

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

# What drives flood trends along the Rhine River: climate or river training?

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Received: 30 November 2012 – Accepted: 2 December 2012 – Published: 7 December 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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## Abstract

The Rhine River catchment was heavily trained over the past decades and faced the construction of the Rhine weir cascade, flood protection dikes and detention basins. For the same time period, several studies detected positive trends in flood flows and faced the challenge of flood trend attribution, i.e. identifying the drivers of observed change. The presented study addresses the question about the responsible drivers for changes in annual maximum daily flows at Rhine gauges starting from Maxau down to Lobith. In particular, the role of river training measures including the Rhine weir cascade and a series of detention basins in enhancing Rhine floods was investigated. By applying homogenisation relationships to the original 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, the relative changes in the homogenised time series were found to be smaller up to about 20% points 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 was partly caused by the unfavourable superposition of the Rhine and Neckar flood waves. It resulted from the acceleration of the Rhine waves due to construction of the weir cascade. However, at the same time, the tributary flows across the entire Upper and Lower Rhine, which enhance annual Rhine peaks, showed very strong positive trends. This suggests the dominance of a large-scale driver such as climate variability/change which acted along with river training. In particular, the analysis suggests that the river training measures fell in a period with increasing flood trends driven by factors other than river training of the Rhine main channel.

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# 1 Introduction

In the recent years, considerable attention was devoted worldwide and particularly in Europe in the hydrological literature to the detection and analysis of trends in flood characteristics such as annual maximum flows, maximum water stages, flood frequencies etc. (Mudelsee et al., 2003; Pinter et al., 2006a,b; Petrow and Merz, 2009; Villarini et al., 2011; Bormann et al., 2011). Particularly, the question of presence and detectability of climate change signal in the flood records was 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 large-scale circulation patterns (Petrow et al., 2009). Recently, the analysis of Hundecha and Merz (2012) attributed the trends in maximum seasonal flows in a few small and meso-scale catchments in Germany to the trends in the corresponding catchment average maximum precipitation, while for others 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, among others 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 the non-climatic drivers such as the construction of reservoirs.

Over the past decades and even centuries, German rivers experienced extensive river training, such as straitening and deepening of channels, construction of reservoirs and flood protection dikes, of wing dikes, detention basins and weirs (Kalweitz et al., 1993; HWSG, 1993; Lammersen et al., 2002; Helms et al., 2002; Bormann et al., 2011). Additionally, many catchments were exposed to land use changes and progressive urbanisation. However, the impact of land use changes on flood flows in large

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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 confidence statement.

Separation of different drivers on flood trends and evidence of consistency and inconsistency of detected changes with changes in driving variables received some but little attention in the past research. Mudelsee et al. (2003) investigated the impact of reservoirs in the Elbe and Oder catchments on the trends in occurrence of heavy floods concluding about their minor influence. Cunderlik and Burn (2004) and Pinter et al. (2006b) established the links between flood characteristics and meteorological driving variables using the 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 run 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.

Anthropogenic land use changes and river engineering effects on flood flows are even more difficult to isolate in the 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 at local authorities, it remains highly fragmented, incomplete and its retrieval is highly laborious.



2002; Villarini et al., 2011). However, a systematic analysis of the wave superposition in the Rhine catchment and its impact on flood flows on *daily* time scale has not been provided.

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), we analysed trends in maximum annual daily discharge series for several Rhine gauges in the period from 1952 to 2009. The changes in trend significance were assessed based on the non-parametric Mann-Kendall test. Additionally, the changes in discharge for the new homogenised time series were evaluated in relation to the originally recorded flows. 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.

## 2 Data and methods

### 2.1 Study area

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

Acknowledging the increased flood hazard due to the loss of 130 km<sup>2</sup> of natural floodplain, which comprise about 60 % of all available natural storage (IKSR, 1997),

