Anatomy of simultaneous flood peaks at a lowland confluence

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Abstract. Lowlands are vulnerable to flooding due to their mild topography in often densely populated areas with high social and economic value. Moreover, multiple physical processes coincide in lowland areas, such as those involved in river-sea interactions and in merging rivers at confluences. Simultaneous occurrence of such processes can result in amplifying or attenuating effects on water levels. Our aim is to understand the mechanisms behind simultaneous occurrence of discharge waves in a river and its lowland tributaries. Here, we introduce a new way of analyzing lowland discharge and water level dynamics, by tracing individual flood waves based on dynamic time warping. We take the confluence of the Meuse river ($\sim$33,000 km^2) with the joining tributaries of the Dommel and Aa rivers as an example, especially because the January 1995 flood at this confluence was the result of the simultaneous occurrence of discharge peaks in the main stream and the tributaries and because independent observations of water levels and discharge are available for a longer period. The analysis shows that the exact timing of the arrival of discharge peaks is of little relevance, because of the long duration of the average discharge wave compared to typical time lags between peaks. The discharge waves last on average 9 days, whereas the lag time between discharge peaks in the main river and the tributaries is typically 3 days. This result in backwaters that can rise up to 1.5 m over a distance of 4 km from the confluence. Thus, local measures to reduce the impact of flooding around the confluence should account for the long duration of flood peaks in the main system.

1 Introduction

In January 1995, water was only a few centimetres below the crest of the dikes in the lowlands of the major rivers Rhine and Meuse. This high water event created fears for major flooding across large parts of the Netherlands, causing the Dutch government to decide to evacuate more than 200,000 inhabitants from the area immediately under threat. Luckily these fears did not materialise and people could return to their homes within a few days. However, this high water event did lead to local flooding (Figure 1). The flood occurred just upstream of the city center of 's Hertogenbosch, where two tributaries (Dommel and Aa) join, and spread over a small region. This small region included an economically important European highway and could have spread over a much larger area if the duration of the overtopping would have been longer (Figure 1). The overtopping was the result of water levels rising to 4.9 m above mean sea level (msl) in the Dommel, indicated by the water authorities as maximum protection level. It was concluded that the simultaneous occurrence of the discharge peaks in the Meuse river and the Dommel tributary likely caused the flooding, but no in-depth analysis of the simultaneous occurrence has been performed so far.

While simultaneous occurrence (coincidence) of high discharge and storm surge has been investigated (Kew et al., 2013; Klerk et al., 2015; Van Den Hurk et al., 2015), only few studies have addressed the processes leading to simultaneous occurrence of discharge peaks. In one of these studies, Pattison et al. (2014) analyzed the sensitivity of changing hydrological response to the relative timing and succession of discharge peaks by sub-watersheds, to investigate the possibility of reducing flood risk. The cause of the relative timing and succession, however, was not considered in their analysis, making it difficult to extrapolate their findings. A key point from their analysis was that flood impacts are unpredictable when synergy occurs between two sub-watersheds. In another study by Vorogushyn and Merz (2013), it is shown that a discharge wave accelerates with river training, resulting in simultaneous occurrence of flood peaks in the Rhine river and the Neckar tributary, which partly causes increasing Rhine flood discharges. Vorogushyn and Merz (2013) analysed the simultaneous occurrence of discharge peaks of the Rhine and Neckar based on trend analysis, without offering details of individual discharge events. While in rain-fed systems, the variability in the hydrograph shapes of individual peak discharge events can be so large, that changes in the relative timing cannot readily be translated to a change in flood risk.

Various factors contribute to the process of simultaneous occurrence of discharge peaks at lowland confluences. These include spatial precipitation distribution, precipitation duration, length of the drainage network, the slope of the catchment area and the antecedent soil moisture. The spatial-temporal variability of precipitation is a key factor in the simultaneous occurrence of discharge peaks. Since there are no discharge peaks to coincide if there is no rain in one of the catchment areas. The spatial precipitation pattern over a larger river basin and the lowland tributary might show little correlation (Betterle et al., 2017). Precipitation events exceeding 1 day can cover more than 10^4 km^2 (Merz and Blöschl, 2003; Skøien et al., 2003; Van de Beek et al., 2011, 2012) and may therefore be comparable for a part of the river basin, but not for the entire basin of medium-sized rivers (river lengths between 300 and 1000 km). On the other hand, the climatological precipitation maxima can be influenced by orographic effects and can therefore be relatively close to the lowland area, which after all lead to a correlated spatial precipitation distribution between both catchments. Even if the precipitation pattern would be homogeneous across both catchment areas, then the shorter drainage network length of the lowland tributary should result in discharge peaks reaching the confluence before the peak in the main river (Marchi et al., 2010; Melone et al., 2002). In addition to the factors spatial precipitation pattern and drainage network length, the process of simultaneous occurrence at confluence is influenced by duration of the discharge peaks (Meade et al., 1991). The multiple lowland tributaries can increase the duration of the discharge peaks due to the different arrival times at the main river and can therefore result in simultaneous occurrence of the discharge peaks, as has been reported for large river basins such as the Amazons (Meade et al., 1991). This leads to the question what the dominant factors are at medium-sized rivers and whether the event described above reflects a general pattern of possible simultaneous occurrence of flood peaks or simply is a rare extreme event.

This study aims to increase our understanding of simultaneous occurrence of flood peaks at confluences in lowland areas, by investigating the precipitation, discharge and water level dynamics for peak discharge events in the lower branch of the River Meuse. We will address the following research questions:

– Under which conditions do discharge peaks coincide at the selected lowland confluences?

– How are water level profiles in lowland tributaries affected by backwater associated with simultaneous occurrence of a flood peaks in the main river?

Peak discharge hydrographs vary in time due to heterogeneity in precipitation patterns and antecedent catchment characteristics. A single flood event may be insufficiently representative to gain generic insight into the conditions when discharge peaks coincide and what the consequences are. Here we carry out an analysis of a selection of events leading to the highest discharges, and establish the impacts on water levels. The precipitation patterns for these events provide insight in the variety of conditions that may lead to simultaneous occurrence of discharge peaks, whereas water level analysis offers insight into the possible consequences. Obviously, extreme water levels in tributaries can lead to inundation of larger areas when the surrounding region is flat (i.e. in lowlands).

The lowland Dommel and Meuse confluence is used as study area for two reasons. First, because simultaneous occurrence reportedly occurred in January 1995. Second, the study area is uniquely suited for this research since routine and independent observations of water height and discharge are available at several locations in the Meuse and its tributaries. The nine highest discharge events of the Meuse between 1999 and 2015 are analyzed in detail, to gain insight in the spatio-temporal precipitation and discharge patterns. For these events, the time lags between peaks in the Meuse and the Dommel and Aa are determined, as the timing indicates the potential of simultaneous occurrence of discharge peaks. We employ a method that is relatively new in hydrology to calculate time lags, dynamic time warping (DTW), which is introduced in Section 2 (Methods and Materials). The Meuse river basin, its tributaries and the employed discharge and precipitation data are described in more detail in the same section. Section 3 (Results) shows the precipitation patterns prior to these discharge events, and the resulting time lags between the Meuse and the tributaries Dommel and Aa for the studied discharge peaks. In addition, the effects of simultaneous occurrence of discharge peaks on water levels in the rivers are analyzed. Finally, we will discuss our results and conclude that the exact timing of the discharge peaks is not the single and most important factor in explaining the hydrological consequences of the simultaneous occurrence of discharge peaks at lowland confluences (Section 4, Discussion, and Section 5, Conclusions).

