The role of flood wave superposition for the severity of large floods

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Abstract. The severity of floods is shaped not only by event and catchment specific characteristics but also depends on river network configuration. At the confluence of relevant tributaries to the main river, flood event characteristics may change depending on magnitude and temporal matching of flood waves. This superposition of flood waves may potentially increase flood severity. However, this aspect is up to now not analysed for a large data set.

5 To fill this gap, the role of flood wave superposition in determining flood severity is investigated. A novel methodological approach to analyse flood wave superposition is presented and applied to mean daily discharge data of 37 triple points from the four large river basins in Germany and Austria (Elbe, Danube, Rhine and Weser). A triple point consists of the three gauges at the tributary as well as upstream and downstream of the confluence to the main river. At the triple points, differences and similarities in flood characteristics are jointly analysed in terms of temporal matching and magnitudes of flood peaks.

10 At many analysed confluences, the tributary peaks arrive consistently earlier than the main river peaks, but mostly high variability in the time lag is detected. No large differences in temporal matching are detected for floods of different magnitudes. In the majority of the cases, the largest floods at the downstream gauge occur not because of a perfect temporal matching of tributary and main river. In terms of spatial variability, the impact of flood wave superposition is site-specific. Characteristic patterns of flood wave superposition are detected for the flood peaks in the Danube, where peak discharges largely increase

15 due to inflow from the alpine tributaries. Overall, we conclude that the superposition of flood waves is not the driving factor of flood peak severity in Germany, but a few confluences bear potential of strong flood magnifications in the case of temporal shift in flood waves.

1 Introduction

Floods result from an interplay of several factors along the cascade of processes starting from precipitation via runoff generation

20 in a catchment down to river routing. Event-specific characteristics such as intensity and spatial patterns of precipitation exert an impact on river discharge. The impact of a precipitation event on the timing and magnitude of a flood is further modulated by the prevailing soil moisture conditions in the catchment that control timing and amount of runoff generation (Merz and Blöschl, 2003; Nied et al., 2013). Moreover, flood patterns are characteristic for each catchment due to the specific physiogeographic

conditions, i.e. elevation and slope or geological formation, that result in site-specific runoff generation processes. In particular, floods are impacted by the river network configuration and related geomorphological catchment characteristics. Several studies indicated the impact of drainage density (or hillslope lengths), which is related to the network configuration, on the runoff coefficients (e.g. Plaut-Berger and Entekhabi (2001)). Travel times of water to the catchment outlet or confluence are also

5   influenced by the distributions of hillslope-channel lengths (Di Lazzaro et al., 2015). Hence, the river network configuration can lead to a higher/lower probability of flood wave superposition (Seo and Schmidt, 2013), and the impact from different tributaries to the main river can be highly variable. Each tributary has specific catchment characteristics and typical flood characteristics. The shape of the flood wave can significantly change at each relevant confluence (Bloeschl et al., 2013; Skublics et al., 2016).

10   Our definition of flood wave superposition considers both (i) the timing of flood peaks and (ii) the peak magnitudes, both in the main river and the tributary. According to the definition in this study, flood wave superposition is based both (i) on a temporal matching of flood peak and (ii) a high peak magnitude both in the main river and the tributary. A superposition of flood waves at confluences may increase the flood magnitude and lead to an acceleration of the flood wave (Bloeschl et al., 2013; Skublics et al., 2014). On the other side, low or medium discharge conditions in a tributary may prevent further aggravation of

15   the flood event (Thomas and Nisbet, 2007; Pattison et al., 2014). In a study of the flood 2013 in the Danube basin, Bloeschl et al. (2013) noted the synchronous occurrence of flood waves at the confluence of Salzach to the Inn river in Austria. Bloeschl et al. (2013) emphasised that at the confluence of the Inn to the Danube at the German-Austrian border, the Inn flood wave typically occurs earlier than the flood wave of Danube. An earlier or later flood occurrence in the tributary relative to the main river leads to a weaker flood wave superposition due to a temporal peak mismatch (Skublics et al., 2014). For a river section of

20   the Bavarian Danube, Skublics et al. (2014) showed that a temporal shifting of the tributary peak to a temporal peak matching would increase the flood peak in the main river downstream of the confluence.

Though flood wave superposition could potentially impact flood magnitudes, only few studies have addressed this topic so far (Vorogushyn and Merz, 2013; Geertsema et al., 2018). Lane (2017) suggested the possibility of de-coupling the tributary and main channel waves, i.e. enforcing a temporal shift through enhanced storage and attenuation, as a measure for flood risk

25   reduction. Geertsema et al. (2018) concluded that at the lowland confluence in the Meuse catchment, the time lag between peaks is of minor importance because of the long duration of flood waves compared to the typical variability of the time lags. A different situation can be expected in smaller and fast reacting catchments with shorter flood durations. Hence, it is important to understand whether patterns of flood wave superposition are typical for a confluence or whether they are event-specific and change between small and large floods.

30   To quantify flood wave superposition, we analyse in this paper the flood wave characteristics at the three gauging stations that are located close to the confluence, i.e. on the tributary and on the main river, upstream and downstream of the confluence. The three gauging stations are denoted as triple point in the following. Two flood event characteristics are considered at the same time. First, the timing of the flood wave peak describes whether the tributary flood peak reaches the confluence simultaneously with the main flood wave or if there is a temporal shift. Second, the flood magnitudes at all three gauges are used for the

assessment of similarities or differences in flood intensity. Hereby, a perfect overlay of flood waves means that a high tributary wave peak matches in time a high main channel peak at the confluence.

The aim of this study is to investigate the role of flood wave superposition for flood severity in the main German catchments including Austrian tributaries. It provides the first analysis on the flood wave superposition problem using a large data set. We develop and test a method to jointly analyse temporal matching and (dis)similarities in flood peak magnitudes between tributary and main river (at upstream and downstream sites). We address the following research questions:

1. Is the temporal matching of flood waves a key factor for the occurrence of large floods?

2. To which extent does the peak discharge in the tributary contribute to the severity of the main river flood through wave superposition?

3. Is the impact of flood wave superposition higher for large floods compared to small floods?

2 Study area and data

2.1 Study area

In this study, triple points from the four large river basins in Germany and Austria (Elbe, Rhine, Danube and Weser) are analysed and the selected gauges are shown in Fig. 1 together with catchment elevation ((EEA, 2017) and data resampling (Samaniego et al., 2018)) and main rivers (De Jager and Vogt, 2007). The Elbe river originates in the Czech Republic and flows through Eastern Germany into the North Sea. The middle Elbe is mainly influenced by two tributaries from the Ore Mountains (Mulde and Saale, both left-sided). The lower Elbe flows through the North German Plains with the major tributary Havel (right-sided). The Rhine river originates in Switzerland and flows northwards to the North Sea. In Switzerland, the Rhine basin is characterised by alpine topography and the nival flow regime. Our analysis is focused mainly on Upper and Middle Rhine. The largest tributaries are the Neckar at the Upper Rhine and Main (both from east, right-sided) and Mosel (from west, left-sided) both at the Middle Rhine. The Danube river drains the catchments in southern Germany and is fed by quick-reacting steep tributaries from the German and Austrian Alps. There are several large tributaries to the Danube within Germany such as Naab and Regen from north (left-sided) and Iller, Lech, Isar and Inn from south (right-sided). The northern and southern tributaries have different climatological and hydrological regimes and exhibit different flow dynamics relative to the main stream. The Weser is the only large river basin that is completely located in Germany and originates in the Central German Uplands at the confluence of Werra and Fulda. It flows through the North German Plains into the North Sea.