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the International Commission for the Protection of the Rhine (ICPR) adopted a plan for construction of a series of detention basins between Basel and Worms following the German-French agreement of 1982 with total storage capacity of  $288 \times 10^6 \text{ m}^3$ . The capacity of  $91.3 \times 10^6 \text{ m}^3$  was realised by 1998 in order to compensate the adverse effects of river engineering in the upstream reaches (BfG, 1999; Lammersen et al., 2002). In exceptional cases for catastrophic floods further  $25 \times 10^6 \text{ m}^3$  can be activated (BfG, 1999). In total, the retention volume in the Upper and Lower Rhine amounted  $160 \times 10^6 \text{ m}^3$  by the year 1995 and was gradually increased to  $211 \times 10^6 \text{ m}^3$  by 2005 and  $229 \times 10^6 \text{ m}^3$  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 the recent Rhine history five periods can be roughly distinguished for which distinct flow regimes are anticipated: (1) prior to 1955, (2) between 1955 and 1977, (3) from 1977 till 1998, (4) from 1998 to 2005, and (5) after 2005. For the time points 1977 and 1998, BfG (1999) and Lammersen et al. (2002) carried out the homogenisation of the flood discharges for gauges Cologne, Rees and Lobith using two numerical models: the hydrological routing model SYNHP developed at the Environmental Protection Agency of Federal State Baden-Württemberg and setup for the reach Basel-Andernach and the one-dimensional hydrodynamic model SOBEK (Delft Hydraulics and the Ministry of Transport, Public Works and Water Management, 1997) applied to the reach Andernach-Lobith. These routing models were setup for river conditions in five mentioned training periods. By simulating a number of historical floods for different stages of channel training, the relationships between the observed and reconstructed peak flows can be derived at each gauge. The reconstructed peak discharges represent those that would have occurred if the construction of the weir cascade and detention basins had not taken place.



1955/1977, (s2) 1977/1977, (s3) 1955/1998, (s4) 1977/1998, where 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 regressions were applied to discharge values above the threshold at gauge Maxau of  $Q = 3800 \text{ m}^3 \text{ s}^{-1}$  which approximately corresponds to a return period of 10 yr. Below this threshold the detentions basins are not activated and hence do not affect peak flows (BfG, 1999).

### 2.3 Monotonic trends, change-point and variability analyses

In the following 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, a robust approach of multiple trend tests was applied. Multiple trend matrices indicate trends and their significance for multiple time periods. The multiple trends were computed for the periods with minimum of 30 yr between 1952 and 2009.

Monotonic trends in discharge were characterised by the slope of the Kendall-Theil Robust Line (KTRL) (Theil, 1950). Statistical significance of trends was tested by the Mann-Kendall test with the 2-sided option and 10 % significance level. The time series were pre-whitened by removing autocorrelation which may affect the significance of trends (Yue et al., 2003). 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 between the years 1952 and 2009 given by KTRL to the mean flood discharge in this period (Eq. 1).

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$$\Delta Q_r = \frac{Q_{2009}^* - Q_{1952}^*}{\bar{Q}} \times 100\% \quad (1)$$

where  $\Delta Q_r$  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 respectively, and  $\bar{Q}$  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 test Mann-Whitney statistic  $U_{t,T}$  is given by Eq. (2):

$$U_{t,T} = \sum_{i=1}^t \sum_{j=i+1}^T D_{ij}, \quad (2)$$

and used to test whether two samples  $Q_1, \dots, Q_i$  and  $Q_{i+1}, \dots, Q_T$  come from the same population and where  $D_{ij} = \text{sgn}(Q_i - Q_j)$ .

Contrary to the classical formulation of the Pettitt-test, which investigates the significance of the most probable change-point corresponding to the maximum absolute value of the Mann-Whitney statistic, we look at the significance of a change-point in any specific year by plotting the significance probability along the time axis. The significance probability is determined by the robust resampling method, which poses no restriction on the probability range in contrast to the approximation used by Pettitt (1979).

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 was computed for all four scenarios and reveals the effect of the weir cascade and detention basins on variability of flood flows.

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## 3 Results and discussion

### 3.1 Analysis of flood changes

Multiple trend matrices for the original non-homogenised annual maximum flow series for gauges Maxau, Worms, Mainz, Kaub, Andernach, Cologne, Rees and Lobith are summarised in Fig. 2A1–H1. They show for all gauges periods of statistically significant flood increase starting around 1960 till 2009, and for gauges downstream of Worms additionally from around 1970 till 2005 with relative changes from about 40 % to above 100 %. For the longer terms starting in the beginning of the fifties till 2009, only a few positive flood trends with moderate relative changes from about 10 % 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 late seventies to late 2000s are negative, although this period includes two major Rhine floods in 1993 and 1995. The first decade of the 21st century seems to manifest a period with little flood changes.