2 Methods and Materials

2.1 Dynamic Time Warping

Dynamic time warping (DTW) is a relatively new method and has so far seen few applications in the field of hydrology (Ouyang et al., 2010; Dupas et al., 2015). The DTW method compares time series to determine, for example the time shift or the similarity between these time series. Within hydrology, the DTW method can have great value to determine transports through the system, for example of substances or water quantities (Dupas et al., 2015). The method can therefore be used to compare transport effects through and between catchment areas, for example rainfall-runoff characteristics or distribution of pollutions. This comparison can be preformed for one discharge event or for multiple years. We have used the DTW method to determine the time lag between rainfall and runoff, and the time lag between the nine highest discharge peaks of the different catchments, namely of the Meuse and the Dommel and Aa. The advantage of DTW is that no assumptions are needed regarding

the definition of a wave in discharge time series. This is in contrast to common methods based on the centre of mass and the unit hydrograph. The only required input data are the discharge time series and a possible restriction of the warping path. We have used one week before and after the discharge peak as input signal. Considering discharge wave propagation, the time lags between stations cannot be infinite. Therefore, warping paths greater than one week are not used, but this warping path restriction can be increased for larger catchments. Moreover, the method has no difficulty with different diffusion effects of the discharge time series and DTW is unique in considering the time axis elastic / dynamic, which is desirable to match similar shapes in different phases, such as long wave propagation. Kruskal and Liberman (1983); Keogh and Ratanamahatana (2005) provide a detailed description of the DTW method. Below, we describe step-by-step the essence of the method using two discharge time series as an example (Figure 4a), x_i (upstream) with $i = 1..n$ and y_j (downstream) with $j = 1..m$.

– Step 1: Standardisation

For optimal matching of the time series, the amplitudes of x and y should be similar, which is achieved by standardizing both time series (through subtracting the mean and dividing by the standard deviation). This operation changes the hydrographs in terms of scale, but not in terms of shape and is similar to common methods such as cluster analysis. It is also used in other hydrological studies employing DTW (Ouyang et al., 2010; Dupas et al., 2015). A property of standardization is that the euclidean distances between two standardized time series can become equally spaced in periods without peaks, which makes the method unsuitable for DTW in these circumstances. This was prevented by limiting the analysis to the nine highest discharge peaks. The Derivative Dynamic Time Warping (DDTW) method can provide a solution to the need of standardization (Keogh and Pazzani, 2001), but the minor tidal influence at the lowland confluence makes DDTW not applicable in this case.

– Step 2: Euclidean and cumulative distance

The Euclidean distance, $d(x_i, y_j)$, between the two time series is expressed as an n-by-m matrix,

$$d(x_i, y_j) = |x_i - y_j|, \tag{1}$$

which should not be confused with the physical distance between the two stations. The distance is used to find optimal matches by minimizing the distances. The cumulative distance, $r(i, j)$, is the sum of the distance $d(i, j)$ of the current element and the minimum of the cumulative distances of the surrounding elements:

$$r(i, j) = d(x_i, y_j) + \min\{r_{i-1, j-1}; r_{i-1, j}; r_{i, j-1}\}. \tag{2}$$

Figure 4b shows the x and y time series below and to the left of the figure with the cumulative distance. The cumulative distance is shown using colors, with the lighter colors showing a smaller cumulative distances and the darker colors a larger cumulative distances between the samples of the time series. The figure also shows that the cumulative distance

increases to the end of the time series, which results from the summation of the (cumulative) distance from the smallest horizontal left, vertical up or diagonal upperleft element (right hand-side of the equation Equation 2) In the next step, we will further explain the path of the cumulative distance. The white spaces in the figure correspond to the warping path restriction of one week.

– Step 3: Warping path

The warping path, W, is a matrix that maps x to y with the lowest cumulative distance (black line in Figure 4b) and basically reconstructs the $i's$ and $j's$ of the right hand-side of the plus in Equation 2 (black line in Figure 4b). The warping path in Figure 4b connects thus the path with the lightest colours. The length of the path is not necessarily equal to the length of x or y due to the dynamic time lags, where i is not equal to j (horizontal and vertical movement of the warping path in Figure 4b). Hence,

$$W_x = w_1, w_2, ..., w_l, ..., w_L, \tag{3}$$

$$W_y = w_1, w_2, ..., w_l, ..., w_L, \tag{4}$$

where W_x and W_y are the $x's$ and $y's$, respectively, of the lowest cumulative distances with lengths, L, of $\max(m, n) \leq L < m + n$. In the given example n and m have 17 samples and L has 20 (Figure 4a and Figure 4c). The warping path is subject to the following constraints related to the dependency on the cumulative distance:

1. Boundary conditions: requires the warping path to start in the top left and end in the bottom right of the matrix (Figure 4b);

2. Continuity: restricts the allowable step size not to be greater than 1 relative to the previous i and j, thus moving horizontally, vertically or diagonally with steps of 1 (Figure 4b);

3. Monotonicity: forces the points in W not to go back in time (black line is only going down and/or to the left Figure 4b).

The boundary conditions constrain requires a start-up time before a 'stable' time lag is found. We used a start-up time equal to the warping path limitation, thus one week. The example in Figure 4b shows a start-up time of one day therefore w_1 and w_L are connected to the 2nd and the 16th sample, respectively. The final result of the warping path into a time serie is shown in Figure 4c. Note that the time series before and after warping are not equal. The W_x and W_y are not used for further analysis, because of the lack of physical interpretation of the time series after the warping proces, instead the indices to transform x and y into W_x and W_y are used in the further analysis.

– Step 4: Time lag and duration of discharge peaks

The difference between indices to transform x and y into W_x and W_y was not constant during the analyzed discharge wave, for example due to diffusion. When a diffusive discharge wave is compared with a non-diffusive discharge wave, the slope of the rising and falling limbs differ between the two waves. This difference results in a variation of the time lag along the rising and falling limbs of the discharge waves, regardless of the time lag influenced by advection. The time lag was calculated as the modal difference between the indices to transform x and y into W_x and W_y, as the modal difference is not influenced by diffusion. Figure 4b shows the time lag by the model of (diagonal) difference between the white dashed and the warping path. The time lag at w_1 is zero, at w_2 one and at w_L two, but the model time lag from w_1 and w_L is two days.

The duration of the discharge peaks was defined as the time the discharge is above the 5 % highest discharges over the fifteen analyzed years.

2.2 Study Area and Data

2.2.1 River Meuse

The Meuse drains an area of 33,000 km^2 between northern France and the Netherlands (Figure 2) and experiences a temperate climate. The Meuse is mainly rain-fed and has an average annual discharge of 350 m^3 s^{-1}. The rain-fed flow regime is erratic and the catchment has different geological and orographic settings, causing different response times and precipitation patterns within the Meuse catchment area (Berger, 1992; De Wit et al., 2007; Leander et al., 2005). The Meuse can be divided into three parts: Meuse Lorraine, Ardennes Meuse and the lowland Meuse (see De Wit et al., 2007). Meuse Lorraine has mild valley slopes and lies between two ridges. It therefore responds temperately to precipitation, which is partly retained in reservoirs. The Ardennes Meuse consists mainly of hard rock, has steep valley slopes, and as such responds flashy, besides some retention in reservoirs. The lowland Meuse has very mild slopes and lies in deep alluvial deposits and therefore responds slowly to precipitation. The largest amount of precipitation falls in the Ardennes and therefore contributes most to the discharge (Leander et al., 2005; Rakovec et al., 2012).

2.2.2 Tributaries Dommel and Aa

The Dommel and Aa catchments represent 5 % of the Meuse catchment and flow from the Belgian Kempen region to the Dutch city of 's Hertogenbosch (Figure 2). The average discharges of the Dommel and the Aa are 14 m^3 s^{-1} and 8 m^3 s^{-1}, respectively, and their gradients are $\sim$ 75 m per 100 km. The Dommel and Aa are rain-fed and, due to the high groundwater levels, have a flashy character despite the rivers' deep alluvial basins. The Aa has been straightened and canalized in the past hundred years. The Dommel has mostly kept its natural plan form. Downstream of the confluence of the Dommel and Aa, the river is called Dieze. When the water level in the Dieze is less than 5 centimetres higher than the Meuse, the weir in the Dieze is closed and the water discharges through the Drongelse Canal, which has a capacity of 100 m^3 s^{-1}. The aim of the river training is to prevent the Meuse from flooding areas in the Dommel and Aa catchments. Retention areas of 8.60 million m^3 are

used when the discharge capacity of the Drongelse Canal is not sufficient in discharging the Dommel and Aa when the weir to the Meuse is closed. The weir in the Dieze was closed only for a few hours in the focus period 1999–2015, namely during the January 2011 event.

