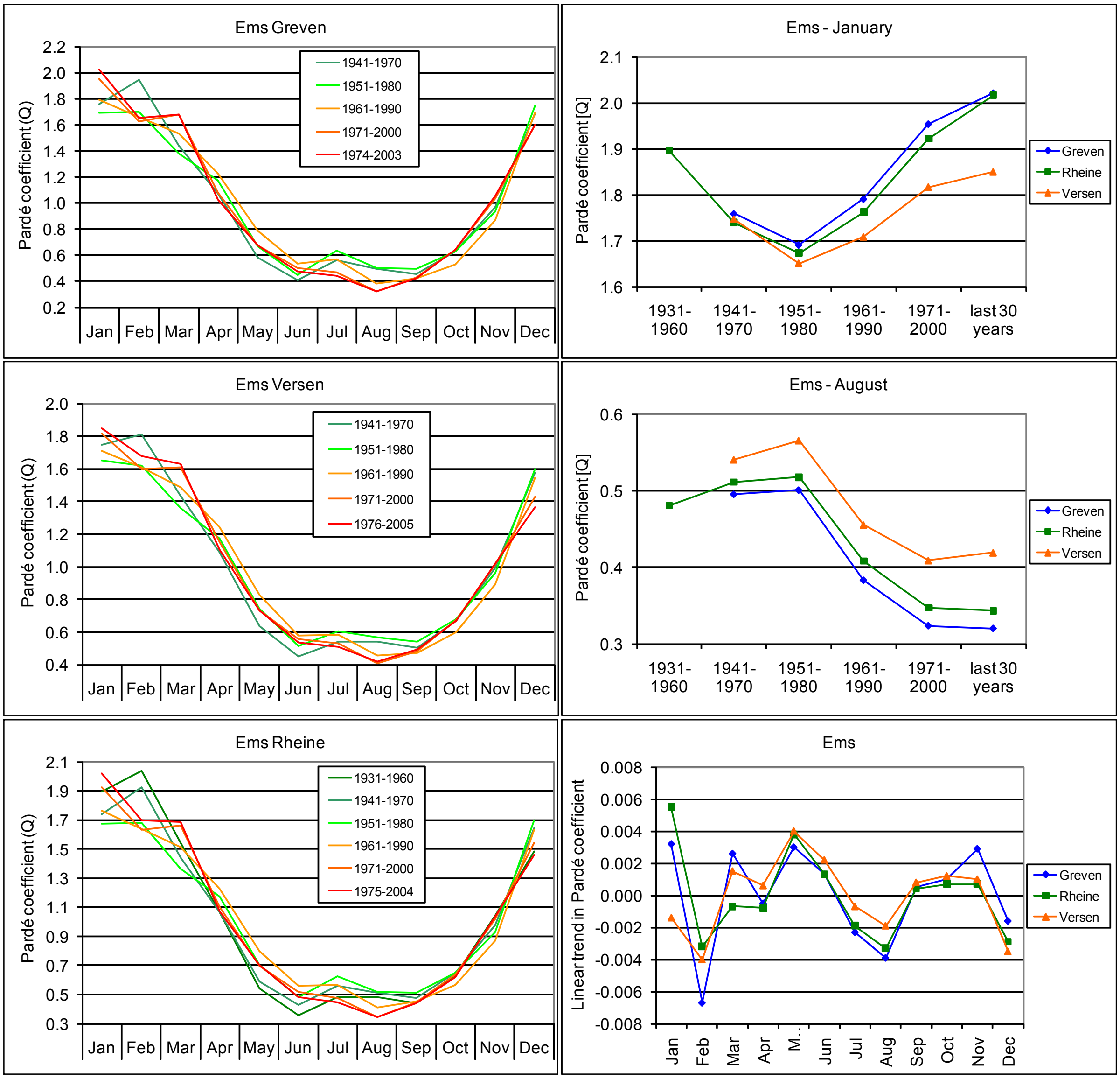

Fig. 10: Change in the shape of the runoff regime of the Ems River and its tributaries since the middle of the 20th century (left). Greenish colours represent the first half, reddish colours the second half of the time period analysed. Right: Change in the Pardé coefficients for exemplary summer and winter months, and monthly, linear trends of the Pardé coefficient of the Ems since 1945

compared to the middle of the 20th century. An increasing percentage of rainfall in winter instead of snow contributes to this tendency, resulting in higher runoff amounts and less snow storage (Günther and Matthäus 2005; Scherrer et al. 2004). The smaller snow pack generates lower discharges in summer because snow melt occurs earlier due to rising temperature. For both regime types, the seasonal variability in runoff decreases (= decreasing amplitude). In contrast, seasonal variability increased for pluvial and pluvio-nival runoff regime types. Winter maxima in runoff further increased while summer minima in runoff decreased. The timing of the maxima remained unchanged in the pluvial regime, while a slight tendency towards an earlier maximum of pluvio-nival types was observed due to snow related processes (less precipitation in terms of snow during winter, earlier snow melt due to the increase in temperature). As a consequence, runoff decreased in spring as well. For both regime types, decreasing minima of the Pardé coefficients in summer can be attributed to decreasing rainfall and increasing evapotranspiration due to rising temperatures. The trends in the available weather data of the Deutscher

