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

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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

- ¹⁵ 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.





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

- ¹⁵ 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
- ²⁰ 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 (Kalweit 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





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

- ⁵ 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.
- ¹⁰ 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
- ²⁰ 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.





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 presence of influence on flood discharges, but the

- quantification of this influence is not possible with SGA. Hence, SGA 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 part of applying lactered a more complex economics of the next changes in
- ¹⁰ by this sort of analysis. Instead a more complex assessment of the past changes is required aiming at the reconstruction of the river system states at different points in time in order to isolate the river training effect on flood characteristics.

Remo and Pinter (2007) and Remo et al. (2009) reported the development of the "retro-models" for the Mississippi River and investigated the effect of river engineering

- ¹⁵ measures and changes in land cover on flood stages. A similar effort was undertaken for the Rhine River (Busch and Engel, 1987; HWSG, 1993; BfG, 1999; Lammersen et al., 2002) in order to investigate the effect of river training, particularly the effect of construction of the weir cascade and detention basins in the second half of the 20th century on flood flows. 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 primarily 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) ²⁵ weaker flood wave attenuation and (ii) superposition of flood waves of the main channel and tributaries, particularly the Neckar River (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 cited or replicated in the peer-reviewed literature in different context (Disse and Engel, 2001; Lammersen et al.,





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
- ¹⁵ 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.
- ²⁵ Acknowledging the increased flood hazard due to the loss of 130 km² 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 construction of a series of detention basins between Basel and Worms following the German-French agreement of 1982 with total storage capacity of 288 × 10⁶ m³. The capacity of 91.3 × 10⁶ m³ was realised by 1998 in order to compensate the adverse
⁵ effects of river engineering in the upstream reaches (BfG, 1999; Lammersen et al., 2002). In exceptional cases for catastrophic floods further 25 × 10⁶ m³ can be activated (BfG, 1999). In total, the retention volume in the Upper and Lower Rhine amounted 160 × 10⁶ m³ by the year 1995 and was gradually increased to 211 × 10⁶ m³ by 2005 and 229 × 10⁶ m³ 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 15 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
- ²⁵ 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.





We complemented the regressions for Cologne, Rees and Lobith derived based on the data from BfG (1999) with those for Maxau, Worms, Mainz, Kaub and Andernach based on data from HWSG (1993) (Table 1). Moreover, HWSG (1993) computed scenarios of historical flood flows which correspond to the Rhine state with 212×10^6 m³

⁵ implemented detention volume. This roughly corresponds to the state of the year 2005. The compiled linear regressions typically show very high coefficients of determination. In such a way, a unique homogenised dataset was compiled here, which allows for the first time to isolate the effect of river training on flood flows for a series of Rhine gauges.

We applied these relationships to the recorded annual maximum flow series (AMS) until 2009 and generated a homogenised AMS for the above-mentioned gauges. This AMS refers to the Rhine conditions prior to 1955 and should represent the river state before the major training measures were put in operation in the second half of the twentieth century.

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 in flood flows, the application of the homogenisation relationship introduces uncertainty. The same applies to the construction of the detention basins that gradually progressed from 1977 till present. To represent this uncertainty, four scenarios were considered which which cover a complete envelope 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 in operation in the year 1955 and 1977, respectively. The real impact on flow trends would be somewhere ²⁵ 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 until 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, (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
⁵ 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 $Q = 3800 \,\mathrm{m^3 \, s^{-1}}$ 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, chnage-point and variability analyses

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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
- ²⁵ difference in flood discharge between the years 1952 and 2009 given by KTRL to the mean flood discharge in this period (Eq. 1).





$$\Delta Q_{\rm r} = \frac{Q_{2009}^* - Q_{1952}^*}{\overline{Q}} \times 100\%$$

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 respectively, 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 test Mann-Whitney statistic $U_{t,T}$ is given by Eq. (2):

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

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and used to test whether two samples Q_1, \ldots, Q_i and Q_{i+1}, \ldots, 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 chnage-point corresponding to the maximum absolute value of the Mann-Whitney statistic, we look at the significance of a chnage-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. **Discussion** Paper HESSD 9, 13537-13567, 2012 What drives flood trends along the **Rhine River? Discussion** Paper S. Vorogushyn and B. Merz Title Page Introduction Abstract **Discussion** Paper Conclusions References **Tables Figures I**◄ Back Close **Discussion** Paper Full Screen / Esc **Printer-friendly Version** Interactive Discussion

(1)

(2)



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 dampen-²⁵ ing effect of homogenisation on positive relative discharge changes in original records for all gauges starting from Maxau downstream to Cologne. This corresponds to an





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 chnage 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.

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

overall, this suggests that the chnage-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.

This hypothesis is further supported by the analysis of chnage-point in the homogenised time series for scenario s4(1997/1998) (Fig. 3b). It shows marginal impact of homogenisation on the significance of chnage-point in flood flows in the late

- 20 pact of homogenisation on the significance of chnage-point in flood flows in the late seventies. Only at gauge Maxau, the chnage-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 corre-
- sponding to the Rhine peak discharges (Fig. 7A4–F4) which shows strongly positive 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.





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.
- ¹⁰ 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
- ¹⁵ 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 num-⁵ ber 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)

- ¹⁵ 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





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 chnage 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),

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- 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





(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 ±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

- ¹⁰ 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 20 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





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

¹⁵ the trends in tributary flows.

4 Conclusions

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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

changes like land use and river training in the tributary catchments may have affected

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 im-

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





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 dissipated from gauge Worms downstream to Cologne, where little difference in flood flow trends between the original and homogenised discharges was

⁵ found. The impact of the detention basins on changes in flood trends at the Rhine gauges 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.

The analysis of abrupt changes in mean of the original and homogenised time series revealed statistically significant change-points towards decreasing flows in the late fifties and around 2005 for several gauges, and towards increasing flows in the late seventies for all gauges. The homogenisation of flood flows had little effect on the signifi-

¹⁵ cance of the detected chnage-points. From this it can be inferred that abrupt changes in flood flows as detected by the statistical tests can also be caused by natural factors and are not necessarily an indication of human intervention. It was shown that the completion of the Rhine weir cascade is likely to coincide with the abrupt change towards increasing flood flows. The increasing flood trends were also detected in this period for ²⁰ 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. This 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

²⁵ 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 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 15 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 analy-
- ses 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.
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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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Table 2. "Mean ratio" indicates the long-term mean contribution of the tributary flow in % to the Rhine discharge during annual maximum flow events.

Gauges	Speyer/	Worms/	Kaub/	Kaub/	Düsseldorf/	Düsseldorf/
	Rockenau	Frankfurt	Kalkofen	Cochem	Hattingen	Schermbeck
	(Neckar)	(Main, from 1964)	(Lahn)	(Mosel)	(Ruhr, from 1968)	(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. 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.























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







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







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.



