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Flood trends along the Rhine: the role of river training

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Abstract. Several previous studies have detected positive trends in flood flows in German rivers, among others, at Rhine gauges over the past six decades. The presence and detectability of the climate change signal in flood records has been controversially discussed, particularly against the background of massive river training measures in the Rhine. In the past the Rhine catchment has been heavily trained, including the construction of the Rhine weir cascade, flood protection dikes and detention basins. The present study investigates the role of river training on changes in annual maximum daily flows at Rhine gauges starting from Maxau down to Lobith. In particular, the effect of the Rhine weir cascade and of a series of detention basins was investigated. By homogenising the original flood flow records in the period from 1952 till 2009, the annual maximum series were computed that would have been recorded had river training measures not been in place. Using multiple trend analysis, relative changes in the homogenised time series were found to be from a few percentage points to more than 10 percentage points smaller compared to the original records. This effect is attributable to the river training measures, and primarily to the construction of the Rhine weir cascade. The increase in Rhine flood discharges during this period was partly caused by an unfavourable superposition of the Rhine and Neckar flood waves. This superposition resulted from an acceleration of the Rhine waves due to the construction of the weir cascade and associated channelisation and dike heightening. However, at the same time, tributary flows across the entire Upper and Lower Rhine, which enhance annual maximum Rhine peaks, showed strong positive trends. This suggests the dominance of another driver or drivers which acted alongside river training.

1 Introduction

In recent years, considerable attention has been devoted in the hydrological literature worldwide and particularly in Europe to the detection and analysis of trends in flood characteristics such as annual maximum flows, maximum water stages or flood frequencies (Mudelsee et al., 2003; Pinter et al., 2006a, b; Petrow and Merz, 2009; Villarini et al., 2011; Bormann et al., 2011). In particular, the question of presence and detectability of a climate change signal in flood records has been controversially discussed (Petrow and Merz, 2009; Villarini et al., 2011).

Petrow and Merz (2009) detected spatially and seasonally coherent changes in maximum flood flows across Germany between 1951 and 2002 and argued that this spatially homogeneous and large-scale response may be caused by large-scale drivers such as climate variability. This hypothesis was further supported by the temporally consistent changes in flood-triggering atmospheric circulation patterns (Petrow et al., 2009). Recently, Hundecha and Merz (2012) attributed trends in maximum seasonal flows in a few small and mesoscale catchments in Germany to trends in the corresponding catchment average maximum precipitation, while for some catchments this link could not be found. Villarini et al. (2011) stated, however, that the presence of the climate change signal in flood flow records at many gauges, also in Germany, cannot be detected due to the presence of abrupt changes in observed time series. Several break points in mean and variance of the peak flow were detected for German gauges which were associated with non-climatic drivers such as the construction of reservoirs.

Over the past decades and even centuries, German rivers experienced extensive training, such as straightening and deepening of channels, and construction of reservoirs, flood protection dikes, wing dikes, detention basins and weirs

(Kalweit et al., 1993; HWSG, 1993; Lammersen et al., 2002; Helms et al., 2002; Bormann et al., 2011). Additionally, many catchments have been exposed to land use changes and progressive urbanisation. However, the impact of land use changes on flood flows in large basins is expected to be marginal (Bronstert et al., 2007). Applying trend analysis to the raw flood records, one would detect a bulk integral signal of all drivers of change, which makes it difficult to unambiguously and quantitatively interpret and attribute flood trends. Trend attribution is, however, a critical and difficult question in the analysis of flood changes, and should be more thoroughly and systematically addressed. Merz et al. (2012) proposed a hypothesis-testing framework for attribution of flood changes to the driving factors. It is comprised of three major ingredients: evidence of consistency of observed changes with drivers in question, evidence of inconsistency with alternative drivers, and provision of a confidence statement.

Separation of different drivers and evidence of consistency and inconsistency of detected changes with changes in driving variables has received some, although still very little, attention in the past. Mudelsee et al. (2003) investigated the impact of reservoirs in the Elbe and Oder catchments on the trends in occurrence of heavy floods, concluding that their influence is minor. Cunderlik and Burn (2004) and Pinter et al. (2006b) related flood characteristics to meteorological variables using correlation analysis, and attributed the changes in flood characteristics to changes in meteorological drivers. Recently, Hundecha and Merz (2012) used a model-based approach to attribute flood trends in several German catchments to changes in temperature and precipitation. They ran a semi-distributed hydrological model with combinations of stationary and non-stationary temperature and precipitation time series obtained from a multisite multivariate weather generator which considered the observed changes in meteorological drivers.

Land use changes and river engineering effects on flood flows are even more difficult to isolate in urbanised catchments primarily due to the lack of detailed historical information on land use changes, changes to river channels, construction of reservoirs and flood protection structures. Even if data is available from local authorities, it remains highly fragmented and incomplete, and its retrieval is highly laborious.

The widely used specific gauge analysis (SGA) (Pinter and Heine, 2005; Pinter et al., 2006a, b; Bormann et al., 2011), which shows changes in stages for specific discharge values along time, is capable of revealing the effect of river engineering on flood stages. It thus also indicates the potential influence on flood discharges, but the quantification of this influence is not possible with SGA. It can only be used to prove the inconsistency of changes in flood discharges with river engineering measures if no changes in specific stages are detected. Moreover, SGA reflects changes in flood characteristics only due to river training measures affecting the reach where the gauge is located. The impact of upstream changes in the river network is not revealed by this sort of analysis. Instead a more comprehensive assessment of the past changes is required for reconstructing the river system states at different points in time in order to isolate the river training effect.

Remo and Pinter (2007) and Remo et al. (2009) developed the "retro-models" for the Mississippi River and investigated the effect of river engineering measures and changes in land cover on flood stages. A similar effort was undertaken for the Rhine (Busch and Engel, 1987; HWSG, 1993; BfG, 1999; Lammersen et al., 2002) in order to investigate the effect of river training on flood flows, particularly the effect of construction of the weir cascade and detention basins in the second half of the 20th century. Based on the results of hydraulic models for different river states, homogenised discharges were calculated for selected flood events – discharges that would have occurred if river engineering measures had not taken place (BfG, 1999; Lammersen et al., 2002). These studies focused on the analysis of changes in flood frequencies, and did not address the impact of river training on flow trends.

The training of the Rhine was associated with increasing flood peaks due to (i) weaker flood wave attenuation and (ii) superposition of flood waves of the main channel and tributaries, particularly the Neckar (Kalweit et al., 1993; IKSR, 1997). First documented in a technical report based on the reconstruction of a selected flood wave from 1882 (Kalweit et al., 1993), this assertion was replicated in the peer-reviewed literature (Disse and Engel, 2001; Lammersen et al., 2002; Villarini et al., 2011). The acceleration of flood peaks, i.e. the reduction of arrival times, was mentioned (Belz et al., 2001; Lammersen et al., 2002) but not investigated in the peer-reviewed literature. The reduction of several hours may not necessarily imply that the effect of acceleration is noticeable on the enhancement of the mean daily flows. Therefore, we investigate the role of acceleration on changes in mean daily flows, for which trend analyses are usually performed.