#### 3.1.1 Impact of the Rhine weir cascade and detention basins

Trend matrices for scenarios s1(1955/1977) to s4(1977/1998) (Fig. 2A2–A5:H2–H5) indicate the difference in relative change between homogenised time series and original recorded flows. The negative values, for example, denote a smaller relative changes in homogenised time series compared to the original ones. It should be, however, noted that a smaller relative change does not necessarily imply smaller mean 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.

The analysis of homogenisation scenarios presented in Fig. 2 shows a dampening effect of homogenisation on positive relative discharge changes in original records for all gauges starting from Maxau downstream to Cologne. This corresponds to an

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enhancement of flood trends due to river training measures that ranges from a few % points in scenarios s1(1955/1977) and s3(1955/1998) to more than 20 % 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.

5 The analysis of change point in mean suggests, however, that the strongest impact of the weir cascade on flood flows is expected around the year 1977 (Fig. 3a). At this time, all Rhine gauges exhibit an abrupt change at 90 % significance level towards increasing flows.

10 However, for several gauges, abrupt changes towards lower flood flows were detected for the late fifties and around 2005. These cannot be associated with river training measures acting towards flood flow reduction such as detention basins. In the fifties, the detention basins were not yet constructed and since 1990 only in the year 1999 the discharge at Maxau exceeded the threshold for detention basin deployment. However, no information is available whether any detention basin was activated for this event. In  
15 overall, this suggests that the change-point analysis may reveal some abrupt changes not necessarily caused by human intervention into the river system but also due to natural variability and occurrence of flood-rich and flood-poor periods.

20 This hypothesis is further supported by the analysis of change-point in the homogenised time series for scenario s4(1997/1998) (Fig. 3b). It shows marginal impact of homogenisation on the significance of change-point in flood flows in the late seventies. Only at gauge Maxau, the change-point towards flow increase is no longer significant in the homogenised series. This suggests that the completion of the Rhine weir cascade coincides with the 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. 7A4–F4) which shows strongly positive  
25 trends for periods starting in sixties and seventies, and negative trends for periods starting in fifties and late seventies. Hence, the entire Rhine catchment experienced the increasing flood flows in the period from sixties to around 2000 which is a sign for a large-scale driver such as climate variability or change.

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A few analysed time periods in the multiple trend analysis, particularly those starting in late seventies, exhibit negative trends in original records (Fig. 2A1–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 value of a few % points. The negative trends in the original records is a result of the high floods in the late seventies compared to the first decade of the 21st century. During homogenisation the high flows are stronger adjusted in absolute terms by multiplying them with a regression coefficient. This leads to a reduction of trend slopes in the homogenised series.

The effect of increase in floodplain storage has a relatively small influence on changes in flood trends. This is inferred from 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 till 1998. In fact, Fig. 2 does not allow to discern the effect of detention basins beyond 1998 because the homogenisation relationship, which considers the effect of detention basins, was 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. In overall, 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 embraced 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 so far compared to the detention basins for upstream gauges Maxau and Worms (Fig. 4). 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 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 and becomes nearly indistinguishable at Cologne. This suggests that not solely the construction of the weir cascade, but another process intruding 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 in more details.

### 3.1.2 Analysis of flood wave celerity and wave superposition

As mentioned in the introductory section, several authors assume that the acceleration of Rhine flood waves due to the construction of the weir cascade caused the superposition of the Rhine and Neckar flood waves and this had a major impact on the enhancement of flood flows. In order to investigate, whether there is indeed a detectable

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change in the arrival time of flood waves to 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. 5a).

Indeed, a change point in 1980 was detected at the 90 % 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 River was tested for changes in relation to the gauge of Basel (Fig. 5b). 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 constructed for the gauges at Rhine tributaries immediately 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 tributary gauges from the daily flow series: flows corresponding to the annual Rhine peak at the nearest upstream Rhine gauge (1) with one day negative time lag between Rhine peak and tributary gauge record

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(Lag -1); (2) recorded at the same day at the tributary gauge (Lag 0); (3) with one day positive time lag between the Rhine peak and tributary gauge record (Lag +1). Finally, (4) the discharge series containing the maximum flows in the time window of  $\pm 3$  days around the Rhine peak. This time window is sufficient to embrace the tributary flood hydrographs corresponding to one flood event. Schematically, one possible constellation of the matching Rhine and tributary hydrographs is depicted in Fig. 6.