Floods in Germany are controlled by two major gradients (Beurton and Thieken, 2009; Merz et al., 2018). The elevation increases from the lowlands in the north via the Central German Uplands up to the Alps in the south. Climate regime changes from maritime in the western and at the coastal areas to more continental in eastern parts of Germany. As a consequence, Weser and Middle Rhine are characterised by winter floods evoked by long precipitation events. Winter floods are also dominant in the Elbe basin and the left-side of the Danube, but here seasonal variability is higher. In the south of Germany, i.e. in catchments

at the right-side of the Danube, floods are mostly occurring in summer due to high precipitation and/or the snowmelt from the Alps.

2.2 Discharge data set

The data set consists of 37 triple points (Fig. 1), for which mean daily discharge data with time series length of more than thirty
5 years are available. We do not consider small catchments (area < 500 km^2) for which hourly discharge data would be required. Tab. 1 shows all triple points clustered by the major basins. They were manually assembled based on three criteria. Firstly, the size of the tributary catchment is larger than 2% of the downstream catchment. Second, the sum of the catchment size of tributary (C_{trib}) and upstream gauge (C_{up}) is at least 70% of the downstream gauge (C_{down}). The latter criterion is needed to avoid too large lateral inflows to the river between the two upstream gauges and the downstream gauge. In such cases, this
10 inflow may dominate the downstream behavior, strongly reducing the value of the information from the two upstream branches for the analysis. Final criterion is the travel time within the river network. A peak discharge could be recorded one day later at the downstream gauge due to the travel time from upstream and tributary gauges. We thus selected triple points with a close distance between the three gauges to minimise the effect of travel time lags. Nevertheless, some peaks can be recorded at two different days if they occur around midnight. This should be kept in mind when interpreting the results.

15 [Figure 1 about here.]

$$
\begin{aligned}
CR_{up} &= \frac{C_{up}}{C_{down}} && \text{Ratio of catchment size of upstream and downstream gauge} \\
CR_{trib} &= \frac{C_{trib}}{C_{down}} && \text{Ratio of catchment size of tributary and downstream gauge}
\end{aligned}
$$

The catchment size of the downstream gauges ranges from 3,803 km^2 to 139,549 km^2. The ratio of tributary catchment size to downstream catchment sizes (CR_{trib}) varies between 4 and 55%. For the upstream gauges, this ratio (CR_{up}) ranges from
20 33 to 95%. Thus, the relevance of tributary and upstream gauges varies considerably between the triple points.

[Table 1 about here.]

Fig. 2 shows the catchment size of upstream and tributary gauges to demonstrate the variability in the contribution of both gauges. Points along the diagonal line show a similar catchment size ratio. Among the major tributaries to the Elbe, the Mulde has much smaller catchment size compared to Saale and Havel. The catchment ratio of the three Rhine tributaries
25 (Neckar, Main, Mosel) is relatively similar. Along the Danube the catchment ratios are mostly increasing downstream. The Weser confluences (Aller, Leine, Werra) are characterised by the highest similarities in catchment sizes between upstream and tributary gauges. Within a triple point, the upstream gauge is always the gauge at the same river, while the tributary gauge is at a different river branch even when the catchment size and/or mean discharge is larger in the tributary.

[Figure 2 about here.]

3 Methods

We distinguish four types of flood wave superposition (Fig. 3). Hereby, the analysis of flood wave superposition is related both to matching in time and in flood magnitude: (I) Perfect overlay: Peaks Q_p occur at all three gauges at the same time with the same intensity, i.e. same specific discharge. (II) Temporal mismatch: There is a time lag Δt_p between the flood peaks while the

5   specific discharge is the same. (III) Peak magnitude mismatch: There is a strong difference in specific discharge. For example, high specific discharge in the upstream gauge is compensated by a low specific discharge in the tributary which prevents an increase in downstream flood severity. (IV) Temporal and peak magnitude mismatch: Both peak magnitude and peak timing vary between the three gauges. Although there are no clear boundaries between these conceptual types of wave superposition, this typology is helpful to classify and describe the superposition.

10   Specific terminology is used for distinguishing between the impact in timing and in magnitude. Flood synchronicity is defined as a temporal matching of flood peaks (types I+III). Flood amplification means that the downstream flood magnitude increases due to the peak overlay of upstream and tributary waves (types I, II and IV). Compensation effect means that high flood magnitude in the upstream gauge is compensated by a low flood magnitude in the tributary or vice versa. Both cases are characterised by a mismatch in peak magnitudes (type III).

15   [Figure 3 about here.]

Our objective of analysing a large set of flood events is to detect whether one of these cases dominates at a particular triple point and in which way it impacts flood severity at the downstream location. Also, we are interested in determining whether spatially coherent patterns of flood wave superposition types occur in Germany. In particular, we investigate if and where the case I (perfect overlay of all gauges) occurs and how it impacts flood severity.

20   ### 3.1 Derivation of flood peaks

For the selected 37 triple points, we consider annual maximum flood series (AMS) at the downstream gauge and the corresponding tributary flood waves for the analysis. To derive flood event hydrographs, the methodology by Klein (2009) is modified. At first, the AMS peak at the downstream gauge is selected. Each event is characterised by a peak value, a start and an end point. The event start point is located between the annual maximum peak and the previous independent peak. An

25   independent peak is identified if it fulfilled the criteria after Bacchi et al. (1992) and LAWA (2018): (1) The lowest discharge between two peaks is smaller than 70% of the smaller peak, (2) the smaller peak is greater than 20% of the annual maximum peak, (3) the minimum flow between two peaks drops below 20% of the annual maximum flow and (4) the time lag between two peaks is at least seven days. These criteria prevent the identification of oscillatory peaks as independent flood events.

The start point of the flood event is identified by tracing back the gradient in discharge between two consecutive days prior

30   to the peak flow. If the gradient is lower than a predefined threshold for seven consecutive days, the starting date is set to the latest date in this time window. An empirical threshold of 90th percentile of all gradients for the selected gauge is identified by trial-and-error procedure and visual inspection. If no starting point is detected within 40 days prior to the peak flow, the lowest

discharge value in this time window is selected. The event end point is analogously determined by forward looking from the peak. The corresponding flood peaks of the upstream and tributary gauge are defined as the largest discharge values within the event period of the downstream gauge (from start to end point).

A flood peak is characterised by two indicators: the time of peak occurrence t_p and the peak discharge Q_p which are cal-
5 culated for all selected events at the three gauges of each triple point. To assess flood wave superposition, the time lags Δt_p, $\Delta t_{p,up}$ and $t_{p,trib}$ between the peak flows at the triple points are calculated.

$t_{p,down}$	=	Time of peak of downstream gauge	
$t_{p,up}$	=	Time of peak of upstream gauge	
$t_{p,trib}$	=	Time of peak of tributary gauge	
$Q_{p,down}$	=	Peak discharge of downstream gauge	
$Q_{p,up}$	=	Peak discharge of upstream gauge	
$Q_{p,trib}$	=	Peak discharge of tributary gauge	
Δt_p	=	$t_{p,up} - t_{p,trib}$	Time differences in peak between upstream and tributary gauge
$\Delta t_{p,up}$	=	$t_{p,down} - t_{p,up}$	Time differences in peak between downstream and upstream gauge
$\Delta t_{p,trib}$	=	$t_{p,down} - t_{p,trib}$	Time differences in peak between downstream and tributary gauge
$\Delta Q_{p,up}$	=	$Q_{p,down} - Q_{p,up}$	Differences in peak discharge between downstream and upstream gauge
$\Delta Q_{p,trib}$	=	$Q_{p,down} - Q_{p,trib}$	Differences in peak discharge between downstream and tributary gauge

3.2 Design of analyses

The impact of flood wave superposition on flood severity in terms of peak magnitude and temporal matching is analysed in three steps shown in Fig. 4 and described in detail below. For each step, four examples are given. These examples do not
15 represent the complete spectrum, thus, Fig. 4 does not correspond to Fig. 3.