The impact of river training on flood discharge trends, which are often readily associated with climate signals, was not systematically investigated. Based on the unique available analyses of Rhine discharges homogenised for several stages of river engineering (HWSG, 1993; BfG, 1999; Lammersen et al., 2002), maximum daily flood flows in the period from 1952 to 2009 were reconstructed that would have occurred had river training measures not been in place. Flood trends in the originally recorded time series and in the homogenised time series were compared, thus signaling the river training effects. Finally, we investigated which mechanisms led to the peak flow changes as a consequence of river engineering. In particular, we analysed whether the superposition of flood waves in the Rhine channel and the tributaries caused a systematic amplification of peak flows, and thus enhanced flood trends.

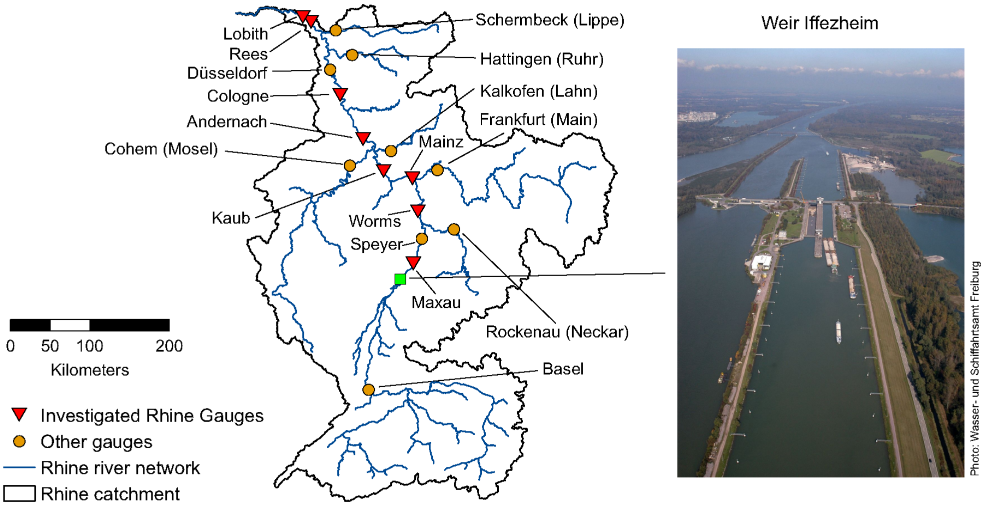

Photo: Wasser- und Schiffahrtsamt Freiburg

Fig. 1. Study area of the Rhine catchment with the river network and location of the major gauges.

2 Data and methods

2.1 Study area

The Rhine has been extensively trained over the past centuries, with the first engineering structures dating back to the Roman times (Kalweit et al., 1993). Massive channel straightening and floodplain constriction due to dike construction was undertaken in the early 19th century. Starting in 1932, a cascade of 10 weirs and hydropower plants was erected on the Upper Rhine between Basel and Maxau, with the last weir, Iffezheim put into operation in 1977 (Fig. 1). Eight of 10 weirs were constructed between 1955 and 1977.

Acknowledging the increased flood hazard due to the loss of 130 km^2 of natural floodplain, which comprise about 60 % of all available natural storage (IKSR, 1997), the International Commission for the Protection of the Rhine (ICPR) adopted a plan for the construction of a series of detention basins between Basel and Worms with a total storage capacity of 288×10^6 m^3. By 1998 the capacity of 91.3×10^6 m^3 was realised in order to compensate the adverse effects of river engineering in the upstream reaches (BfG, 1999; Lammersen et al., 2002). In exceptional cases, during catastrophic floods, a further 25×10^6 m^3 can be activated (BfG, 1999). In total, the retention volume in the Upper and Lower Rhine amounted to 160×10^6 m^3 by the year 1995, and was gradually increased to 211×10^6 m^3 by 2005 and 229×10^6 m^3 by 2010 (IKSR, 2012). A more detailed description of the Rhine regulation history is given by Kalweit et al. (1993), HWSG (1993), Lammersen et al. (2002) and Bormann et al. (2011).

2.2 Flood flow homogenisation

In recent Rhine history, five periods with distinct flow regimes can be distinguished: (1) prior to 1955, (2) between 1955 and 1977, (3) from 1977 to 1998, (4) from 1998 to 2005, and (5) after 2005. The years 1955 and 1977 mark the start and end points of extensive weir construction, whereas 1998 and 2005 were selected to mark the progress in the construction of detention basins. BfG (1999), Lammersen et al. (2002) and HWSG (1993) homogenised flood discharges for selected flood events at gauges along the Rhine. The studies used two numerical models: the hydrological routing model SYNHP developed for the reach Basel–Cologne (LWRP, 1990a, b), and the one-dimensional hydrodynamic model SOBEK applied to the reach Andernach–Lobith (Barneveld and Meijer, 1997). These routing models were set up for river conditions in the five mentioned training periods. The hydrological routing model SYNHP simulates the translation and attenuation of the flood waves through the channel represented by a storage cascade. It considers the effect of river engineering on channel morphology through the calibration of the storage coefficients. Detention areas are represented by the area–volume relationships. Thirty historical flood events ranging from a 3 yr to a 50 yr flood were used for model calibration for the Rhine stage before 1955 (LWRP, 1990a). The accuracy of peak flow simulation was in the range of approximately ±2 % (LWRP, 1990a). The hydrodynamic model SOBEK explicitly describes channel geometry with cross sections, and uses calibrated roughness coefficients and detention basin storages to capture river training effects. Both routing models used flow hydrographs in the main channel and tributaries as boundary conditions. By simulating a number of historical floods for different stages of river training, a set of homogenised flood peak flows was constructed.

The homogenised peak discharges were regressed to the originally recorded flows for these events. In this way, linear regressions between the observed and reconstructed peak flows were derived at each gauge. The reconstructed peak discharges represent those that would have occurred if

Table 1. Homogenisation relationships for Rhine gauges for different stages of river training. Number of events indicates the sample size of historical events used to derive a homogenisation relationship.