2.2.3 Discharge and Precipitation Data

In this study, we used hourly measured water levels and discharges of the Meuse at Megen (MU) and of the Dommel (DD) and Aa (AD) between 1999 and 2015 (Figure 1). Flow velocities were measured every 15 minutes using a current meter, FLOW 2000 measuring device. The flow velocities were converted to discharges using a known cross sectional area. The water level differences were computed by subtracting MD from MU, and DA from DD or AD (Figure 1). The water levels in this area are controlled by weirs and dikes due to the high flood risk, but the position of the gauging stations were chosen such that the water levels would be least influenced by the weirs.

In addition to discharge and water level data, a data set of daily precipitation for Europe was used (Haylock et al., 2008). The data set interpolates the European precipitation observations (using the European Climate Assessment Data set; https://www.ecad.eu/) on a grid of 0.25°latitude by 0.25°longitude. The combined Dommel and Aa catchment areas and the Ardennes catchment area are extracted from the data set using the green boxes in Figure 2. The precipitation sum over the catchment, thus the sum over the area of the boxes, are used in the analysis, because the highest discharge and precipitation peaks will generally have the largest flood implications in case of simultaneous occurrence. The nine highest discharge peaks at Megen (MU) were analyzed (Figure 3). High evaporation rates in summer cause a strong seasonal discharge cycle. The highest precipitation peaks in summer will therefore be stored in the soil or evaporated, and will not result in discharge peaks. As a result, the timing of the nine highest discharge peaks does not match with the nine highest precipitation peaks in the Meuse and Dommel.

2.3 Response Times and Time Lags

Simultaneous occurrence of discharge waves is caused by a combination of similar precipitation and discharge patterns in two catchments (Betterle et al., 2017). We first analyze the rainfall-discharge response times for the nearest gauging stations upstream of the confluences subject to study, indicated with DD, AD and MU in Figure 1. For these stations, we calculate the time lags between peaks in rainfall and discharge using the dynamic time warping method (DTW). The time lags are calculated in days and hours for ,respectively, the rainfall and discharge.

Subsequently, we analyse the travel time needed for a discharge peak to move from the gauging station to the confluence, based on the celerity of the flood wave (Jansen et al., 1994, p. 64-65). In order to be able to determine the time lag between a main river and a tributary at a confluence, the celerity from the nearest gauging station to the confluence is determined and added to the timing of the measured discharge peaks. The travel time of the discharge peak can be approximated by:

$$t_c = \frac{s}{\sqrt{g \cdot h}}, \tag{5}$$

where t_c (s) is the travel time of a discharge peak from gauging station to confluence, s (m) the distance from gauging station to confluence, g (m s^{-2}) the gravitational acceleration and h (m) the mean water depth during the discharge peak. We used the mean water depth to keep the travel time constant during the discharge wave. The average travel time from the gauging station to the confluence for the Meuse is 2 hours. It is negligible for both the Dommel and the Aa. Hence, in order to calculate the degree of simultaneous occurrence of discharge peaks at the confluence, 2 hours are subtracted from the time lag between the main river and tributary determined from the gauging stations.

Together, these two time lags serve to understand the meteorological and hydraulic conditions leading to the discharge events. In addition, the time lags between the main river and its tributaries were determined, again based on DTW.

3 Results

Rainfall in the Meuse river basin is mainly concentrated in the Ardennes and surrounding area as a result of orographic effects (Figure 5). The precipitation patterns of 5-daily precipitation sums preceding discharge peaks show that both catchments typically receive large sums, with the sums over the Ardennes part of the basin generally being larger. Even though the combined Dommel/Aa catchment and the Ardennes catchment are separated by 150 kilometres (the green boxes in Figure 5), daily precipitation patterns over the two catchments are spatially correlated (Figure 6). Figure 6 shows the daily precipitation summed over the Ardennes and the Dommel/Aa catchment areas over the period of the past 45 years. As result of the multiple measurements without precipitation, the data has been transformed into a Gumbel distribution to focus on the high precipitation events. The scatter plot shows that the simultaneous occurrence of the high precipitation events in both the Meuse and the Dommel/Aa catchment areas occur 2.9% over the past 45 years in relation to 5% and 0.25% in case of complete correlation and in case of randomness, respectively. The daily precipitation summed over the Ardennes and the Dommel are not completely correlated due to travel times and increase or decrease of rainfall events. The lines in Figure 6 indicate that most precipitation events do not consist of a single day event and therefore a combination of multi-day and heavy precipitation event results in high discharge events. The highest discharge events are caused by multi-day precipitation events or by a series of precipitation events with an interval of a couple of days.

The average response times between precipitation and discharge at the three gauging stations close to the junctions subject to study are 3 days for MU (Figure 5), 2 days for DD and 1 day for AD, with standard deviations of approximately half the average response times. These standard deviations emphasize the large variability of the events. The response times suggest that precipitation events occurring within a two-day interval may lead to a higher probability of simultaneous occurrence of the maxima of discharge waves. Inundations with societal impacts are reported for the discharge events of 2003, 2010 and 2011 in Wallonia (Belgium) and in the southern regions of the Netherlands. The computed response time for the severe precipitation event of 2003 to a discharge peak is negative, because the discharge measuring device failed and consequently leads to an incomplete discharge wave. The high discharge events show that the response time from precipitation to discharge not only depends on the intensity and duration of the precipitation event, but also on wave attenuation (Woltemade and Potter, 1994;

Turner-Gillespie et al., 2003; Sholtes and Doyle, 2011) and initial conditions of the catchment before the discharge peak, such as antecedent soil moisture (Figure 3).

Our results show that the precipitation patterns for the Dommel/Aa and Meuse catchment areas are correlated (Figure 6), which underlines the importance of the time lags between the discharge peaks of the Meuse and the Dommel/Aa to assess the potential for simultaneous occurrence of discharge waves. The discharge waves in the Dommel and Aa arrive at the confluence 3.2 and 2.7 days prior to the discharge wave in the Meuse, respectively (Figure 7). The time lag of the Aa is thus half a day smaller, likely because of the shorter drainage length and the higher degree of canalization of the channels. The corresponding standard deviations are 16 hours (0.67 days) for the Dommel and 28 hours (1.17 days) for the Aa. Note that the discharge of the Aa has been measured only since 2004, which explains the absence of time lags prior to 2004. Figure 8 shows the average travel time of the nine highest discharge waves along the Meuse catchment. The tributaries increase the peak discharges in the Meuse, which is shown by the increasing circle sizes along the Meuse. In addition, some tributaries show similar time lags at the confluence joining the Meuse, which indicates possible simultaneous occurrence of upstream confluences. We conclude that the average time lags between the arrival of discharge peaks from the Meuse-Dommel and Meuse-Aa confluences are larger than the average response time of discharge at the monitoring stations to precipitation events. Thus, when processes of runoff generation are fast, simultaneous occurrence of discharge peaks is unlikely.

Although discharge peaks may not coincide, the question remains whether the time lag between the discharge waves is large enough to prevent simultaneous occurrence of high discharges. Figure 9 shows the precipitation of the Meuse and the tributaries Dommel and Aa, as well as the standardized discharge waves. The colored discharge waves are the periods during which the standardized discharge exceeds the 95th percentile of the time series. Unfortunately, some data gaps (caused by measurement errors) are present in the time series during discharge waves. Despite this, it is evident that all nine highest discharge waves show color overlap and thus coincide.