[Figure 4 about here.]

3.2.1 Degree of temporal flood wave superposition

In the first step, it is investigated whether temporal flood wave superposition is a key factor for the occurrence of large floods (Fig. 4A1-A4). The degree of temporal flood wave superposition is represented by the time lags between flood peaks at the
20 tributary and upstream gauges Δt_p. The time lags of all events at a triple point are presented as empirical density curve. A peaky density curve shows low variability of temporal matching, i.e. a relatively constant time lag. A perfect temporal flood wave superposition is indicated by $\Delta t_p = 0$. Additionally, it is analysed whether small time lags are (inversely) related to the magnitude for the largest events. In this way, the hypothesis that temporal peak matching leads to larger flood peaks is tested. For this, the time lags of the ten largest flood peaks are shown as shaded circles to check whether the largest floods are amplified
25 due to flood wave superposition (flood synchronicity).

Due to the daily resolution of the discharge data, a tributary peak occurring around midnight may be recorded in the previous/next day compared to the main stream peak. Thus, time lags of ± 1 day may also be seen as strong superposition. At this point, we neglect the flood wave travel time from the gauges to the confluence, or assume it to be within the same day for the tributary and the upstream gauge.

5   Four cases of temporal flood wave superposition are schematically shown in Fig. 4A. The first two cases show a high relevance of temporal flood wave superposition for the occurrence of large floods at the downstream gauge. Here, the largest floods coincide with zero time lag, which suggests that temporal superposition contributes to high severity. Thus, flood synchronicity, i.e. a temporal matching of floods at upstream and tributary gauges, is detected for the cases A1 and A2. The last two cases are examples with low impact of flood wave superposition.

10   1. Case A1: The time lags between tributary and upstream gauge Δt_p are widely spread around 0. In contrast, the four largest floods have a perfect temporal matching which can potentially explain the occurrence of these large floods.

   2. Case A2: The peak discharge occurs earlier in the tributary. Most of the largest floods occur also earlier with a constant time lag. However, the two largest floods occur when flood waves are synchronous, which suggests that temporal superposition is a relevant driver for large floods.

15   3. Case A3: Time lags are variable around zero as in case A1, but there seems to be no systematic difference in the temporal matching between small and large floods.

   4. Case A4: As in case A2, most of the flood peaks occur earlier in the tributary. Similar to case A3, the superposition of flood waves does not result in the occurrence of large floods.

3.2.2   Contribution of tributary and main river to downstream flood severity

20 In the next step, peak magnitude and temporal matching are jointly investigated for all events of a triple point. An analysis of flood synchronicity only is not sufficient to evaluate flood wave superposition. It is also required to understand the impact of flood amplification and to analyse whether high discharge values both at the tributary and upstream gauges cause an increase in flood severity at the downstream gauge. Otherwise, a low discharge magnitude either in the tributary or upstream gauge may lead to a compensation effect and a low downstream flood severity.

25   The relationship between peak magnitude at the tributary and upstream gauges is analysed under consideration of their time lag and the downstream peak magnitude (Fig. 4B). In this analysis, both axes are scaled to the same specific discharge. The diagonal line indicates the same specific discharge at the tributary and upstream gauges. A flood peak below the 1:1 line indicates a higher specific discharge in the main river compared to the tributary and vice versa. The size of the triangles is scaled with the flood magnitude at the downstream gauge and the color code corresponds to the time lag between tributary and upstream gauge. Four cases are distinguished in Fig. 4B:

30   1. Case B1: The specific discharge is similar at the tributary and upstream gauge. Thus, with increasing discharge in the main river also the tributary and the downstream discharges increase. The flood peak occurs at the tributary and upstream

gauge within the same day for the four largest events (grey colors), while the tributary peak occurs earlier (blue color) or later (red color) for smaller flood events (here ranks 5-8). This suggests that synchronous peaks at upstream and tributary gauges contribute to large downstream floods.

2. Case B2: The specific discharge is similar at the tributary and upstream gauges for most of the flood events, but the tributary peak typically occurs some days earlier. Only the two largest flood peaks occur at the same day. High peaks in the tributary and main river lead to large floods at the downstream part of the river, and flood wave superposition clearly contributes to the amplification of the largest flood peaks.

3. Case B3: The specific discharge is partly higher and partly lower in the tributary. The peak occurs partly earlier and partly later and rarely at the same day as at the upstream gauge. Flood peak severity at the downstream gauge is rather driven by the upstream and tributary flows and the superposition plays a minor role for peak amplification.

4. Case B4: The specific discharges are variable as in case B3. However, for the majority of the events the peak occurs earlier in the tributary (dark blue triangles). The largest floods downstream are rather driven by specific flows in the tributary and upstream branches and flood wave superposition is of minor importance for flood amplification.

3.2.3 Contribution of tributary and main river to the largest downstream floods

In the last step, it is analysed whether the impact of tributary and upstream gauges on the downstream gauge changes for different flood magnitudes. In this way, we test whether the relevance of flood synchronicity and flood amplification increases for large downstream floods. In contrast to the previous analyses, the flood timing of the tributary and upstream gauge is related to the downstream gauge. The time lags between the upstream and downstream gauges $\Delta t_{p,up}$ and between tributary and downstream gauges $\Delta t_{p,trib}$, respectively, are coloured accordingly. This shows whether the flood peak magnitudes at the tributary and upstream gauge change relative to each other for the largest downstream flood peaks.

Four cases are distinguished (Fig. 4C):

1. Case C1: High discharges both at tributary and upstream gauge lead to high floods in the main river downstream of the confluence. For the largest floods, the flood peaks occur at all three gauges at the same day and thus flood wave superposition enhances the flood peaks at the downstream gauge. A temporal mismatch is observed for lower ranked flood events.

2. Case C2: Also here, high discharges in tributary and upstream gauges evoke large floods downstream. Due to flood wave synchronicity for the two largest events, the flood peaks at the downstream gauge are disproportionally amplified. This indicates a significant role of flood wave superposition in driving flood severity.

3. Case C3: The relevance of peak flows in the two upstream branches changes between different events. A relatively small flood at the upstream gauge (compared to other events) can be compensated by a large flood in the tributary and vice versa. The synchronicity of flood peak occurrence is not systematic and not a major driver of large floods downstream.

4. Case C4: The relevance of peak flows also changes between different events. However, the tributary peaks systematically occur earlier and flood wave superposition is not a significant driver for flood severity downstream.

The cases C3 and C4 show a flood compensation effect for some events. A high flood magnitude in upstream gauge can be compensated by a low flood magnitude in the tributary and vice versa.

5 4   Results and discussion

All results are presented in separate subplots for the four major basins (Elbe, Danube, Rhine and Weser) and analysed consecutively.

4.1   Degree of temporal flood wave superposition

In the Elbe river basin, the tributaries have overall the lowest degree of temporal superposition among the four basins (Fig. 5).
10   The flood peaks in the Mulde occur about four days earlier for most of the events including large floods. The time lags of the Saale peaks are more variable with some waves arriving few days earlier, but also later than the main Elbe flood. Few large floods show strong temporal superposition, but this is not an unequivocal pattern: Large floods also occur for preceding and subsequent waves. The vast majority of the Havel peaks runs behind the Elbe flood wave and appears not to control the peak magnitude downstream. A perfect matching of flood waves is detected for the small catchment of Zschopau, where flood wave
15   superposition enhances the majority of flood events (case A1). All confluences in the Elbe basin except Zschopau thus belong to the case A4.