Gauge	Relationship	r^2	Number of events	Based on data from
Maxau	$Q_{1955} = 0.8286 \cdot Q_{1977} + 351.06$	0.98	79	HWSG (1993)
Maxau	$Q_{1955} = 0.9923 \cdot Q_{1998} - 180.12$	0.94	40	HWSG (1993)
Maxau	$Q_{1955} = 1.0173 \cdot Q_{2005} - 172.61$	0.99	26	HWSG (1993)
Worms	$Q_{1955} = 0.7353 \cdot Q_{1977} + 751.66$	0.94	79	HWSG (1993)
Worms	$Q_{1955} = 0.7533 \cdot Q_{1998} + 747.2$	0.91	39	HWSG (1993)
Worms	$Q_{1955} = 1.0571 \cdot Q_{2005} - 1.333$	0.96	26	HWSG (1993)
Mainz	$Q_{1955} = 0.8605 \cdot Q_{1977} + 411.87$	0.98	67	HWSG (1993)
Mainz	$Q_{1955} = 0.8823 \cdot Q_{1998} + 315.23$	0.98	26	HWSG (1993)
Mainz	$Q_{1955} = 0.9153 \cdot Q_{2005} + 284.75$	0.98	14	HWSG (1993)
Kaub	$Q_{1955} = 0.8698 \cdot Q_{1977} + 386.13$	0.98	67	HWSG (1993)
Kaub	$Q_{1955} = 0.8885 \cdot Q_{1998} + 310.07$	0.98	26	HWSG (1993)
Kaub	$Q_{1955} = 0.9389 \cdot Q_{2005} + 179.39$	0.99	14	HWSG (1993)
Andernach	$Q_{1955} = 0.9202 \cdot Q_{1977} + 333.89$	0.98	41	HWSG (1993)
Andernach	$Q_{1955} = 0.9153 \cdot Q_{1998} + 359.85$	0.98	17	HWSG (1993)
Andernach	$Q_{1955} = 0.9986 \cdot Q_{2005} - 243.39$	0.98	10	HWSG (1993)
Cologne	$Q_{1955} = 0.9623 \cdot Q_{1977} + 52.21$	0.98	35	BfG (1999)
Cologne	$Q_{1955} = 0.9969 \cdot Q_{1998} - 289.34$	0.98	18	BfG (1999)
Cologne	$Q_{1955} = 0.9922 \cdot Q_{2005} - 194.11$	0.98	10	HWSG (1993)
Rees	$Q_{1955} = 0.9809 \cdot Q_{1977} - 73.57$	0.99	35	BfG (1999)
Rees	$Q_{1955} = 1.0273 \cdot Q_{1998} - 557.19$	0.99	16	BfG (1999)
Lobith	$Q_{1955} = 0.9827 \cdot Q_{1977} - 89.76$	0.98	35	BfG (1999)
Lobith	$Q_{1955} = 1.0111 \cdot Q_{1998} - 368.15$	0.99	20	BfG (1999)

construction of the weir cascade and detention basins had not taken place. We complemented the regression relationships for Cologne, Rees and Lobith based on the data from BfG (1999) with those for Maxau, Worms, Mainz, Kaub and Andernach based on data from HWSG (1993) (Table 1). The figures for regressions are provided in the Supplement. The regressions relate the flood flows as they would be prior to the construction of the weir cascade (Q_{1955}) to the flows corresponding to the river state after the construction of the cascade (Q_{1977}) as well as after the implementation of the detention basins with the volume corresponding to the years 1998 (Q_{1998}) and 2005 (Q_{2005}). The compiled linear regressions typically show very high coefficients of determination r^2 between 0.91 and 0.99. By applying the homogenisation relationships to the entire annual maximum flow series, a unique homogenised dataset of annual maximum flood flows was compiled here, which allows for the effect of river training on flood flows for a series of Rhine gauges to be isolated for the first time. This annual maximum series (AMS) refers to the Rhine conditions prior to 1955, and represents the river state before the major training measures were put in operation.

The major construction of the Rhine weir cascade took place gradually between 1955 and 1977. Since no detailed information is available on the impact of each particular weir within this period, the application of the homogenisation relationships introduces uncertainty. The same applies to the construction of the detention basins that gradually progressed from 1977 till present day. To represent this uncertainty, four scenarios were considered which cover a complete extent of possible river states and effects on flood flows.

The homogenisation relationships relating Q_{1955} to Q_{1977}, which reflect the impact of the weir cascade, were applied (1) starting from 1955 and (2) from 1977. These two extreme scenarios imply that the entire weir cascade was put into operation in the years 1955 and 1977. The real impact on flow trends would be somewhere between those two extremes, but probably more towards the assumption of the 1977 starting point. Analogously, the homogenisation relationships relating Q_{1955} to Q_{1998}, which consider the accumulated effect of the weir cascade and the detention basins built up to 1998, were applied (1) starting from 1977 and (2) from 1998. The combination of these assumption results in four different scenarios of river training impact: (s1) 1955/1977, (s2) 1977/1977, (s3) 1955/1998 and (s4) 1977/1998, for which the combination of years refers to the assumption of the operation start of the weir cascade and detention basins, respectively. The flood events after 1999 were relatively small and were not affected by detention basins. Hence, the homogenisation relationship for the year 2005 was not applied to the recorded discharges and was not considered in the scenario set.

After the operation of the detention basins was assumed, the homogenisation relationships were applied to discharge values above the threshold at gauge Maxau of

$Q = 3800\,\mathrm{m^3\,s^{-1}}$, which approximately corresponds to a return period of 10 yr. Below this threshold the detention basins are not activated and do not affect peak flows (BfG, 1999).

2.3 Monotonic trends, change point and variability analyses

We investigated the changes in flood trends between the homogenised AMS and original historical records. Since the trend sign and trend significance are typically sensitive to the selected start and end year, i.e. to the selected time period, multiple trend tests were applied. Multiple trend matrices indicate trends and their significance for multiple time periods with the minimum of 30 yr between 1952 and 2009.

Statistical significance of monotonic trends in flood time series was tested by the Mann–Kendall test with the two-sided option and 5 % significance level. Trends in discharge were characterised by the slope of the Kendall–Theil robust line (KTRL) (Theil, 1950), also known as Sen's slope (Sen, 1968). It is defined as the median of all pairwise slopes between distinct points in a time series. Significance of the linear model representing the monotonic change was additionally tested by performing the Mann–Kendall test on the residuals between the time series and KTRL. If the Kendall test statistic is significantly different from zero, the significant monotonic trend is described by the model other than linear.