The fact that simultaneous occurrence of discharge waves takes place for all analyzed extreme events can be explained from the relatively long durations of the discharge waves. The duration of the discharge waves is 9 days on average at MU and even 13 days for the three highest discharge waves (Figure 7). The average time lag between the discharge waves of 3 days is therefore too small to prevent simultaneous occurrence. Figure 10 shows the discharges in the Meuse and Dommel upstream of the confluence over the analysed 15 years , with and without applying a 3-day time shift corresponding to the left and right panels (respectively). Similar to the precipitation sum, the discharges are transformed into a Gumbel distribution to emphasize the high discharges over the low discharges. The Meuse and Dommel discharge are in 2.5% of the time both higher than 5% of their discharge, which is in between complete correlation and randomness. The Meuse and Dommel discharges are not completely correlated as consequence of the time lag between Meuse and Dommel discharge. The application of the time shift increases however the correlation for the highest discharges only slightly, which is apparent from the increase of data points in the top right quadrant from 2.5% to 2.7%. The lines in Figure 10 show that, besides the time shift, most of the nine events move through all quadrants, which implies that the scatter is due to the different peak duration length by for example, spatial rainfall distribution and size of catchment.

From a water management perspective, it is relevant to establish the degree to which simultaneous occurrence of discharge waves affects extreme water levels. During high discharge events the water level difference over a distance of 40 km in the Meuse between MU and MD (Figure 1) increases by about 1.5 m (Figure 11). Afterwards, it decreases to the water level difference typical for normal discharges (0.5 to 1 m). The water level differences in the Dommel (between DD and DA) and Aa (between AD and DA), on the other hand, decrease from about 1.5 m to 0.5 m and in some cases the difference even vanishes during peak discharges, and increases afterwards over a distance of 4 and 6 km, respectively (Figure 11). Hence, the water level differences decrease during a discharge event in the tributaries, reflecting backwater effects of the Meuse on the tributaries also visible in the the corresponding stage-discharge relation (Figure 12). The backwater height can reach 1.5 m over 4 km from the confluence in the Dommel and Aa tributaries.

4 Discussion

The exact time lag between discharge waves in the main river and the tributary is shown to be less relevant than the duration and magnitude of the discharge waves. The impacts of simultaneous occurrence of discharge waves depend strongly on the detailed hydrograph of the discharge wave, which may have a composite character. The probability of simultaneous occurrence of discharge peaks, as referred to in existing studies (De Wit et al., 2007; Vorogushyn and Merz, 2013), becomes less relevant when the duration of the discharge waves becomes large compared to the time-lag between the arrival of discharge waves from branches joining at a confluence. The amount of discharge before or after the peak can be relatively high, and can lead to backwater effects in the tributary similar to those generated during a true event of wave peak coincidence. The choice of an appropriate discharge threshold is critical in the analysis, because it determines the portion of the discharge wave taken into consideration. The threshold here employed to isolate the 9 extreme discharge events does not influence the results of the DTW method, which shows that DTW can be considered a robust tool when analysing the interaction between discharge waves. Catchment properties and climate characteristics are known to determine the duration of discharge peaks (Gaál et al., 2012). This study adds main stream-tributary interaction as an important factor influencing the local duration of a discharge wave in lowland areas.

Based on our analysis and a literature review, the following conceptual framework for simultaneous occurrence emerges (Figure 13). The time lag between discharge peaks at the confluence and the duration of the discharge waves are the most important parameters for determining whether discharge peaks coincide (given that precipitation falls over both drainage areas). Figure 13 shows the proposed conceptual framework with relations between factors influencing the time to peak discharge at the outlet and the duration of discharge waves. Since the time lag between the catchment is of interest for simultaneous occurrence of discharge peaks, we consider the differences of the factors influencing the time to peak discharge as conceptual representation of the time lag between the catchments (dashed box in Figure 13). The time to peak discharge at the confluence is positively related to the drainage network length, amount of precipitation / discharge and friction and a negatively related to slope and antecedent soil moisture. The slope and drainage length are the predominant factors influencing the time to peak discharge in catchments. The duration of the discharge wave is positively related to the amount of tributaries, friction,

duration of precipitation and time to discharge and is thus also related to the factors influencing time to peak discharge. The friction factor can occur in various forms, such as roughness in watercourse, transport through soil or river training by e.g. weirs. Figure 13 can be used to conceptual understand the effects of other climates and catchment areas. For example, if most precipitation in the Meuse basin would be concentrated further upstream (which may be expected in many other lowland areas), the difference in travel time would merely increase by about two days (Figure 8). Two days extra travel time would still result in simultaneous occurrence of discharge peaks at the confluence for most of the analyzed discharge waves. Another example is the Amazon River for which simultaneous occurrence of discharge peaks is described by Meade et al. (1991). A discharge wave in the Amazon River lasts for 4 months in the wet season and coincides with discharge waves from tributaries that can peak one month to two months earlier. The simultaneous occurrence of discharge waves in the Amazon region is the result of the duration of precipitation in the Amazon area, which can also last for four months (Arvor et al., 2017; Marengo et al., 2001; Buarque et al., 2011). A more extensive investigation into multiple confluences and climates would have an added value in understanding simultaneous occurrence of discharge peaks and the presented method provides a generic tool for further investigation of the influencing factors and processes.

The common practice of determining the discharge using stage-discharge relations is not applicable near confluences, because one cannot account for the backwater effects apparent as hysteresis in a rating curve (Figure 12, see also Hidayat et al., 2011, 2016). Especially during the highest discharge waves, backwater effects show the most variation. For this reason, the exceedance levels of the upstream stations of the confluence cannot directly be projected to locations closer to the confluence. Establishing the exceedance levels and stage-discharge relations for regions near a confluence therefore presents challenges for water management and introduces one of the causes for spatial variation in flood risk.

The aim of the current Dutch water policy is to retain water in small catchments contributing to the main rivers, mainly to prevent drought and to improve water quality. From a flood risk perspective, water should preferably be retained for the duration of the discharge peak in the main river. An existing concern is that the current practice of water retention in the Dommel and Aa catchments increases flood risk, by enhancing the probability of coinciding flood waves. Our analysis puts the importance of the relative timing of flood waves in perspective. The average duration of extreme discharge events is 9 days in the study area, and it is not so relevant when in this period the peaks in discharge of the Dommel and Aa occur. A significant reduction in flood risk would only be achieved when the water is retained for a period covering multiple rainfall events, which is far from the present-day situation.

5 Conclusions

Extreme discharge events at the confluence of the River Meuse and two joining lowland tributaries are studied, introducing a new method of analysis based on dynamic time warping. The method offers robust means of tracing individual discharge waves in discharge time series collected throughout a catchment. The study shows that the precipitation patterns in the catchment areas are spatially correlated. Spatial correlation of the precipitation patterns is a prerequisite for simultaneous occurrence at the confluence. From a comparison of the nine highest discharge waves in the main stream and the joining lowland tributaries

it follows that the exact timing of the discharge peaks and the probability of simultaneous occurrence of discharge peaks are little relevant to flood risk. The duration of the discharge wave in the main stream is large compared to the time lags between discharge peaking in the main channel and the tributaries. Initial catchment characteristics produces ambiguous discharge responses to precipitation, such that the timing of duration and magnitude of the discharge peak relative to the precipitation is variable. When discharge waves coincide, the water level difference in the Meuse increases and the water level differences in the tributaries Dommel and Aa decrease. The decrease of water level differences indicates backwater effects in the tributaries due to simultaneous occurrence. The backwater height can increase to 1.5 m over 4 km from the confluence in the Dommel and Aa rivers. A public belief is that rapid drainage in a lowland tributary will reduce flood risk, because it diminishes the likelihood of coincident discharge peaks in the main stream and the tributary. In addition, there is a concern that measures of water retention, for example to prevent drought and to improve water quality, will increase flood risk. Our analysis puts this concern into perspective, as a systematic retention in the order of days will only marginally affect peak water levels.