In the Danube basin, high flood synchronicity is identified in most of the tributaries (case A1 and A2). There is a high share of perfect matching for several triple points (e.g. Wertach, Ziller, Naab). In the Wertach, the largest flood peaks occur at the same day showing a perfect wave superposition. For the largest flood events at the confluences of Salzach, Regen, Naab and
20   Isar a perfect matching or a time lag of one day is observed. This suggests a strong role of temporal wave superposition in flood generation at the lower German Danube. This applies in particular for Salzach, where a perfect temporal matching or a time lag of one day is observed for the largest events, whereas small events exhibit high variability of time lags (case A1). Hence, at this triple point a difference in temporal matching is detected between small and large floods and wave superposition appears to enhance large floods.

25   In the Rhine river basin, high flood synchronicity is identified for the small tributaries (Itz, Enz, Regnitz). They exhibit relatively small time lag variability due to short catchment reaction times. At the Neckar/Rhine confluence the largest flood is characterised by strong peak synchronicity, whereas the bulk of the events arrive slightly earlier (case A2). This could indicate an enhanced role of wave superposition. For this confluence, a higher probability of temporal matching due to river training and flood wave acceleration has been detected (e.g. Vorogushyn and Merz (2013) and references therein). The Main tributary shows
30   the highest variability of time lags around zero in the Rhine basin (case A3). The largest floods downstream of the confluence occur with the Main wave preceding or following the Rhine flood a few days later, respectively. this indicates that large floods

are not generated by temporal superposition. The vast majority of Mosel floods occurs a few days prior to the Rhine floods. Several floods occur at the ideal superposition of both waves, though these are not the largest recorded discharges.

In the Weser river basin, high flood synchronicity is found at the smaller tributaries (Oker, Innerste). In contrast, there is high time lag variability at the confluence of Eder and Aller. At the Aller confluence, the largest recorded flood notably is generated
5   under perfect wave matching (case A2). The temporal matching is high at the Fulda confluence (case A1) with several high floods characterised by the time lag of zero to one day.

[Figure 5 about here.]

Many triple points show flood synchronicity with a sharp peak around -1 to +1 day. For the majority of the triple points,
10   either most of the large floods are regularly enhanced by wave superposition (case A1) or the superposition is not related to large floods (cases A3 and A4). For A3 and A4, flood synchronicity is not decisive for the generation of large floods. A strong difference in temporal matching between the all selected floods (AMS) and the 10 largest floods could only be observed for a few triple points. The largest floods appear to emerge during the perfect matching of the main river and tributary waves (e.g. Salzach, Neckar). At the Salzach it also seems to be the case and we characterised it with A1. For the other cases, the causal
15   relationship between superposition and the emergence of the largest floods needs to be further investigated. In the next steps, it is analysed whether these large floods are indeed generated by the strong superposition of high floods in the tributary and upstream branch. In this case, the wave superposition would have the potential to produce large magnitude floods.

4.2   Contribution of tributary and main river to downstream flood severity

Small tributaries in the Elbe basin (Zschopau and Bode) have similar specific discharge as the respective upstream gauge in
20   the main river (Fig. 6) (case B1 and B3). The Mulde river has a much higher specific discharge than the Elbe, but its waves reach the confluence more than 3 days prior to the main river flood peak (case B4). The tributaries of Saale and Havel have much smaller specific discharges and, similar to Mulde, there is a time lag of several days. In the Danube basin, higher specific discharges than in the main river are found in the major tributaries (e.g. Iller, Inn, Lech, Regen and Salzach). There is a temporal mismatch between Inn and the upstream gauge with earlier occurrence of Inn. The Isar peak arrives mostly earlier
25   than the main river peak (Fig. 6). In the Rhine basin, high specific discharge is identified in several tributaries (Mosel, Neckar, Nahe, Kinzig, Tauber) with an earlier flood peak. A different pattern is found for the Main river with changing contributions from Main and the upstream Rhine gauge and later peak occurrence in the tributary (case B3). For most of the largest events the specific discharges of either tributary or the main river are exceptionally high. This suggests that flood magnitudes in the upstream branches are the major drivers of large floods downstream rather than the wave superposition alone. In the Weser
30   basin, similar specific discharges are detected for flood events in the Aller and Fulda catchments. Overall, the tributary peaks are often later in the Weser basin.

[Figure 6 about here.]

The analysis shows that in many cases, the specific discharge is larger in tributaries compared to the main stream, but the tributary peaks often occur earlier. The largest downstream floods (largest triangles) are often characterised by the highest specific discharges either in both branches or in one of them. Many subplots show a quasi-linear relationship, often deviating from the diagonal line that would indicate similar specific discharge (Fig. 6). Other triple points are characterised by event-specific

5 behaviour with varying contributions from tributary and upstream gauges. There is no clear indication that a perfect temporal matching (grey triangles) leads to the largest floods, when the specific discharges are moderate. Hence, wave superposition does not seem to play a major role in generating large floods in Germany.

4.3 Contribution of tributary and main river to the largest downstream floods

The contribution of tributaries in the Elbe basin is variable among tributaries and across the largest flood events (Fig. 7). While

10 the Zwickauer Mulde has a similar contribution as the main stream Freiberger Mulde (case C1), the contribution of e.g. the Havel to the Elbe floods is minor. The strong delay between upstream and downstream peaks at the main river around the Saale confluence for the two largest floods (2002, 2013) clearly points to floodplain inundation and wave attenuation, which indeed occurred after several dike failures.

In the Danube basin, the largest floods are caused by much larger peaks in the tributary Inn compared to the upstream

15 Danube. However, at the Inn/Danube confluence, the Danube wave has typically a two-days lag. At the confluence of Salzach to Inn similar peak values are observed. Thus, large flood peaks at the Inn confluence to the Danube are driven by both Inn and Salzach. Notably, the tributaries Woernitz, Naab, Regen, Isar and partly Inn appear to behave somewhat asynchronously with respect to the Danube floods ("see-saw" pattern). Large floods in the main river are typically matched by lower floods in the tributaries and vice versa (flood compensation effect). At the confluence of Lech to Danube, a high variability in the flood peak

20 values is detected. The largest downstream flood peaks only occur if both rivers show large peaks. Low flood peaks in the Lech also lead to lower values at the Danube downstream gauge. The same situation is observed for the Danube tributaries Regen and Naab. The ranking of the flood peaks is largely different between upstream and downstream gauges due to the changing contribution from Regen and Naab.

In the Rhine basin, large floods occur with relevant contributions from the three major tributaries (Mosel, Main, Neckar),

25 however, the relative contributions vary between the events (cases C3 and C4). These tributaries and the main river flows exhibit the "see-saw" pattern (Fig. 7), where relatively low magnitudes in the main river are compensated by the relatively large flows in the tributaries and vice versa. For example, the flood severity in the Rhine is partly reduced due to a relatively low flood peak in the Mosel. Otherwise, a large flood peak in the Mosel could increase the downstream flood peak in the Rhine. The effect of wave superposition is not dominant in these cases either. This pattern suggests that in the past the extent of flood

30 generating storms or their specific tracks were not able to affect the upstream Rhine catchment and the tributary catchments equally strong. The largest flood downstream of the Neckar confluence is caused by moderate main stream and tributary flows, but here the temporal matching of the Neckar wave is strong, which suggests an enhanced role of wave superposition at this confluence as mentioned above.