It is widely acknowledged that the presence of serial correlation in a time series may affect the significance test and result in less frequent rejection of the null hypothesis (Yue et al., 2003; Khaliq et al., 2009; Önöz and Bayazit, 2012). Several approaches can be used to account for serial correlation such as prewhitening (PW), trend-free prewhitening (TFPW), variance correction (VC) and bootstrap methods (see Khaliq et al., 2009, for a review). Whereas the first two approaches assume and correct only the presence of autocorrelation with lag 1, the variance correction and bootstrap methods correct for presence of high-order serial correlation. In this study we applied the block bootstrap method as recommended by Kundzewicz and Robson (2004) and Khaliq et al. (2009) to account for the high-order dependencies. Lags with statistically significant serial correlation were identified with the Ljung–Box test (Ljung and Box, 1978) under 5 % significance level. The test statistic LB is given in Eq. (1):

$$LB = T(T+2)\sum_{k=1}^{L}\frac{r_k^2}{T-k}, \tag{1}$$

where T is the length of a time series, L is the total number of investigated lags and r_k is the autocorrelation at lag k. In the absence of autocorrelation in a time series, the test statistic follows the χ^2 distribution with k degrees of freedom.

Autocorrelation for lags up to one-quarter of the total time series length was tested. Higher-order autocorrelations are considered statistically unreliable. The block size for the block bootstrapping was taken as $m+1$, where m is a number of contiguous significant lags of autocorrelation function. Sensitivity tests with different block sizes revealed negligible differences in test outcomes, as also supported by Khaliq et al. (2009). Instead of resampling with replacement we applied a more stringent resampling without replacement. It allows also for having blocks of different size in case the remainder from the division of the number of elements in a time series by the block size is different from zero.

The impact of river training on the trend magnitude was assessed by the relative change in flood flows, which was computed by relating the difference in flood discharge given by KTRL to the mean flood discharge in the tested period (Eq. 2):

$$\Delta Q_\mathrm{r} = \frac{Q^*_\mathrm{endyear} - Q^*_\mathrm{startyear}}{\overline{Q}} \times 100\,\%, \tag{2}$$

where ΔQ_r is the relative change of discharge in the investigated time period, Q^* are the values of the estimated trend line in the last and the first year of investigation period, and $\overline{Q}$ is the mean flood discharge.

Abrupt changes in mean of the time series were investigated by using the non-parametric Pettitt test (Pettitt, 1979). The Pettitt test proves the hypothesis of whether two pieces of a time series $Q_1, \ldots, Q_i$ and $Q_{i+1}, \ldots, Q_T$ separated at a certain point i come from the same population (or distribution). If the hypothesis is rejected under a certain confidence level, the point i is considered to be a change point. The test statistic $U_{t,T}$ is given by Eq. (3):

$$U_{t,T} = \sum_{i=1}^{t}\sum_{j=i+1}^{T} D_{ij}, \tag{3}$$

where $D_{ij} = \mathrm{sgn}(Q_i - Q_j)$.

Instead of checking the significance of the most probable change point corresponding to the maximum absolute value of the test statistic, we check the significance of a change point in any specific year. We applied the robust resampling method to compute significance probabilities for having a change point in any year within the investigation period. For this, 10 000 permutations of the original time series were generated, for which the test statistic (Eq. 3) was computed. The test statistic based on the original time series was compared to the empirical distribution of the test statistic resulting from the permutations. Significance probability of a change point is given by the corresponding percentile of the original statistic.

Finally, the change in variability of flood flows due to river training was analysed by comparing the 10 yr running mean of the coefficient of variation (CV). The running mean over the time window of 10 yr was computed for all four scenarios, and reveals the effect of the weir cascade and detention basins on variability of flood flows.

Table 2. Year of the most significant change point at 5 % significance level in original and homogenised time series. A dash indicates no significant change point.

Gauges	Original	s1 (1955/1977)	s2 (1977/1977)	s3 (1955/1998)	s4 (1977/1998)
Maxau	1976	1976	–	1976	–
Worms	1976	1976	1976	1976	1976
Mainz	1976	1976	1977	1976	1977
Kaub	1976	1976	1977	1976	1977
Andernach	1976	1979	–	1978	–
Cologne	1978	1978	–	1979	–
Rees	1978	1978	–	1978	–
Lobith	1978	1978	1978	1978	–

3 Results and discussion

Multiple trend matrices for the original non-homogenised annual maximum flow series at gauges Maxau, Worms, Mainz, Kaub, Andernach, Cologne, Rees and Lobith are summarised in Fig. 2 (A1–H1). They show for all gauges periods of statistically significant flood increase starting from around 1955 till 2009, and at gauges downstream of Worms additionally from around 1970 till 2005, with relative changes up to 40 to 60 %. For all significant trends the linear model (KTRL) is suitable for describing the relative change in flood flows. For the longer terms starting at the beginning of the 1950s up until 2009, only a few positive flood trends with moderate relative changes from a few percentage up to about 30 % are detected. Generally, the study period is dominated by positive trends for all gauges. Only the trends in the last decades starting from the late 1970s to late 2000s are negative, although this period includes two major Rhine floods in 1993 and 1995.

3.1 Impact of the Rhine weir cascade and detention basins

Trend matrices for scenarios s1 (1955/1977) to s4 (1977/1998) (Fig. 2, A2–A5:H2–H5) indicate the difference in relative change between homogenised time series and original recorded flows. Negative values, for example, denote smaller relative change in homogenised time series compared to the original ones. It should be noted that a smaller relative change does not necessarily imply smaller mean flood discharge value within a certain period. It solely describes the change in flow within a period as given by the Kendall–Theil robust line. In this analysis we focus on changes in trends and not on the impact on mean flows or flood quantiles.

Figure 2 shows a dampening effect of homogenisation on positive relative discharge changes in original records for all gauges starting from Maxau and extending downstream to Cologne. This corresponds to an enhancement of flood trends due to river training measures that ranges from a few percentage points in scenarios s1 (1955/1977) and s3 (1955/1998) to more than 10 percentage points in scenarios s2 (1977/1977) and s4 (1977/1998). This range represents the uncertainty caused by variation in the time of construction of the Rhine weirs and detention basins. However, the strongest impact of the weir cascade on flood flows is expected around the year 1977 (s2/s4), when the last and the largest weir, Iffezheim, was constructed.

As suggested by Villarini et al. (2011), the construction of the weir cascade lead to a change point in mean of the flood time series at several gauges around the year 1977. Indeed, all Rhine gauges exhibit an abrupt change at 5 % significance level towards increasing flows in the original recorded flood flows (Table 2).

The change-point analysis of the homogenised time series shows an impact of homogenisation on the significance of change points in flood flows in the late 1970s (Table 2). For two scenarios, the homogenisation has no impact on change-point significance (s1, s3). In another two scenarios – s2 and s4 – the change points remain significant at 4 and 3 gauges, respectively. This suggests that the completion of the Rhine weir cascade has influenced the flow time series, but its impact coincides with a positive change in flood flows caused by other drivers than river training. This is further corroborated by the analysis of tributary flows corresponding to the Rhine peak discharges (Fig. 6, A4–F4), which shows strongly positive trends for periods starting in the 1960s and 1970s, and negative trends for periods starting in the 1950s and late 1970s. Hence, the entire Rhine catchment experienced increasing flood flows in the period from the 1960s to around 2000, which is a sign for a large-scale driver such as, for example, climate variability or change.