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 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 reaches the confluence on the same day than 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 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 of the corresponding events. Trend analysis of the maximum tributary flows for the flood events corresponding to annual maximum discharges in the main channel should reveal monotonic changes which reflect the changes in the catchments of the tributaries.

The results of the multiple trend tests for the Lag -1/0/1 time series for six gauge pairs indicate the strong positive trends nearly for all time periods (Fig. 7). Indeed, for the Rhine-Neckar confluence the trends particularly for the Lag -1 discharge are strongly positive (Fig. 7A1). However, the trends in the peak flows of the corresponding flood events at the gauge Rockenau also exhibit pronounced positive trends (Fig. 7A4) which are however weaker than for the Lag -1 series. This suggests that besides the systematic wave superposition, the Rhine annual flood peak flows are enhanced by the 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

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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 more than 150–200 % since 1960s clearly indicate the increasing contribution of tributary waters. Particularly, Neckar, Main and Mosel can contribute on average up to a quarter or even a third of the Rhine peak discharge as shown for the respective gauges Rockenau, Frankfurt and Cochem in Table 2. For these tributaries, no clear indication of the wave superposition can be 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, also they 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. 7A4–F4). This suggests the impact of a large-scale driver such as climatic variability/change. However, also other changes like 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 Rhine gauges Maxau, Worms, Mainz, Kaub, Andernach, Cologne, Rees and Lobith. These homogenisation relationships 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 detention basins had not taken place between 1955 and 2009 along the Rhine.

The construction of the Rhine weir cascade was found to strongly impact flood trends over the past fifty-year period. The relative changes from a few % points to more than 20 % points in the original flow records at several gauges are attributable to the impact of river training depending on the selected time period. Moreover, trends for some periods in the multiple trend analysis were found to be not statistically significant in

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effects in the Rhine catchment: Rhine/Neckar flood wave superposition and increasing flows in the Rhine tributaries.

The presented work showed that the detected significant positive trends in historical flood records at eight gauges along the Rhine channel are seriously contaminated by a signal attributable to the river training measures. The analysis of the homogenised annual maximum flow series reveals remarkable 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 but river training in the main Rhine channel are responsible for this residual change such as climate variability/change, land use change and also river engineering in the tributaries. Further investigations would be needed to attribute the residual part of the observed change in flood flows to the alternative drivers. However, one has to admit that the uncertainty associated with the routing models used to derive the homogenisation relationships was not taken into account. Thus, still one 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 and good practice in the contemporary hydrological literature so far.

*Acknowledgements.* Funding by the “Helmholtz Climate Initiative REKLIM” (Regional Climate Change), a joint research project of the Helmholtz Association of German research centres (HGF) is gratefully acknowledged. Discharge time series were provided by the Global Runoff Data Centre, 56068 Koblenz, Germany and Lippe-Verband.

The service charges for this open access publication have been covered by a Research Centre of the Helmholtz Association.

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**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)

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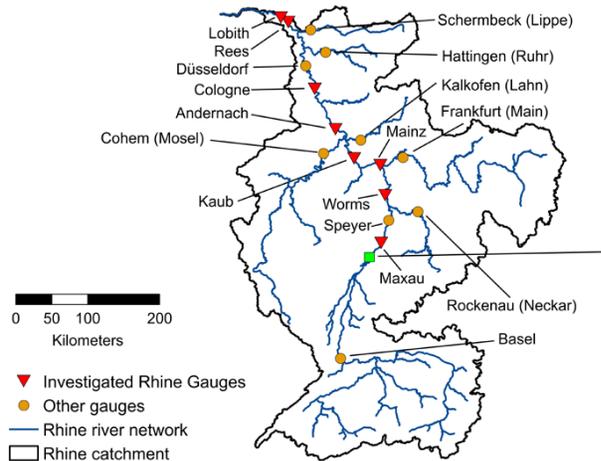