In the Weser basin, the contribution from upstream and tributary is similar at the Fulda and Aller confluences. The largest flood peaks at the confluence of Leine and Aller are evoked by large flood peaks from both upstream branches. In the majority of the cases, the Leine peak is one day later and the upstream Aller peak one day earlier. For the 7th largest flood at the Leine-Aller confluence, the tributary peak is clearly larger than the downstream peak, which indicates strong attenuation effects due

5 to inundation in the tributary. A flood compensation effect is found at the confluence of Werra and Fulda. Here, large discharges in the Fulda alone are not sufficient to generate a large flood downstream.

[Figure 7 about here.]

It was shown for some triple points that flood peaks in the main river can be strongly enhanced due to inflow from the tributaries. Flood wave superposition alone is not identified as a driver of the largest floods. However, in a few cases at some

10 confluences, flood wave superposition appears to compromise for lower discharges in the upstream branches and thus, contributes to the generation of floods.

A perfect temporal matching of flood peaks could potentially lead to a large increase in peak discharge. For example, in the Mulde, the two largest events (2002, 2013) have the highest specific discharges in both streams (Elbe, Mulde). A meteorological situation in combination with a catchment response, which would reduce the time lag at the Mulde confluence would be rather

15 dangerous. Hence, the potential for a delayed Mulde response in comparison to the Elbe needs to be investigated in the future. A possible scenario would be a long lasting extreme rainfall (e.g. Vb cyclone) in combination with dry catchment conditions, which could occur during hot summers. This could result in a delayed Mulde response and a surprisingly large flood downstream.

5   Conclusions

20 In this study, flood wave superposition is analysed at 37 confluences in four large basins in Germany. Each confluence is characterised by a triple point of three gauges (tributary, main river (upstream, downstream)) which are jointly analysed regarding temporal matching and similarities in specific peak discharge during flood events. An approach is presented to disentangle the impact from tributaries on the downstream peak flow in terms of the temporal occurrence and peak magnitude.

The major outcomes of this study are:

25   1. Flood wave superposition is not the major driver for flood peak occurrence downstream of most confluences. Flood wave superposition can be regarded as an amplification mechanism for downstream flood peaks. These are largely driven by discharges from upstream branches.

  2. In general, the temporal superposition is partly constant in time lag and partly there is a strong variability of time lags among the floods at a specific triple point. In several cases, the tributary peaks precede the main river peak by about 2-5

30   days for most flood events. Several highly relevant tributaries in terms of their contribution show a prevailing peak delay (Mulde, Mosel, Inn), but bear a potential for strong flood amplification in case of delayed response. Future work will

analyse the probability for specific storm and catchment states capable of reducing the time lag with simultaneously high peak magnitude.

3. The impact of flood wave superposition is event-specific in terms of peak discharges in tributary and main river. At most of the confluences, no systematic differences are observed between small and the large floods. Either all floods are
5 enhanced systematically by wave superposition or the mechanism does not lead to extremes. Solely, at the Inn confluence, the flood wave superposition is found to be the driver of two medium large floods.

4. At several confluences, "see-saw" patterns of main stream and tributary flows are detected, i.e. lower flows in the main stream are compensated by larger flows in the tributary and vice versa. These confluences bear the potential to generate large floods if both upstream subcatchments react in resonance. Future work will investigate under which circumstances,
10 such reasonance is possible (different event and soil moisture patterns, different storm tracks).

Overall, we conclude that the superposition of flood waves is not the driving factor of flood severity in Germany. The developed methodology can be transferred to other basins and confluences and is not region-specific.

Author contributions. All authors have contributed to the design of the study, the discussion of the results and the writing of the article. SU did the GIS analyses and prepared the discharge data. SV and BG implemented the flood wave separation algorithm. BG carried out the
15 analyses and prepared the figures.

Competing interests. We declare that there are no competing interests

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Figure 1. Map of Germany with catchment elevation, major basins, rivers and gauges.

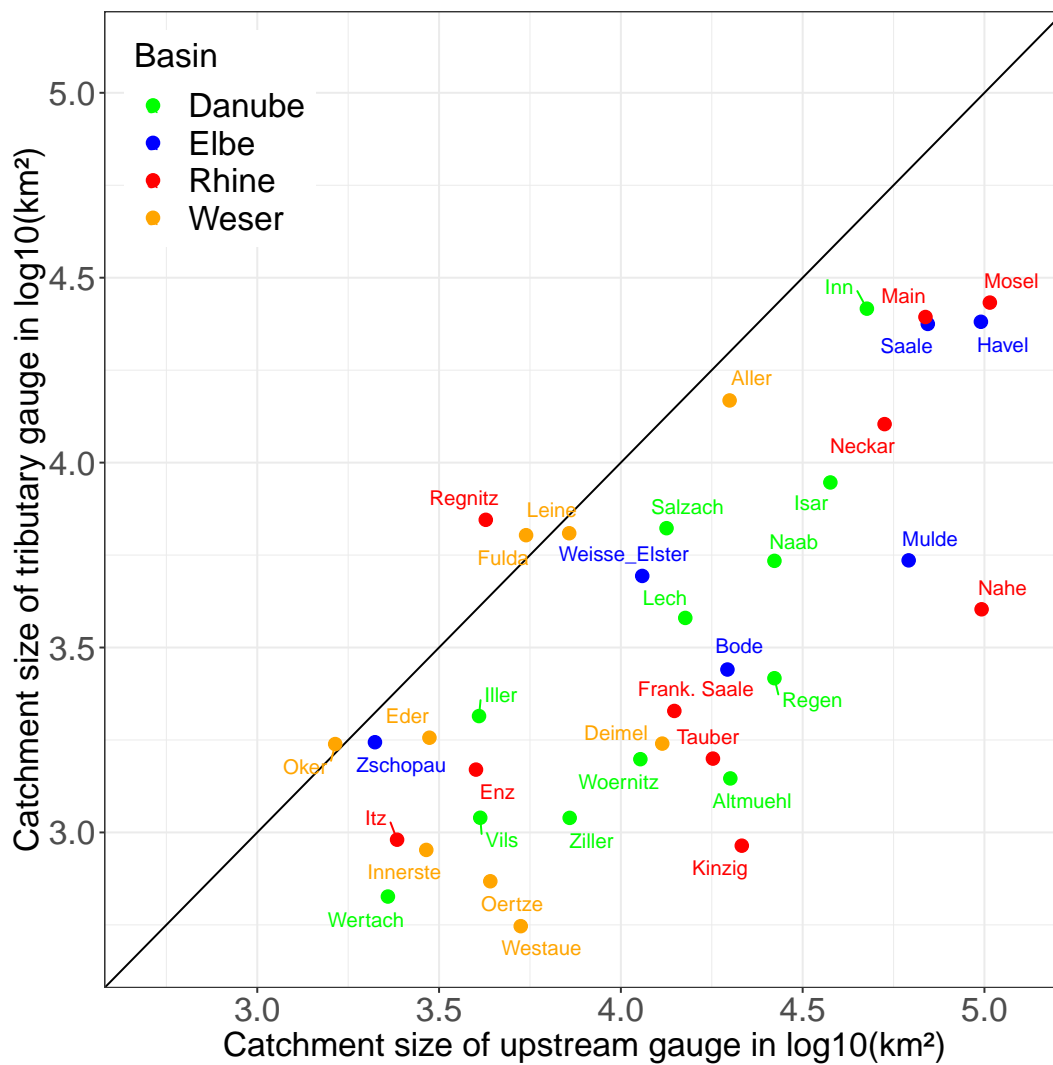



Figure 2. For each triple point, the catchment size of upstream and tributary gauge is shown in log scale. The tributary name is coloured according to the major river basins.