Table 5: Specific, climate induced changes in the runoff regimes of the investigated German rivers (PC: Pardé coefficient; + : increase; – : decrease; 0 : no trend; MQ: mean runoff)

River	Regime type	PC maxima	PC minima	PC variability	PC summer	PC winter	Trend in MQ
Rhine	nival	–	+	–	–	+	+
	nivo-pluvial	–	0	–	–	+	+
	pluvio-nival	+	–	+	–	+	+
Rhine tributaries	pluvial	+	–	+	–	+	+
Danube	nival	–	+	–	–	+	+
	nivo-pluvial	0	+	–	–	+	+
	pluvio-nival	0	+	–	–	–	+
Danube tributaries	pluvial	–	0	–	0	–	+
	nival	–	+	–	–	+	+ / 0
Elbe	pluvio-nival	(+)	0	(+)	0	+	+
Elbe tributaries	pluvial	+	–	+	–	+	–
Weser	pluvio-nival	+	–	+	–	+	+ / 0
Weser tributaries	pluvio-nival	+	–	+	–	+	+ / 0 / –
Ems	pluvial	+	–	+	–	+	+

Wetterdienst (Tab. 2, 3), the correlation analysis between changes in precipitation and runoff (Fig. 2, 3) and the results of recent studies on climate change (Schönwiese 1999; Wechsung et al. 2006; Belz et al. 2007) confirm these assumptions.

Figure 11 gives an overview of the changes in the amplitude of Pardé coefficients since the middle of the 20th century. Obviously, seasonal variability has decreased for snow dominated regimes types while it has increased for rainfall dominated regime types. Complex (= bimodal) types do not show well-defined trends, but mostly follow the tendency of the dominant runoff generation process.

With respect to the average annual discharge (MQ), all large German rivers, except the Elbe River, show positive trends. However, the trends of the tributaries were found to be indifferent. Only in the Rhine catchment, did all tributaries show increasing mean discharges as well. This corresponds with the pronounced increase in annual precipitation between 1961 and 1990 reported by Schönwiese (1999).

Of course, not all changes in the runoff regime detected in this study can be attributed to climate change. For example, reservoir operation amplifies the trends due to climate change in snow dominated river catchments (Belz et al. 2007; IKSE 2005; Finke et al 1998; Wechsung et al. 2006). However, the effect of melting glaciers in the Alps can be estimated to be small (<1 % according to Belz et al. 2007). During low flow periods, trans-basin water transport for drinking water supply is detectable (e.g., transport of water from Lake Constance to the Neckar catchment; Belz et al. 2007). As mentioned before, a similar impact can be attributed to lignite open-cast mining (Finke et al. 1998; Wechsung et al. 2006; IKSE 2005). Finally, the increase in sealed surfaces and land use change in general can have an impact on the runoff generation as well. However, Bronstert et al. (2004) found that land use change has a significant effect on the local scale only, while effects on the scale of river catchments are small. This was confirmed by Belz et al. (2004), indicating that anthropogenic influences have an effect on small spatiotemporal scale, only. Finke et al. (1998) concluded that direct anthropogenic impacts on the water cycle are small compared to the climate change impact. Thus, especially in small catchments we are faced with a superposition of effects of different kinds of change. However, on the regional scale the dominance of climate change induced trends is likely, as demonstrated in this study for the changes in the runoff regimes of rivers in Germany.

5 Conclusion

This study has shown that climate change has an impact on the hydrological behaviour of river catchments and their mean seasonal variability. Average discharge as well as the flow regime of German rivers have been affected since global warming has accelerated dramatically since the middle of the 20th