A few time periods in the multiple trend analysis, particularly those starting in the late 1970s, exhibit negative trends in original records (Fig. 2, A1–H1). The homogenisation makes the negative trend slopes gentler, which results in positive differences in relative changes for all scenarios: the upper-right corner of all panels (A2–H5) shows positive values of a few percentage points. The negative trends in the original records are a result of the high floods in the late 1970s compared to the first decade of the 21st century.

An increase in floodplain storage has a relatively small influence on changes in flood trends. This is inferred from

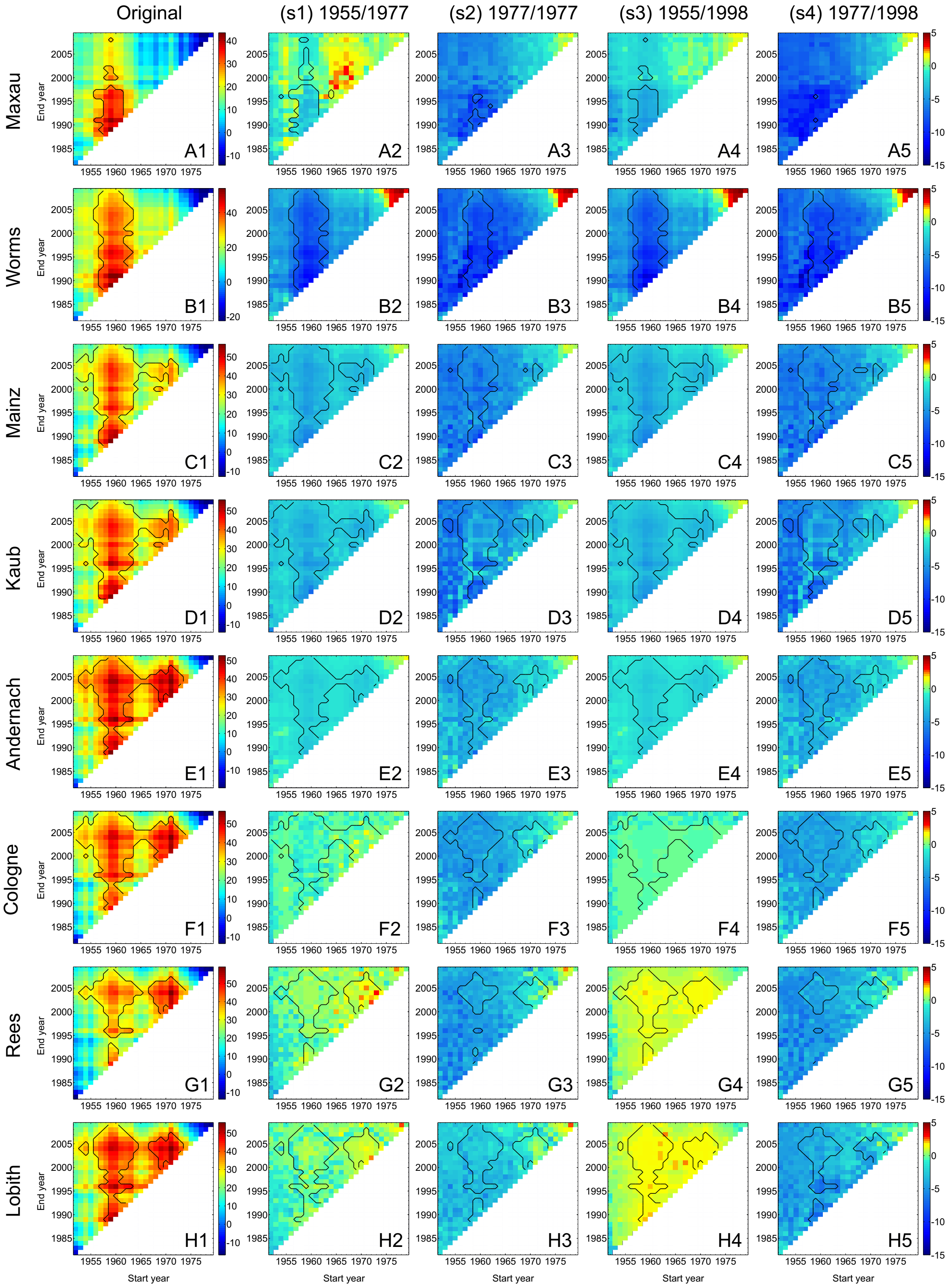

Fig. 2. Multiple flood trends for Rhine gauges with relative change in [%](A1–H1) and shifts in relative changes in [percentage points] for different homogenisation scenarios with respect to the original time series. Legends in A5–H5 apply to A2–H2:A5–H5. Black contour lines encompass the regions of statistically significant monotonic trends in original and homogenised flood flow series.