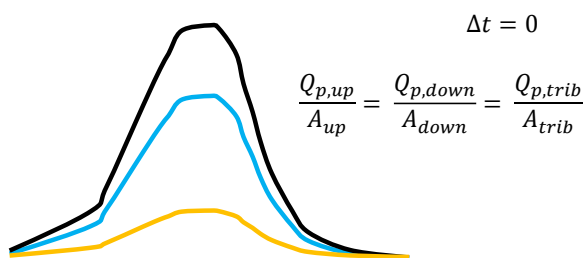
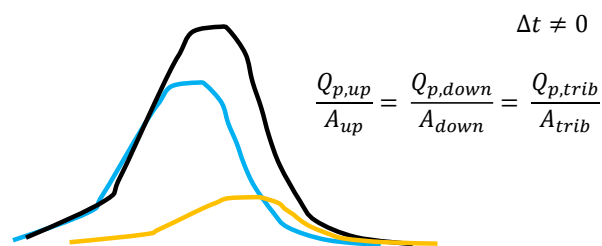
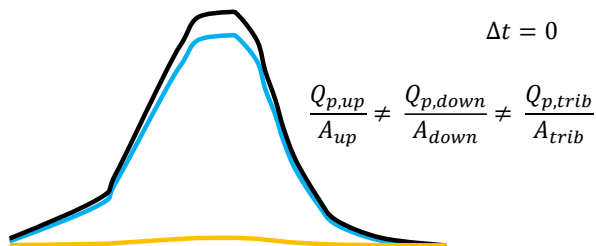
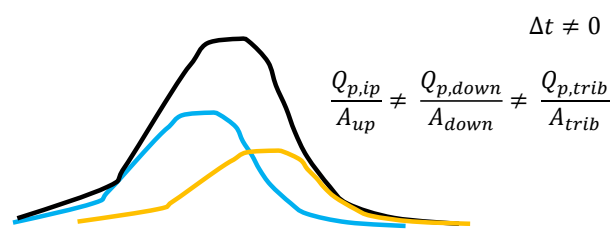
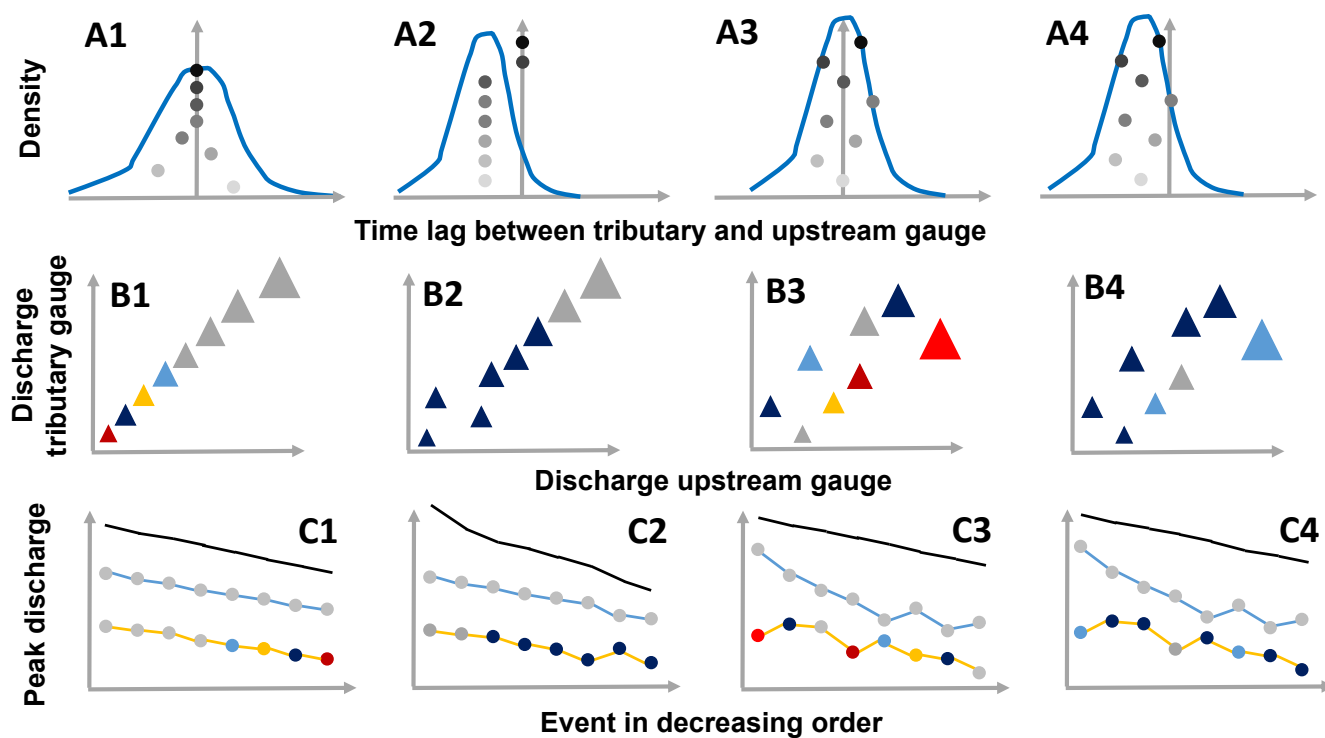



Figure 3. Four types of flood wave superposition.