Code and data availability. The DTW code can be requested from the corresponding author and the data can be requested at the mentioned organizations:

– Dutch water level and discharge data are measured by Rijkswaterstaat, which are available via https://www.rijkswaterstaat.nl/water/waterdata-en-waterberichtgeving/waterdata/index.aspx

– Walloon water level and discharge data are measured by Service Publique de Wallonie (SPW), which are available via http://voies-hydrauliques.wallonie.be/opencms/opencms/fr/hydro/Archive/annuaires/index.html

– French water level and discharge data are measured by Direction Générale de la Prévention des Risques/Service des Risques Naturels et Hydrauliques (DGPR/SRNH), which are available via http://www.hydro.eaufrance.fr/

– Dommel water level and discharge data are measured by "De Dommel" water board, which are available via the contact person Michelle Berg

– Aa water level and discharge data are measured by "Aa en Maas" water board, which are available via the contact person Pim van Santen

– Rainfall data are collected from the E-OBS dataset, which are available via http://www.ecad.eu

Competing interests. The authors declare that they have no conflict of interest

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hydrauliques, Département des Etudes et de l'Appui à la Gestion, Direction de la Gestion hydrologique intégrée; HYDRO Bank MEEDDAT (Direction Générale de la Prévention des Risques/Service des Risques Naturels et Hydrauliques) / DGPR / SRNH ; Dutch water boards "De Dommel" and "Aa en Maas" in collaboration with STOWA, Dutch Foundation of Applied Water Research, for providing discharge and water level data. In addition, the authors acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu). Data can be requested at the aforementioned organizations. The authors furthermore would like to thank Michelle Berg for organising a meeting with the water managers to evaluate the problems and together with Pim van Santen for helping out with the datasets. The authors also would like to thank their colleagues Lieke Melsen and Claudia Brauer for reading the first drafts.