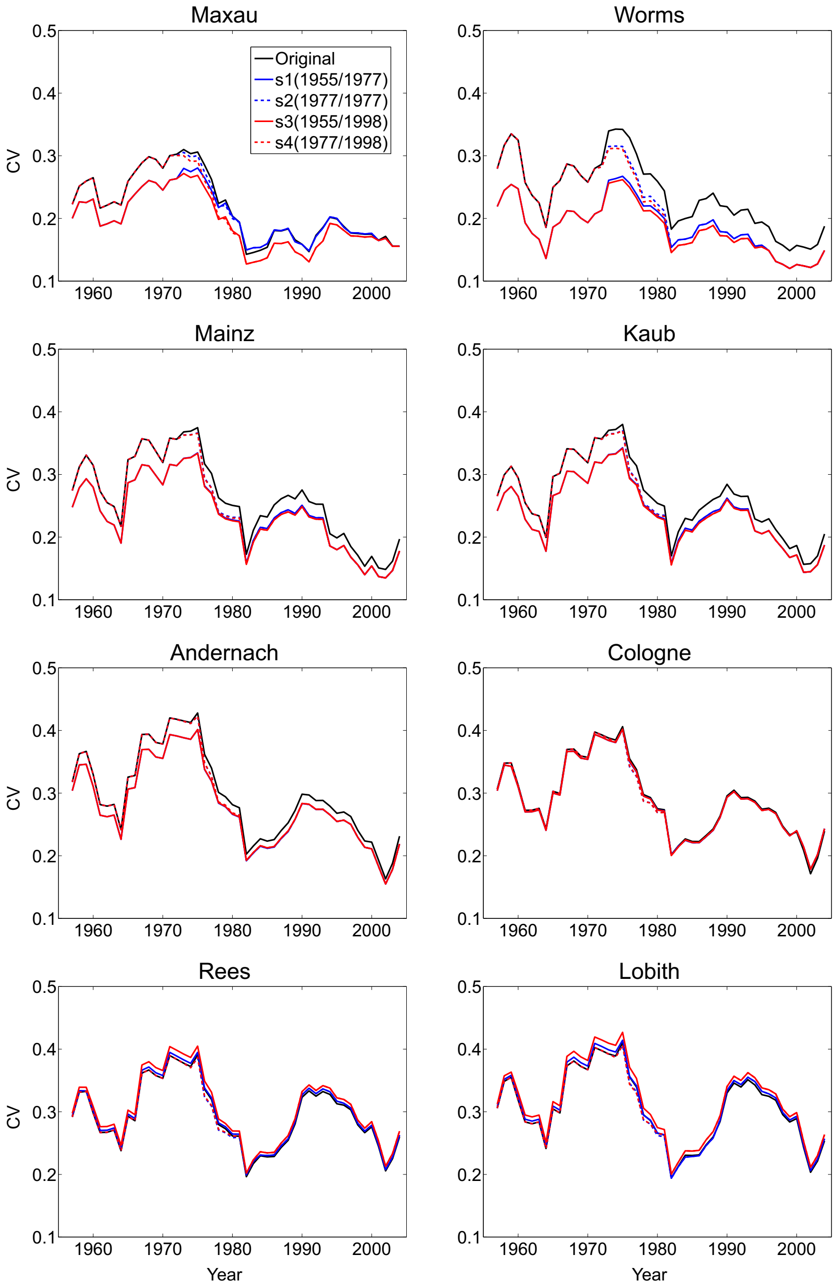

Fig. 3. Ten-year running mean of the coefficient of variation (CV) of annual maximum flows at Rhine gauges.

comparing the scenarios s1 (1955/1977) to s3 (1955/1998) and s2 (1977/1977) to s4 (1977/1998), respectively. The variation of the starting point for the detention basin deployment (1977 vs. 1998) does not result in notable changes of flood trends for time periods up to 1998. In fact, Fig. 2 does not allow for the effect of detention basins beyond 1998 to be discerned, because the homogenisation relationships, which considers the effect of detention basins, were applied to all scenarios. After 1998 the discharge for only one flood event in 1999 was adjusted at a few gauges during homogenisation. All other flood events after 1999 were below the adopted threshold value for detention basin deployment at gauge Maxau. It is therefore very unlikely that the enhanced floodplain storage capacity exerted a notable impact on trends beyond 1998. This suggests that the changes in flood trends revealed by homogenisation are rather attributable to construction of the Rhine weir cascade than to deployment of the detention basins.

It can be generally observed that the number of periods with statistically significant trends (the area encompassed by the contour lines) decreases in the homogenised time series compared to the original records. The loss of significance is stronger for the scenario s2 (1977/1977) and s4 (1977/1998) compared to s1 (1955/1977) and s3 (1955/1998), respectively. As for the trend magnitudes, the assumption of the entire weir cascade starting its operation in 1977 exerts a stronger impact on the trend significance and results in fewer periods for which the change signal is discernible from the background noise.

Comparing the scenarios s1 (1955/1977) to s2 (1977/1977) and s3 (1955/1998) to s4 (1977/1998) (Fig. 2) also suggests that the effect of the weir cascade on the number of periods with significant trends is much stronger than the effect of the detention basins. The variation of the detention basin operation starting point results in nearly no difference in the significance of trends.

The analysis of flood flow variability expressed in terms of the 10 yr running mean of the coefficient of variation (CV) shows that the Rhine weir cascade seems to exert a much stronger impact compared to the detention basins for upstream gauges Maxau and Worms (Fig. 3). This can be inferred from comparing the difference between e.g. scenarios s2 (1977/1977) and s4 (1977/1998), which reflects the effect of the detention basins on flood variability. This difference is much smaller than the difference between e.g. scenario s2 (1977/1977) and the original record, or between scenario s1 (1955/1977) and the original record that indicates the effect of the weir cascade.

As for the trend magnitude, the difference in variability between the original and homogenised time series is greater for the gauge Worms compared to Maxau, and further dissipates downstream, becoming nearly indistinguishable at Cologne. This suggests that not only the construction of the weir cascade but also another intruding process between gauges Maxau and Worms enhances the flood intensity and variability. This may be the superposition of the Rhine and Neckar flood waves indicated by Belz et al. (2001), Disse and Engel (2001) and Lammersen et al. (2002), and will be investigated in the next section.

3.2 Analysis of flood wave celerity and wave superposition

As mentioned in the Introduction, several authors assume that the acceleration of Rhine flood waves due to the construction of the weir cascade lead to the superposition of the Rhine and Neckar flood waves, and that this had a major impact on the enhancement of flood flows. In order to investigate whether there is indeed a detectable change in the arrival time of flood waves at the Rhine–Neckar confluence, the time difference in days between the peak flow record at gauge Basel upstream of the Rhine weir cascade and gauge Maxau was analysed for the presence of an abrupt change (Fig. 4a).

A change point in 1980 was detected at the 95 % confidence level. This suggests an acceleration of Rhine flood waves between Basel and Maxau. A reduction of the arrival time of one day on average was observed for this Rhine reach. Additionally, the wave celerity in the Neckar was tested for changes in relation to the gauge of Basel (Fig. 4b). No significant changes in the arrival time of the Neckar floods, which correspond to the peak flows at gauge Basel, were detected. Thus, it can be concluded that only the Rhine waves have experienced a noticeable acceleration. Does this imply that the Rhine wave is superposed with the Neckar flood waves and maybe some other tributary waves? Do these superpositions systematically enhance the Rhine floods?

To answer these questions, multiple trend analyses were carried out for the flow series extracted for the gauges at Rhine tributaries directly downstream of the respective Rhine gauge (Fig. 1). The following gauge pairs in the main channel and the tributary were considered:

- Speyer (Rhine) – Rockenau (Neckar)
- Worms (Rhine) – Frankfurt (Main)
- Kaub (Rhine) – Kalkofen (Lahn)
- Kaub (Rhine) – Cochem (Mosel)
- Düsseldorf (Rhine) – Hattingen (Ruhr)
- Düsseldorf (Rhine) – Schermbeck (Lippe).

In total, four time series were extracted at each tributary gauge from the daily flow series: flows corresponding to the annual Rhine peak at the nearest upstream Rhine gauge (1) with a 1-day negative time lag between the Rhine peak and tributary gauge record (Lag -1), flows (2) recorded at the same day at the tributary gauge (Lag 0), and (3) with a 1-day positive time lag between the Rhine peak and tributary gauge record (Lag $+1$). Finally, (4) discharge series containing the maximum flows in the time window of ± 3 days around the Rhine peak was selected. This time window is sufficient to encompass the tributary flood hydrographs corresponding to a flood event in the main channel. Schematically, one possible constellation of the matching Rhine and tributary hydrographs is depicted in Fig. 5.