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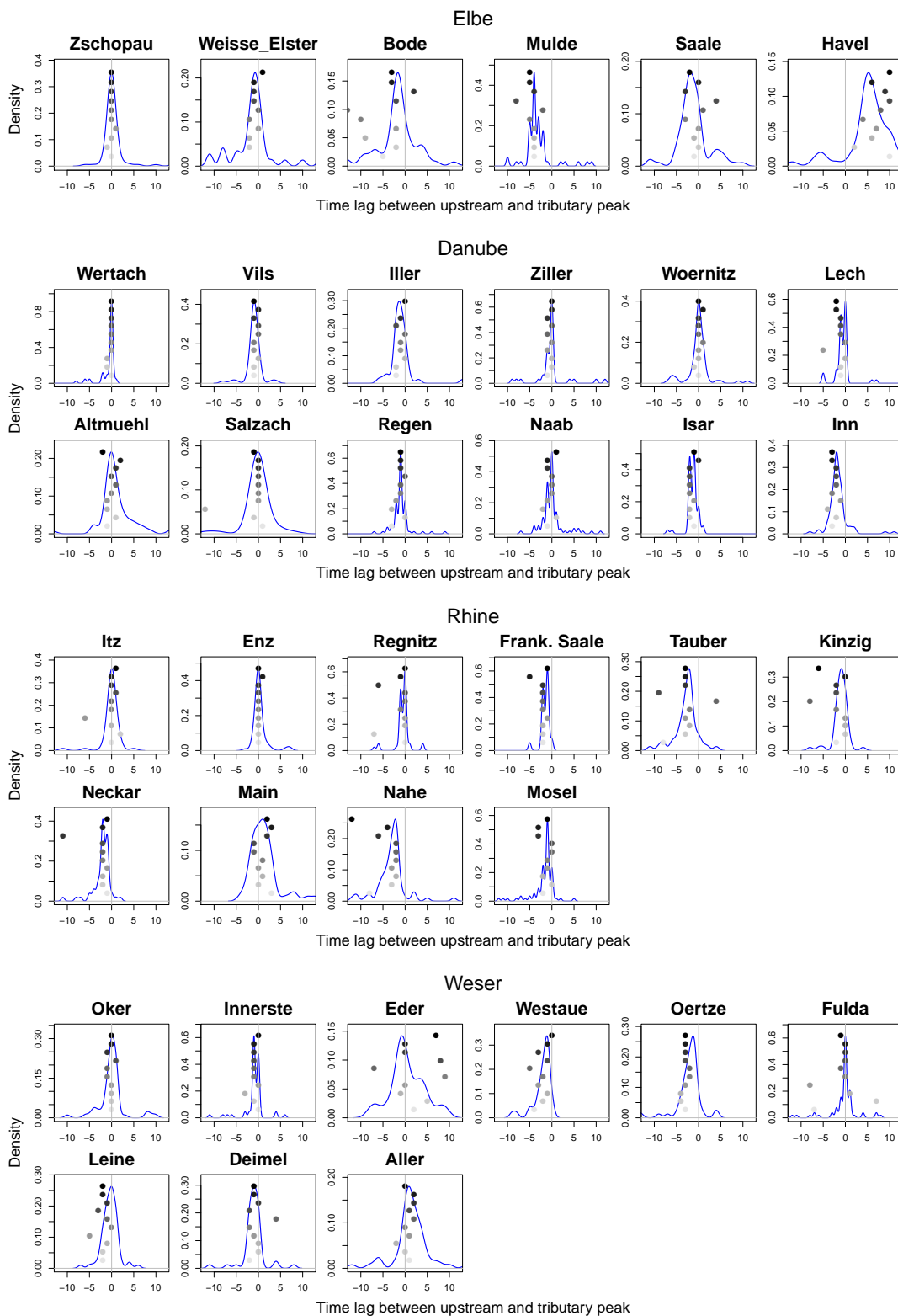
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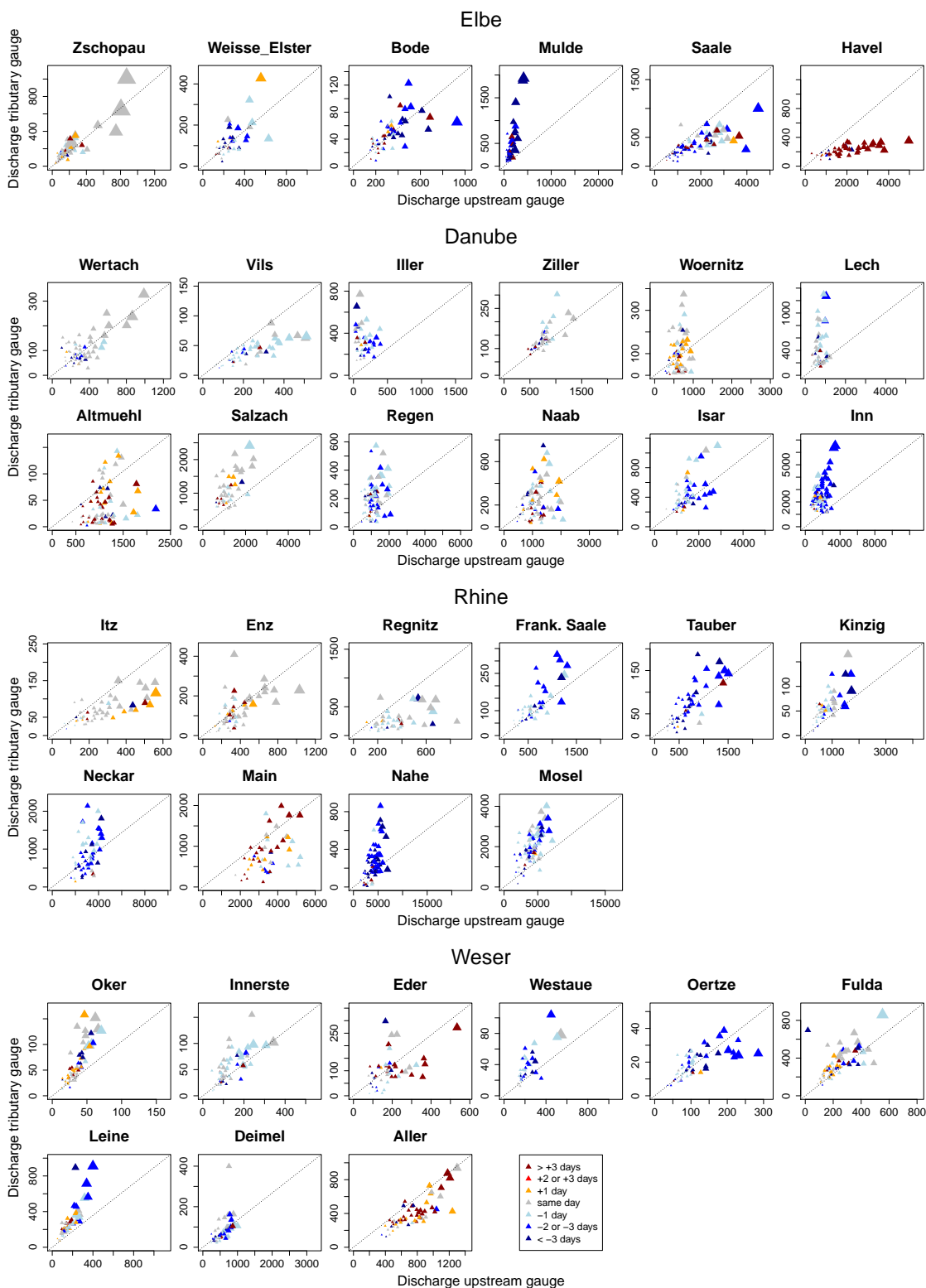
Figure 6. Relationship of peak discharge in upstream and tributary gauges for all selected events. The size of the triangles shows the downstream peak magnitude, normalised by the mean peak discharge. The colour expresses the time lag between tributary and upstream peak. Blue: upstream peak occurs later, Red: tributary peak occurs later.
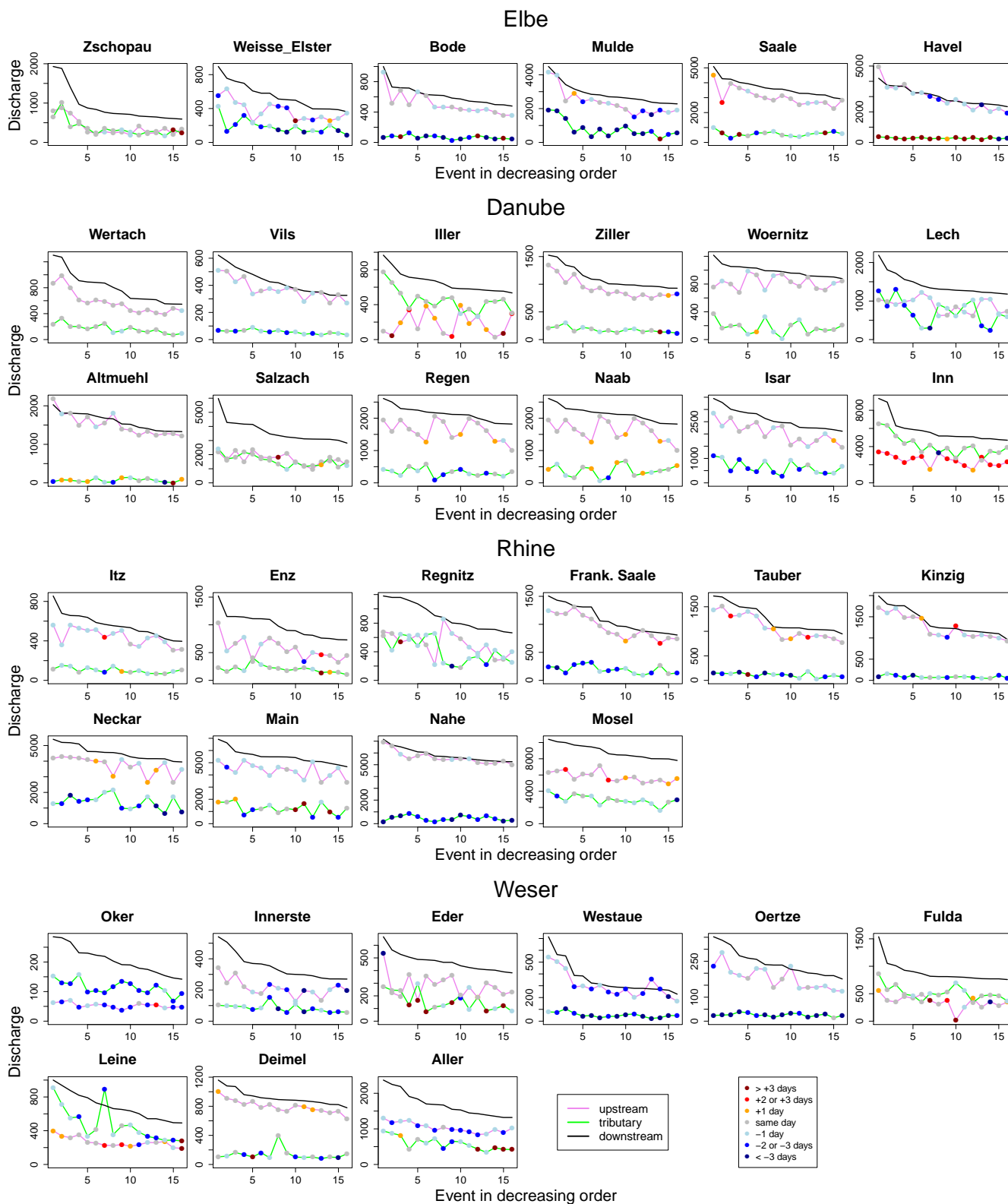
Figure 7. Event peak at upstream, tributary and downstream gauge, shown in decreasing order according to the downstream discharge. The points show the timing of upstream and tributary peak in relation to the downstream peak.