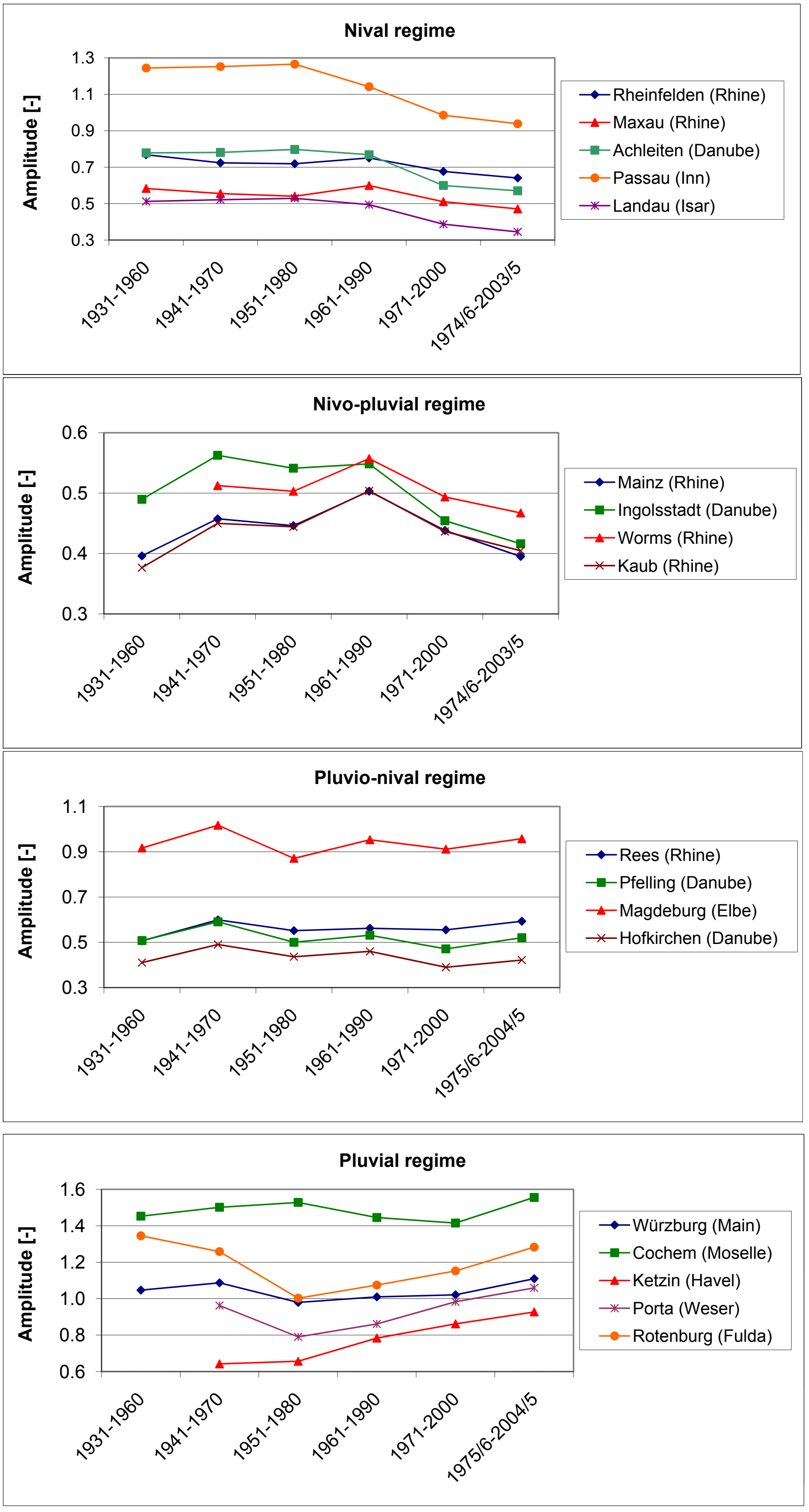

Fig. 11: Change in the amplitude of Pardé coefficient depending on the runoff regime

century. The changes, observed at the river gauges since the middle of the 20th century, cover most of the variability in runoff that have been recorded since observations started. They show a high correlation with observed changes in the regional climates. Therefore, it can be assumed that a good portion of the effect can be explained by climate change.

The identified changes depend on the type of the runoff regime. They partly induce increasing (snow melt dominated flow regimes) or decreasing seasonal variability (rain dominated flow regimes). In accordance with recent and projected future climate trends, summer Pardé coefficients decrease (consistent with a decrease in precipitation, inducing less runoff) while winter Pardé coefficients increase (consistent with an increase in precipitation, generating more runoff). A few exceptions were observed in the Danube catchment where partly opposite trends were observed.

The general findings of this study are constrained by the fact that – due to limited data availability and partly too short time series – time series of only 57 gauges within five large German river catchments were analysed. Unfortunately, not all important rivers in Germany could be covered by the investigation. Thus, local anomalies in climate trends might induce local trends in the runoff behaviour of local to regional scale catchments, despite contrasting large scale trends. In addition, at the same time, climate and land use may have changed. Mining activities and water management affected discharge behaviour as well. Therefore, detailed local analyses would be helpful to quantify catchment specific impacts of the different changes in the landscape on the regional flow regimes. Nevertheless, the results of this study indicate that the hydrological regimes of German rivers have started to change in the last decades due to climate change. Future climate change, assessed for example by the emission scenarios of the Intergovernmental Panel on Climate Change (IPCC 2007) and by regional climate changes projections (UBA 2007), will further affect the runoff regimes. Model based analyses of the effects of projected climate change on the runoff regimes are already available for many regions of Germany (e.g. Bormann 2009; Hattermann 2005; Middelkoop et al. 2001; Kwadijk and Rotmans 1995). For example, for the Elbe and Rhine rivers, simulations projected a continuation of the trends identified in this study such as an increase in the amplitude for pluvial flow regimes. They suggested that even runoff regime types could change in future due to climate change processes (e.g., from nival to pluvial flow regime).

Acknowledgements

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