Photo: Wasser- und Schifffahrtsamt Freiburg

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

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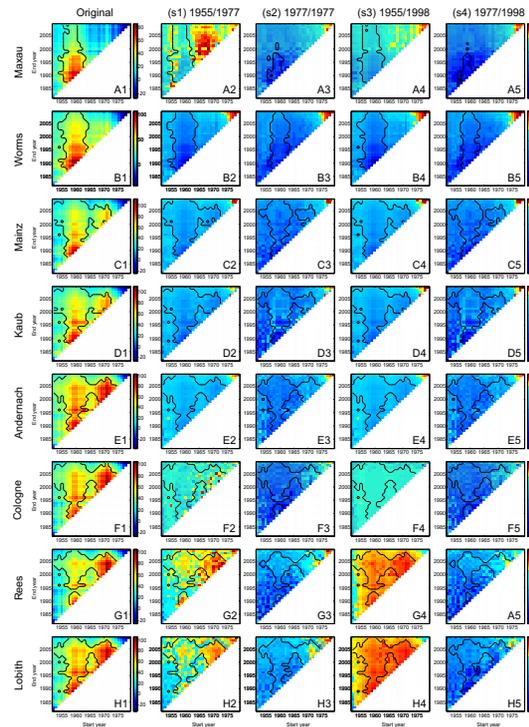
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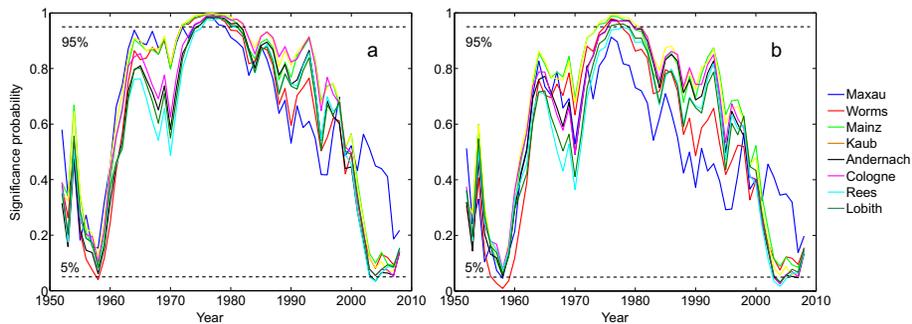


**Fig. 2.** Multiple flood trends for Rhine gauges with relative change in [%] (A1–H1) and shifts in relative changes in [% points] for different homogenisation scenarios with respect to the original time series. Legends in (A5–H5) apply to (A2–H2: A5–H5), respectively. Black contour lines embrace the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

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**Fig. 3.** Significance probability of a change-point in **(a)** original annual maximum flow series at Rhine gauges and **(b)** in homogenised series for scenario s4(1977/1998).

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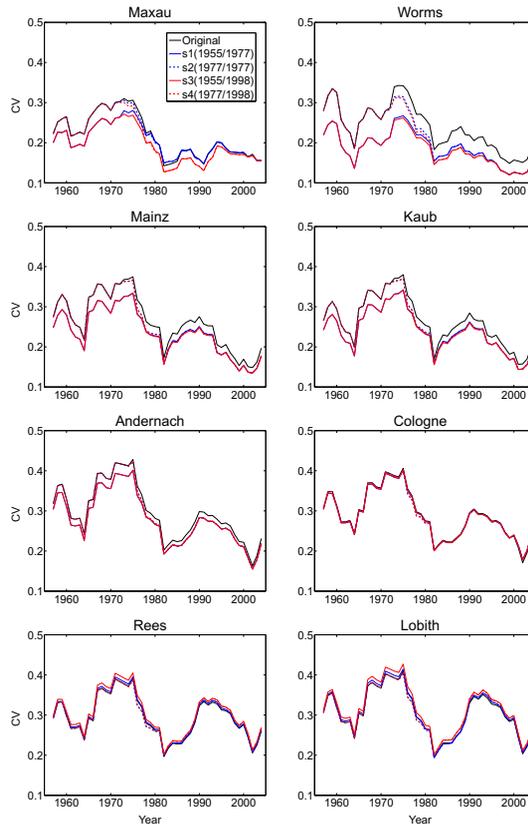
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**Fig. 4.** 10-yr running mean of the coefficient of variation (CV) of annual maximum flows at Rhine gauges.