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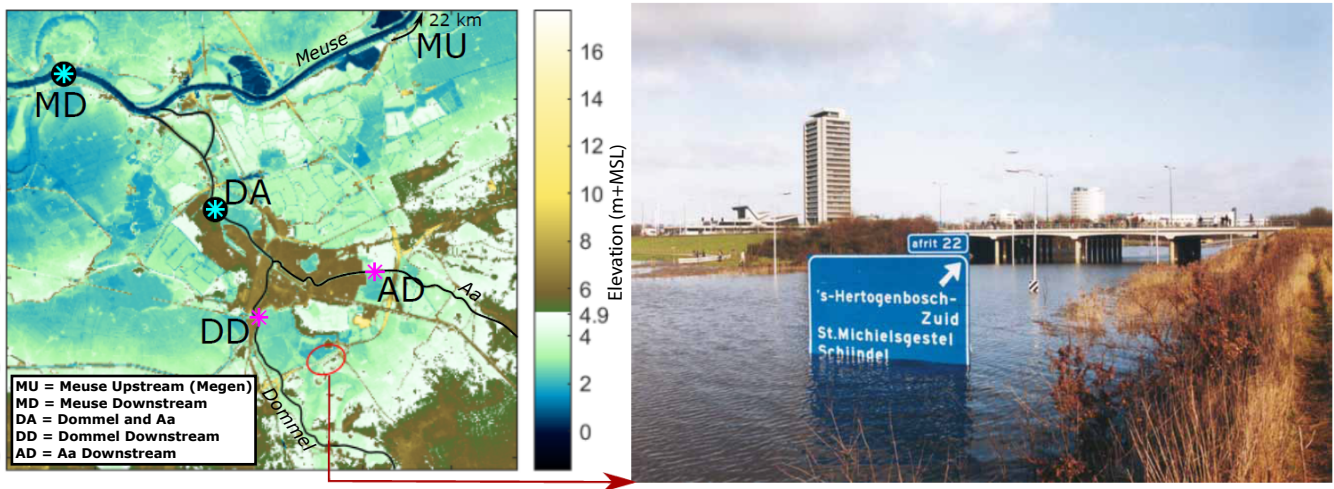
Figure 1. Flood proneness near the confluence of the Meuse and the tributaries Dommel and Aa. Left panel: DEM of the area around the Dutch city of 's Hertogenbosch is shown. The green and blue colors indicate areas below 4.9 m above MSL (the maximum water level in the Meuse that was reached in January 1995 and also the maximum protected flood level). These areas are, at least potentially, prone to flooding. The magenta asterisks indicate gauge stations with discharge and water level data and the cyan asterisks indicate stations with only water level data. The red circle indicates the flooded area of the European highway E25 (right panel; IJpelaar et al., 2009).
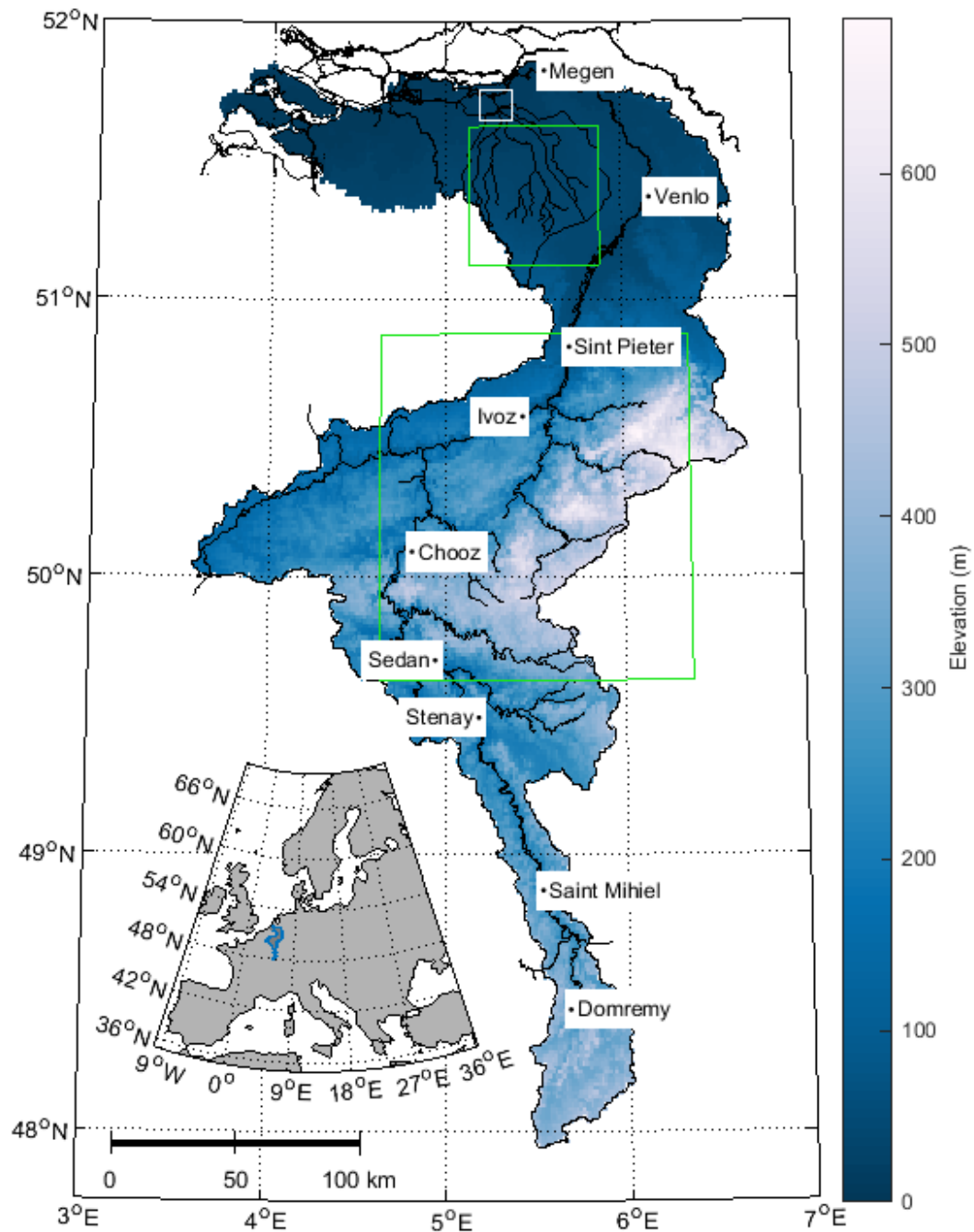
Figure 2. Map of the Meuse, Dommel and Aa catchments. The locations of the main gauging stations in the Meuse are shown. Color indicates elevation, and green boxes indicate the areas over which the precipitation is assumed representative for the Meuse and Dommel/Aa catchments, respectively. The white box indicates the area of Figure 1
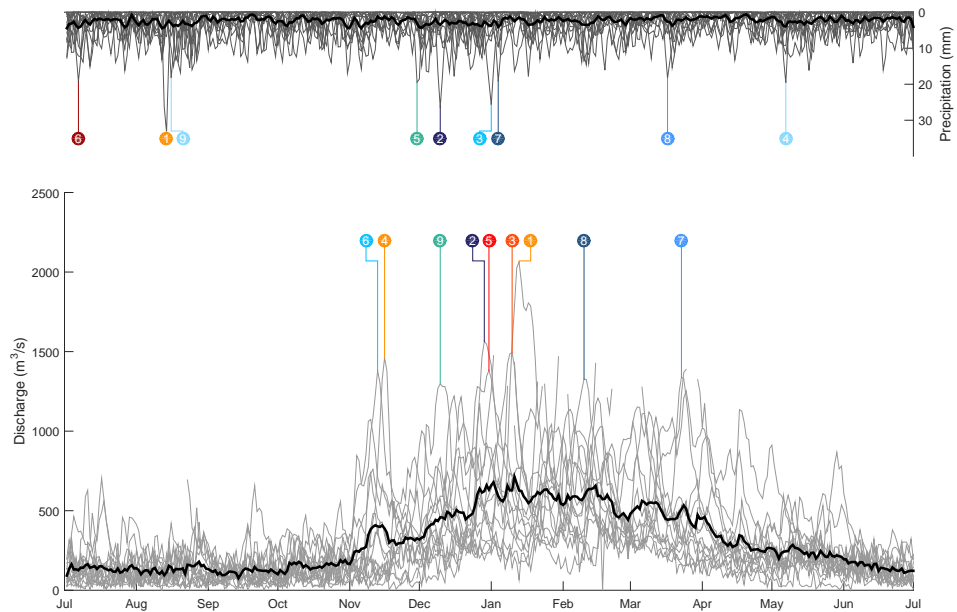
Figure 3. Precipitation and discharge extremes for the Meuse. The grey lines show measurements and the black line shows the average value over the measuring period. The colors of the peaks indicate the year and the numbers the decreasing order of the maximum discharges. Note the strong seasonality in discharge, with peaks only occurring in the period November–March, whereas precipitation events occur year-round.