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Table 1. Triple points ordered by the catchment size of the downstream gauge. The percentages in brackets denote the share of the tributary and of the main river upstream gauge in relation to the catchment size of the downstream gauge. The last column shows the number of years for each triple points.

Upstream main river		Tributary		Downstream main river		Number of
Gauge name / River	Size [km2]	Gauge name / River	Size [km2]	Gauge name / River	Size [km2]	events/years
Elbe:						
Wechselburg/Zwickauer Mulde	2,107 (39%)	Kriebstein/Zschopau	1,754 (32%)	Golzern/Vereinigte Mulde	5,442	78
Naumburg-Grochlitz/Saale	11,449 (64%)	Oberthau/Weisse Elster	4,939 (28%)	Halle-Trotha/Saale	17,979	40
Bernburg/Saale	19,639 (83%)	Hadmersleben/Bode	2,758 (12%)	Calbe/Saale	23,719	56
Wittenberg/Elbe	61,879 (89%)	Golzern/Vereinigte Mulde	5,442 (8%)	Aken/Elbe	69,849	61
Aken/Elbe	69,849 (74%)	Calbe/Saale	23,719 (25%)	Barby/Elbe	94,060	76
Tangermuende/Elbe	97,780 (79%)	Havelberg/Havel	24,037 (20%)	Wittenberge/Elbe	123,532	54
Rhine:						
Schwuerbitz/Main	2,424 (57%)	Schenkenau/Itz	956 (23%)	Kemmern/Main	4,251	52
Plochingen/Neckar	3,995 (51%)	Pforzheim/Enz	1,479 (19%)	Lauffen/Neckar	7,916	66
Kemmern/Main	4,251 (33%)	Pettstadt/Regnitz	7,005 (55%)	Schweinfurt/Main	12,715	50
Wuerzburg/Main	14,031 (78%)	Wolfsmuenster/Fraenk. Saale	2,131 (12%)	Steinbach/Main	17,914	43
Steinbach/Main	17,914 (83%)	Tauberbischofsheim/Tauber	1,584 (7%)	Kleinheubach/Main	21,505	48
Kleinheubach/Main	21,505 (87%)	Hanau/Kinzig	921 (4%)	Frankfurt/Main	24,764	50
Speyer/Rhein	53,131 (77%)	Rockenau/Neckar	12,710 (19%)	Worms/Rhein	68,827	56
Worms/Rhein	68,827 (70%)	Frankfurt/Main	24,764 (25%)	Mainz/Rhein	98,206	50
Mainz/Rhein	98,206 (95%)	Grolsheim/Nahe	4,013 (4%)	Kaub/Rhein	103,488	71
Kaub/Rhein	103,488 (74%)	Cochem/Mosel	27,088 (19%)	Andernach/Rhein	139,549	79
Danube:						
Landsberg/Lech	2,287 (60%)	Tuerkheim/Wertach	671 (18%)	Augsburg/Lech	3,803	56
Muenchshofen/Naab	4,104 (74%)	Dietldorf/Vils	1,096 (20%)	Heitzenhofen/Naab	5,426	52
Berg/Donau	4,073 (54%)	Wiblingen/Iller	2,064 (27%)	Neu-Ulm/Donau	7,617	45
Jenbach-Rotholz/Inn	7,231 (85%)	Hart/Ziller	1,095 (13%)	Brixlegg/Inn	8,504	38
Dillingen/Donau	11,315 (75%)	Harburg/Woernitz	1,578 (11%)	Donauwuerth/Donau	15,037	70
Donauwuerth/Donau	15,037 (75%)	Augsburg/Lech	3,803 (19%)	Ingolstadt/Donau	20,001	49
Ingolstadt/Donau	20,001 (87%)	Eichstaett/Altmuehl	1,400 (6%)	Kelheim/Donau	22,950	78
Eschelbach/Inn	13,354 (52%)	Burghausen/Salzach	6,649 (26%)	Schaerding/Inn	25,664	48
Oberndorf/Donau	26,448 (75%)	Marienthal/Regen	2,613 (7%)	Schwabelweis/Donau	35,399	81
Oberndorf/Donau	26,448 (75%)	Heitzenhofen/Naab	5,426 (15%)	Schwabelweis/Donau	35,399	81
Pfelling/Donau	37,687 (79%)	Plattling/Isar	8,839 (19%)	Hofkirchen/Donau	47,496	54
Hofkirchen/Donau	47,496 (62%)	Passau/Inn	26,084 (34%)	Achleiten/Donau	76,653	81
Weser:						
Brenneckenbrueck/Aller	1,638 (37%)	Gross Schwuelper/Oker	1,734 (40%)	Celle/Aller	4,374	66
Greene/Leine	2,916 (55%)	Heinde/Innerste	897 (17%)	Herrenhausen/Leine	5,304	59
Grebenau/Fulda	2,975 (47%)	Fritzlar/Eder	1,804 (28%)	Guntershausen/Fulda	6,366	48
Herrenhausen/Leine	5,304 (82%)	Wunstorf/Westaue	558 (9%)	Schwarmstedt/Leine	6,443	34
Celle/Aller	4,374 (61%)	Feuerschuetzenbostel/Oertze	738 (10%)	Marklendorf/Aller	7,209	53
Guntershausen/Fulda	6,366 (51%)	Letzter Heller/Werra	5,487 (44%)	Hann.-Muenden/Weser	12,442	72
Marklendorf/Aller	7,209 (49%)	Schwarmstedt/Leine	6,443 (44%)	Rethem/Aller	14,730	71
Wahmbeck/Weser	12,996 (88%)	Helmarshausen/Diemel	1,739 (12%)	Karlshafen/Weser	14,794	51
Liebenau/Weser	19,910 (53%)	Rethem/Aller	14,730 (39%)	Intschede/Weser	37,720	58