The first three cases (Lag -1, Lag 0 and Lag $+1$) cover all possible combinations of how long the propagation of a flood wave requires to get from the recording gauge to the confluence in both the main channel and the tributary. For example, if a flood peak in the main channel needs one day to reach the confluence and a peak in a tributary arrives at the confluence on the same day, the corresponding flows of the tributary, which match the Rhine peak, would be contained in the Lag -1 time series. For the case of the same time required to reach the confluence, the main channel peak would meet the Lag 0 discharges at the confluence. Now, if we have an unfavourable superposition of flood waves, then we should see significant positive trends in at least one of the first three extracted discharge series, and at the same time no significant trends in the time series with the maximum flows

Table 3. "Mean ratio" indicates the long-term mean contribution of the tributary flow in precentage to the Rhine discharge for annual maximum flow events.

Gauges	Speyer/ Rockenau (Neckar)	Worms/ Frankfurt (Main, from 1964)	Kaub/ Kalkofen (Lahn)	Kaub/ Cochem (Mosel)	Düsseldorf/ Hattingen (Ruhr, from 1968)	Düsseldorf/ Schermbeck (Lippe, from 1964)
Mean ratio Lag −1/0/1	19/13/11	18/19/18	5.3/4.4/3.6	36/34/29	5.3/4.4/3.7	2.6/2.4/2.2

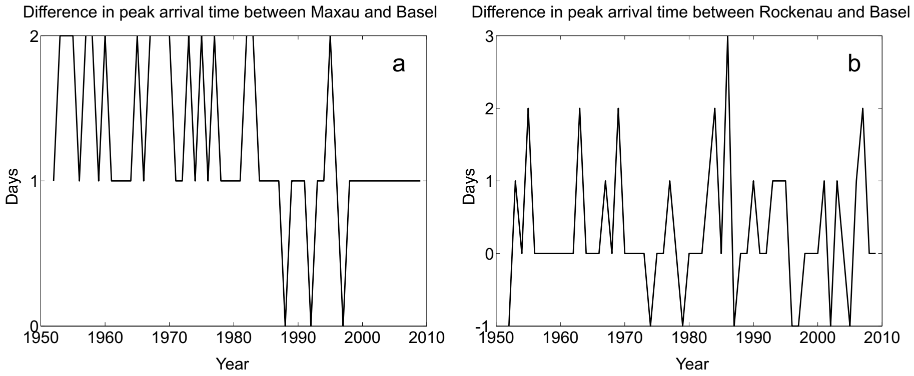

Fig. 4. Difference in the arrival time of flood peaks at Maxau and Rockenau (Neckar) in relation to the gauge Basel.

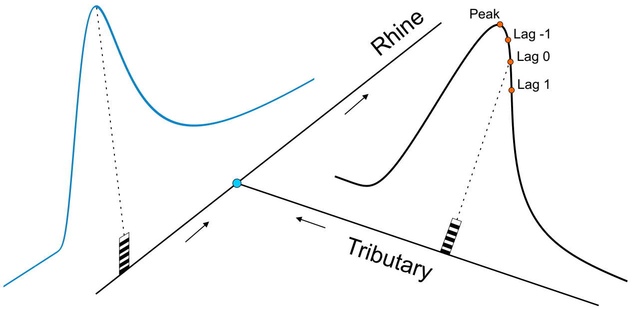

Fig. 5. Schematic representation of a possible matching of Rhine and tributary hydrographs and indication of the extracted tributary time series.

of the corresponding events. Changes in the maximum tributary flows corresponding to annual maximum discharges in the main channel reflect changes in the tributary catchments.

The results of the multiple trend tests for the Lag −1/0/1 time series for six gauge pairs indicate strong positive trends nearly for all time periods (Fig. 6).

For the Rhine–Neckar confluence the trends particularly for the Lag −1 discharge are strongly positive (Fig. 6, A1). However, the trends in the peak flows of the corresponding flood events at the gauge Rockenau also exhibit pronounced positive trends (Fig. 6, A4), which are weaker than for the Lag −1 series. This suggests that besides the systematic wave superposition, the Rhine annual flood peak flows are enhanced by increasing corresponding Neckar discharges. The wave superposition seems indeed to play a role that is indicated by the larger contour-line area on the Lag −1 and Lag 0 multiple trend plots compared to the trends in the corresponding peak flows. However, it is not the only reason for increasing Rhine discharges. The strong relative changes in flows of major tributaries of up to 100 % since the 1960s clearly indicate the increasing contribution of tributary waters. In particular, the Neckar, Main and Mosel can contribute on average up to one-quarter or even one-third of the Rhine peak discharge as shown for the respective gauges Rockenau, Frankfurt and Cochem in Table 3. For the latter two tributaries, no clear indication of wave superposition was detected from the multiple trend analyses.

The tributaries Lahn, Ruhr and Lippe appear to contribute on average not more than 5–6 % of the Rhine peak flow, and can be regarded as insignificant for enhancing Rhine floods. However, they also exhibit positive trends for multiple periods. Moreover, the periods for which positive and negative flood trends are detected seem to be consistent across the tributaries (Fig. 6, A4–F4). This suggests the impact of a large-scale driver such as climatic variability/change. However, also other changes such as land use and river training in the tributary catchments may have affected the trends in tributary flows.

4 Conclusions

In this work, a unique set of homogenisation relationships was compiled for eight gauges along the Rhine. They were applied to the original discharge records to produce homogenised series of maximum annual flows that would occur if the construction of the Rhine weir cascade and a series of