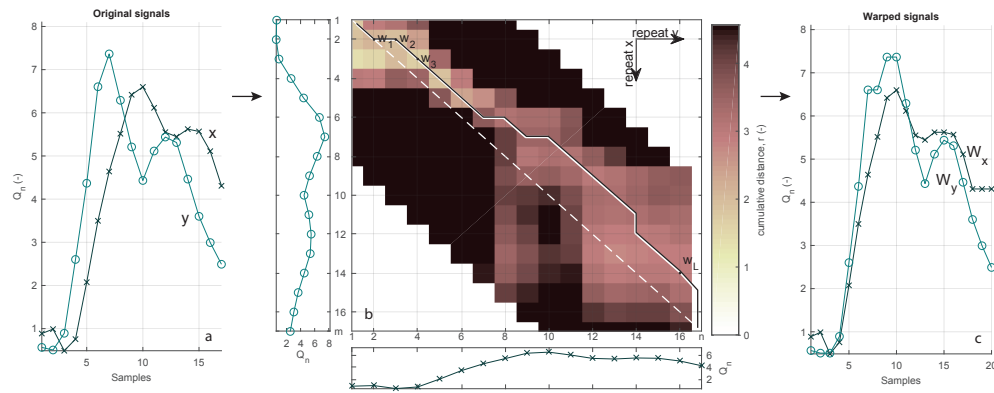
Figure 4. Principle of Dynamic Time Warping. The original time series (a) were used for the cumulative distance matrix (b), which shows the cumulative distance between points in the time series on the x-axis and y-axis. The black line shows the warping path and the white dashed line shows the path without time lag. The difference between the black and the white dashed line is the visualized time lags. The warping path was used to construct the warping signals (c).
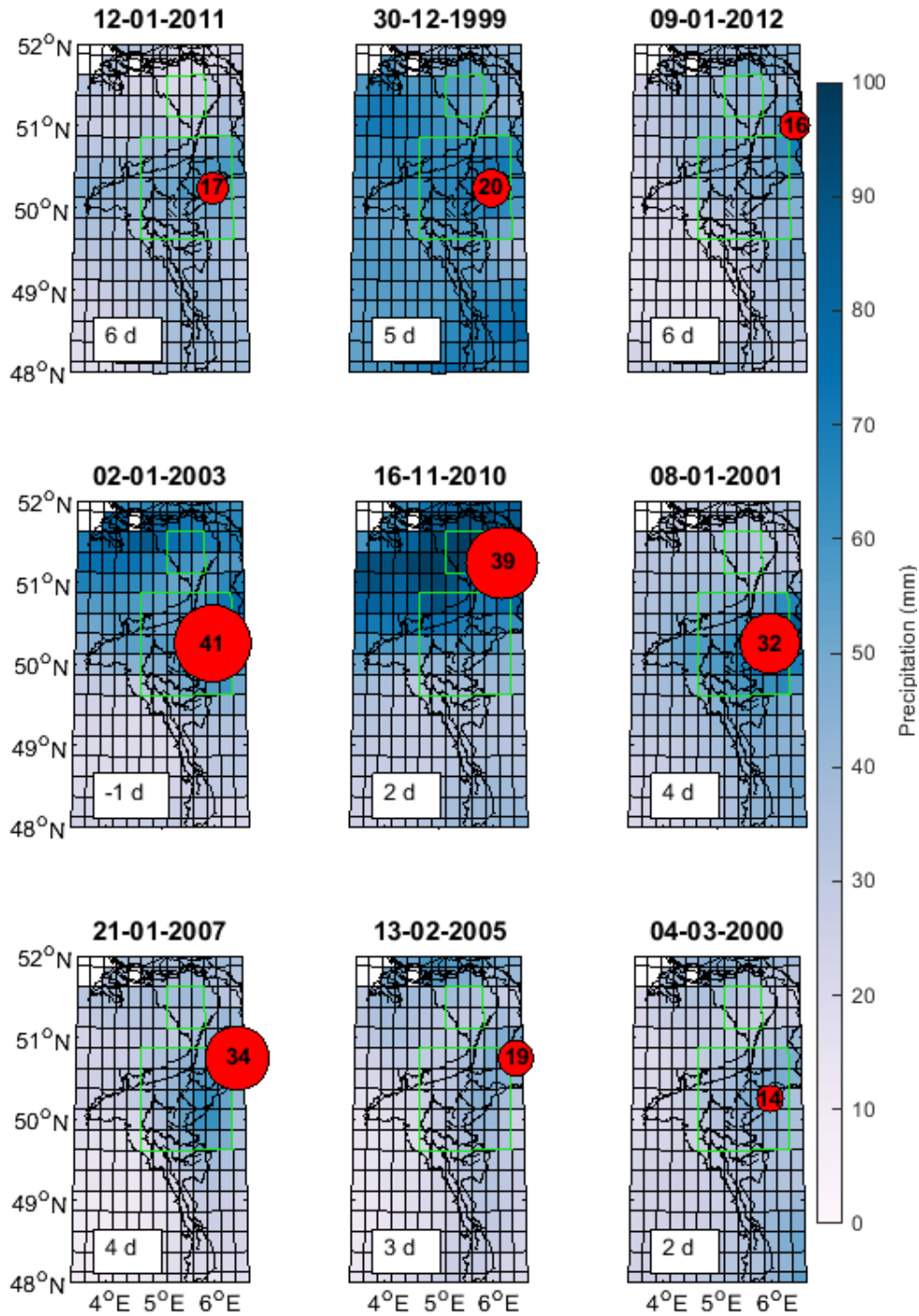
Figure 5. Distribution of the 5-day precipitation sum preceding the discharge peaks at Megen (MU). The red circle represents the location and the amount of the highest daily precipitation sum (mm). The numbers in the boxes show the time delay between the day with the largest precipitation sum and the discharge peak at MU (d). The flood peaks are arranged from highest flood peak (top left) to lowest flood peak of the nine events (bottom right)
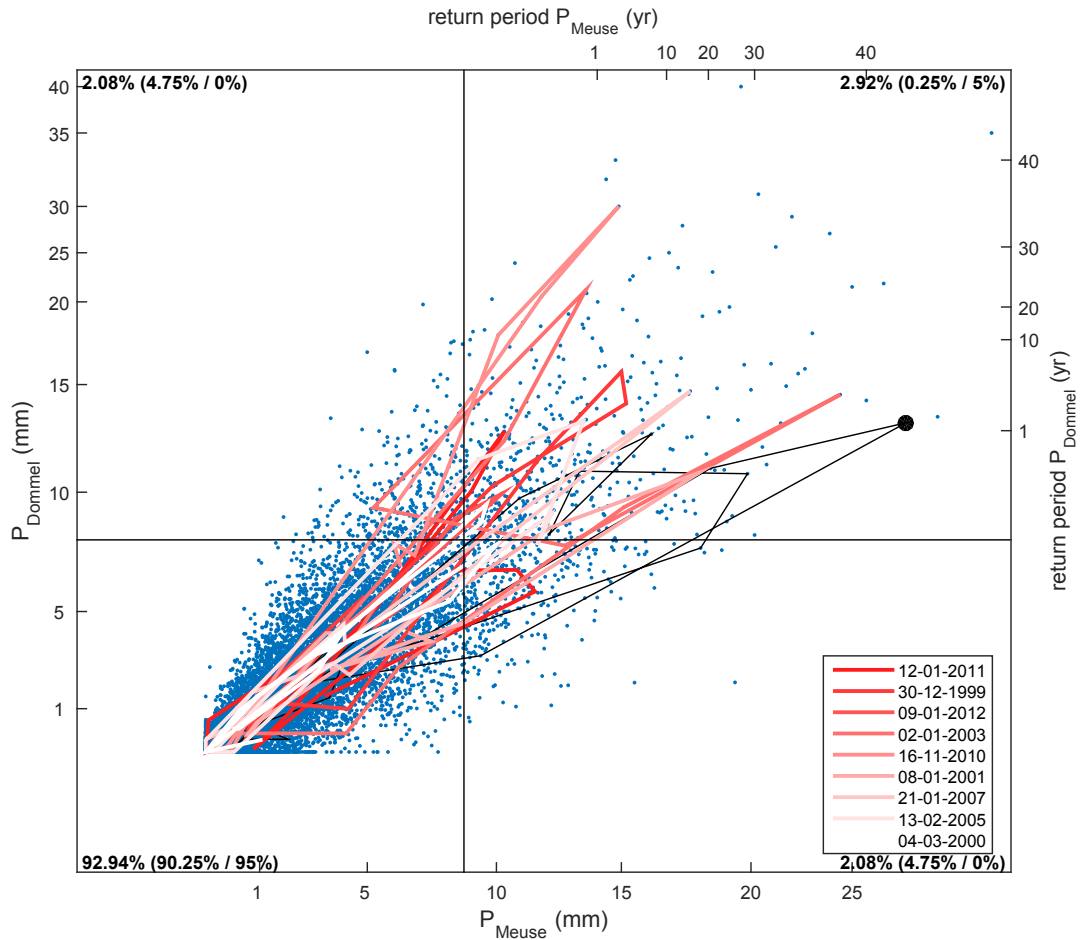
Figure 6. Gumbel distribution of the precipitation in the combined Dommel and Aa catchments and the Ardennes from 1968 to 2015. The red lines shows the precipitation a week prior and a week after the analyzed discharge events in Megen, and the black line shows the precipitation two-weeks prior to the flood event in 1995. The figure is divided in quadrants in such a way that 95 % of precipitation values for the Meuse are located at the left-side of