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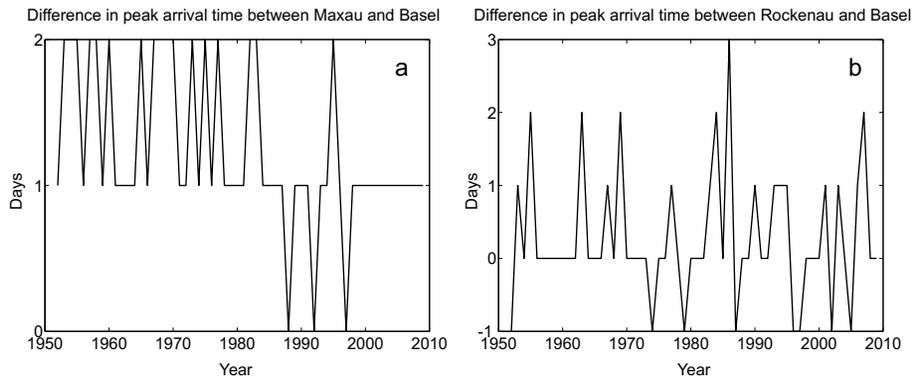
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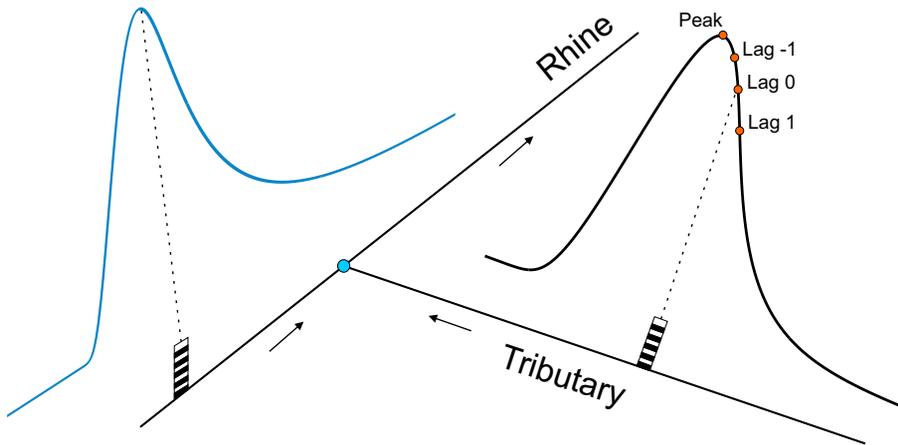
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**Fig. 5.** Difference in the arrival time of flood peaks at Maxau and Rockenau in relation to the gauge Basel.

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**Fig. 6.** Schematic representation of a possible matching of Rhine and tributary hydrographs and indication of the extracted tributary time series.

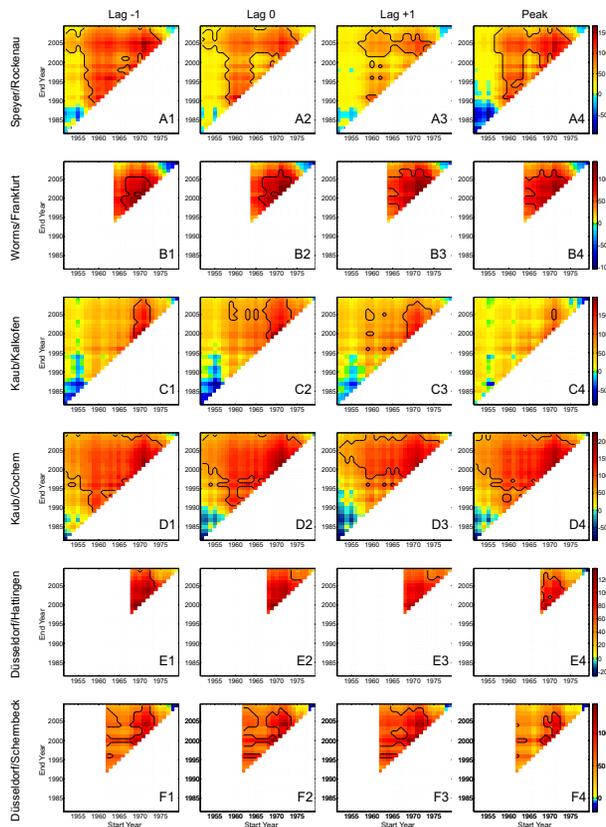
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**Fig. 7.** Multiple flood trends in discharge series corresponding to the Rhine annual peak flows with  $-1/0/+1$  day lag and in maximum discharge series of the corresponding tributary flood event. Black contours embrace the regions of statistically significant trends.

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