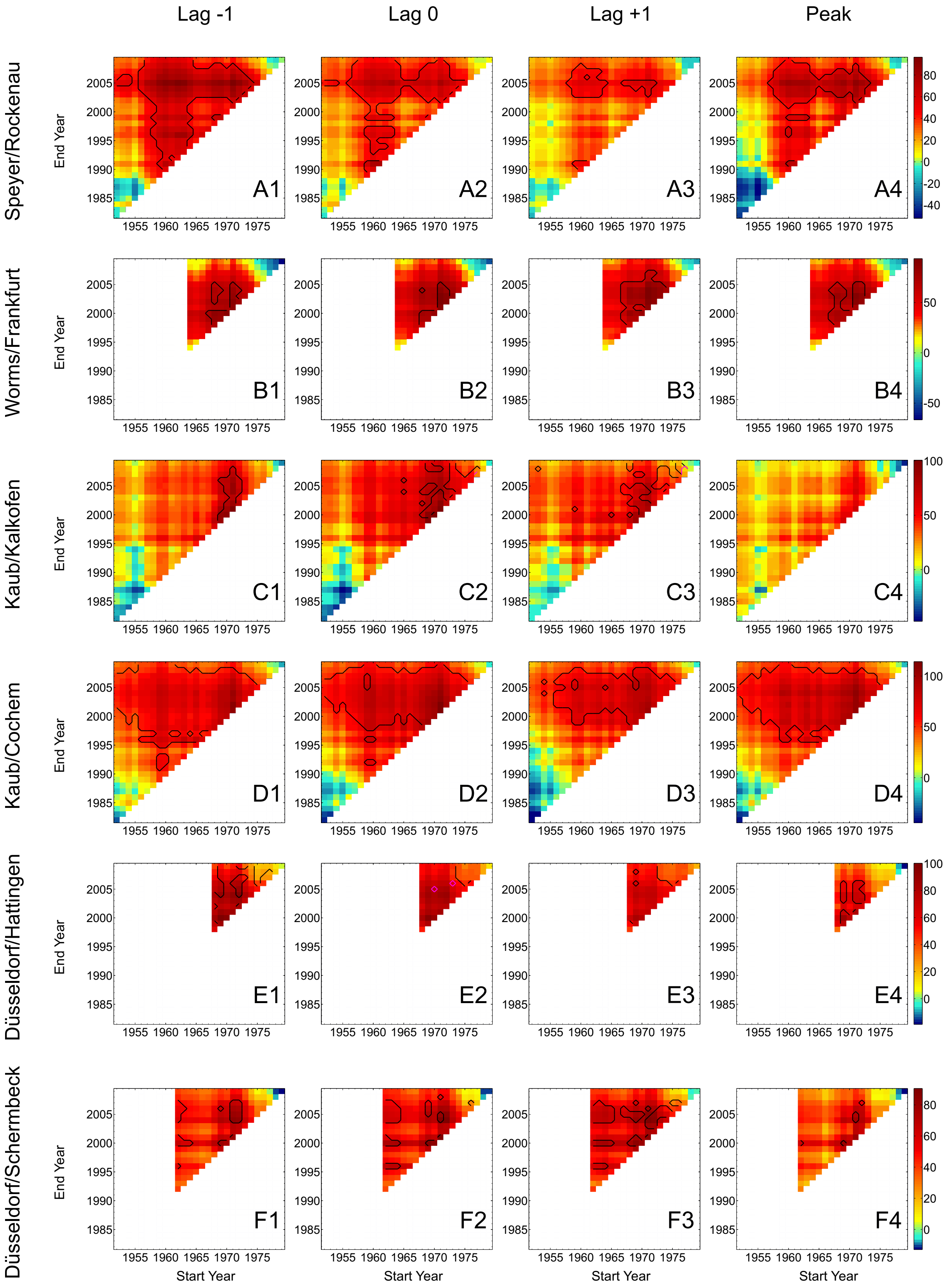

Fig. 6. Multiple flood trends in discharge series corresponding to the Rhine annual peak flows with −1/0/+1 day lag and in maximum discharge series of the corresponding tributary flood event. Black contours encompass the regions of statistically significant trends. Pink contours show the periods of significant monotonic trends for which the linear model (KTRL) is not significant.

detention basins had not taken place between 1955 and 2009. Based on the comparison between original and homogenised flood time series, it is possible to single out the effect if river training on flood trends.

The construction of the Rhine weir cascade was found to substantially impact flood trends for multiple periods between the 1950s and 2009. The relative changes from a few percentage points to more than 10 percentage points in the original flow records at several gauges are attributable to the impact of river training. Moreover, trends for some periods in the multiple trend analysis were found to be not statistically significant in the homogenised time series. The construction of the weir cascade also increased the variability of the maximum annual flows. However, the effect on the flood magnitude and variability dissipates from the gauge Worms downstream of Cologne, where little difference in flood flow trends between the original and homogenised discharges was found.

The impact of the detention basins is much smaller compared to the effect of the weir cascade on both trend magnitude as well as on flow variability. Only a few flood events in the past exceeded the threshold discharge at the gauge Maxau and were dampened by deployment of the detention basins. The uncertainty associated with the assumption of the time point of detention basin construction was found to be very small, which confirms the small effect of the detention basins.

The analysis of abrupt changes in the mean of the original and homogenised time series revealed statistically significant change points towards increasing flows in the gauges of the late 1970s. The homogenisation of flood flows affected the significance of detected change points at some gauges depending on the selected scenario, whereas others were not affected. From this it can be inferred that abrupt changes in flood flows are not necessarily an indication of human interference in the river systems. It was shown that the completion of the Rhine weir cascade is likely to coincide with the abrupt change towards increasing flood flows. Increasing flood trends were also detected in this period for the tributary flows which correspond to the Rhine flood peaks.

The systematic superposition of the Rhine and Neckar flood waves was found to enhance flood trends in the mean daily annual maximum flows. The wave superposition is caused by the acceleration of Rhine flood waves between Basel and Maxau due to the construction of the weir cascade. No acceleration of the Neckar flood waves matching the Rhine maximum annual floods was detected. However, it was shown that the wave superposition is not the only reason for increasing floods in the investigation period. Strong significant positive trends in discharges matching the Rhine floods were found at all tributary gauges. Thus, there is also a superposition of flood-enhancing effects in the Rhine catchment: Rhine/Neckar flood wave superposition and increasing flows in the Rhine tributaries.

The present work showed that the detected significant positive trends in historical flood records at eight gauges along the Rhine are seriously contaminated by a signal attributable to the river training measures. The analysis of the homogenised annual maximum flow series revealed a substantial portion of relative increase that can be attributed to river training. Nevertheless, the homogenised time series still exhibit strong significant positive trends for a number of time periods. This means that other drivers than river training in the main Rhine channel are responsible for this residual change. The potential candidates are climate variability/change, land use change and also river engineering in the tributaries. The large-scale pattern of residual increasing flows in the main channel as well as corresponding increasing flows in all tributaries would support the hypothesis about the dominance of a large-scale driver, which is likely to be climate variability/change. This is consistent with previous studies about the increase in frequency and persistence of flood-generating atmospheric circulation patterns in Germany (Petrow et al., 2009). However, further investigations would be needed to attribute the residual part of the observed change in flood flows to all alternative drivers.

Furthermore, it must be admitted that the uncertainty associated with the routing models used to derive the homogenisation relationships was not taken into account. Thus, still we cannot assert with 100 % confidence that the residual change is cleared from the river training effect. At this point, we stress the necessity to cautiously interpret the results of trend analyses and, where feasible, to identify and quantify the impact of all possible influencing factors. This has not found wide acceptance or been put into good practice in the contemporary hydrological literature so far.

Supplementary material related to this article is available online at http://www.hydrol-earth-syst-sci.net/17/3871/2013/hess-17-3871-2013-supplement.pdf.

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