the vertical line and that 95 % of precipitation values at the Dommel are located below the horizontal line. The numbers in the corners successively indicate the percentage of samples in each quadrant and the percentages that would result from complete randomness and exact (1-to-1) correlation. The latter two are in brackets.
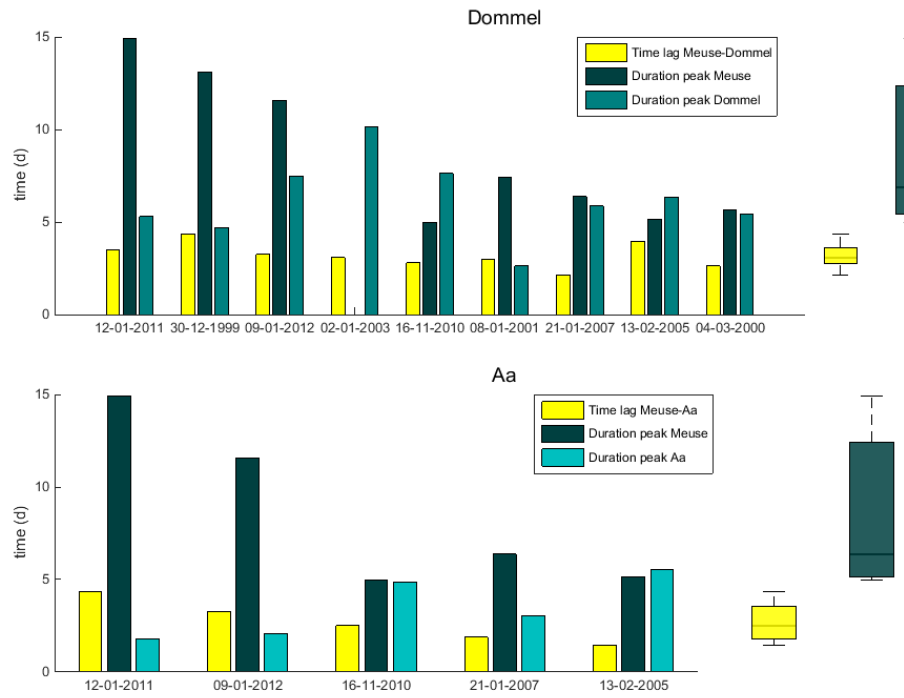
Figure 7. Duration of the discharge peaks in the Meuse (MU), the Dommel (DD) and the Aa (AD) rivers and the time lag at the confluence between the Meuse and the Dommel and between the Meuse and the Aa. Box plots show the median, the 25th and the 75th percentiles and the range of the durations and time lags.
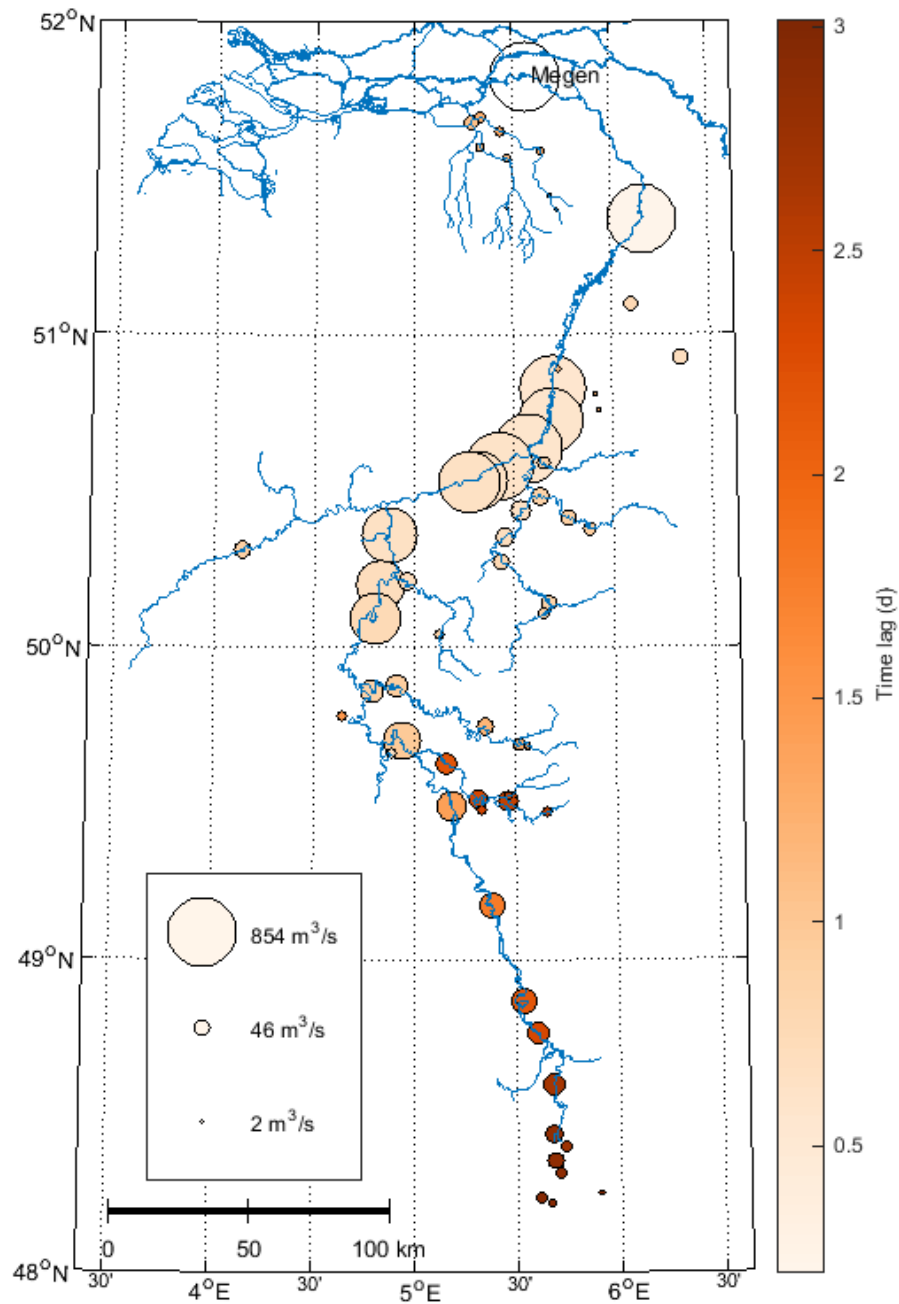
Figure 8. Distribution of the average travel time of the nine highest discharge waves in the period 1999–2015, between various gauging stations along the Meuse and the confluence subject to study. The circle size indicates the 95th percentile discharge of the gauging station.
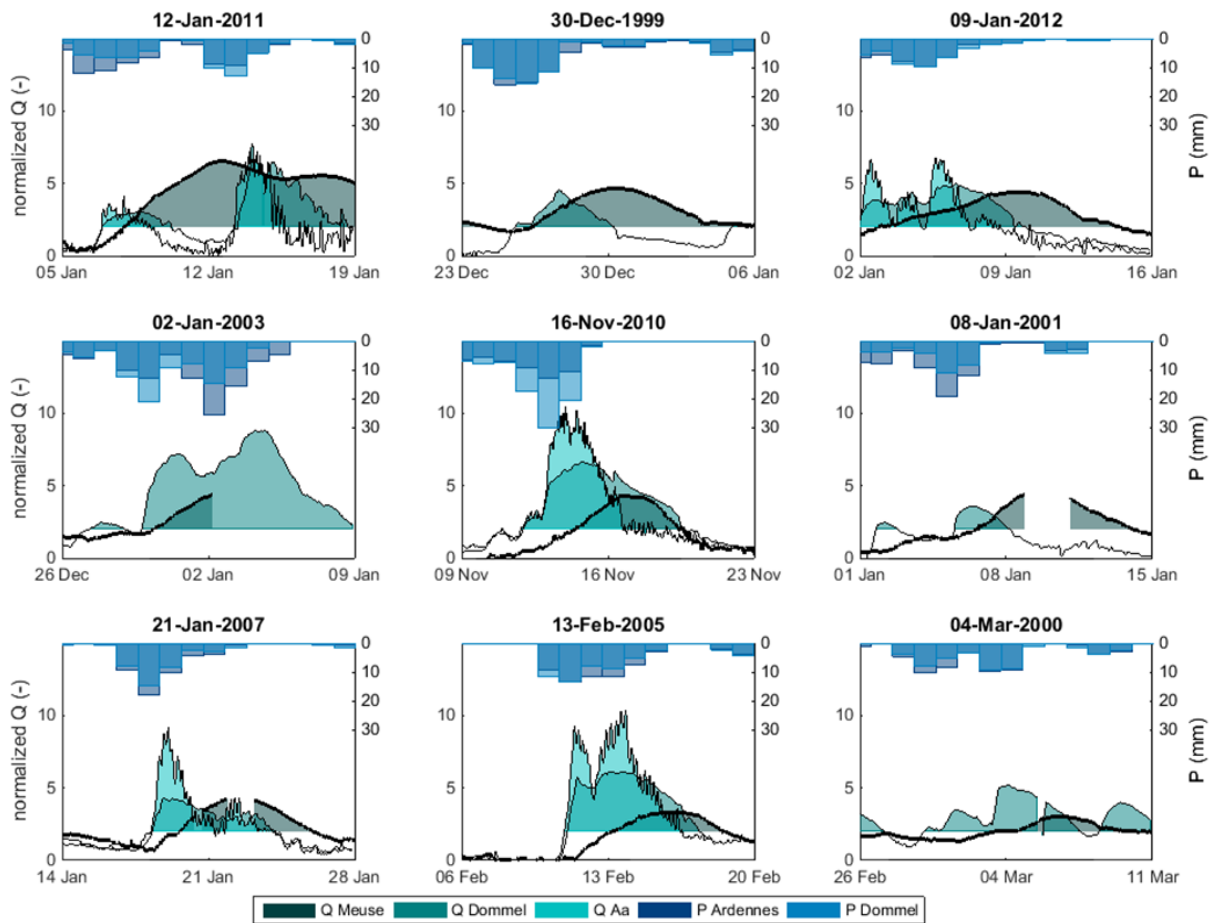
Figure 9. Standardized/normalized hydrographs of the Meuse, Dommel and Aa rivers for the nine highest discharge peaks (Figure 3). The colors indicate discharge exceeding the 95th percentile for the Meuse river (dark green), the Dommel river (lighter green) and the Aa river (light turquoise). The overlap between the colors is indicative of simultaneous occurrence. The precipitation in the catchment areas is indicated by dark blue for the Ardennes catchment and lighter blue for the Dommel/Aa catchment.
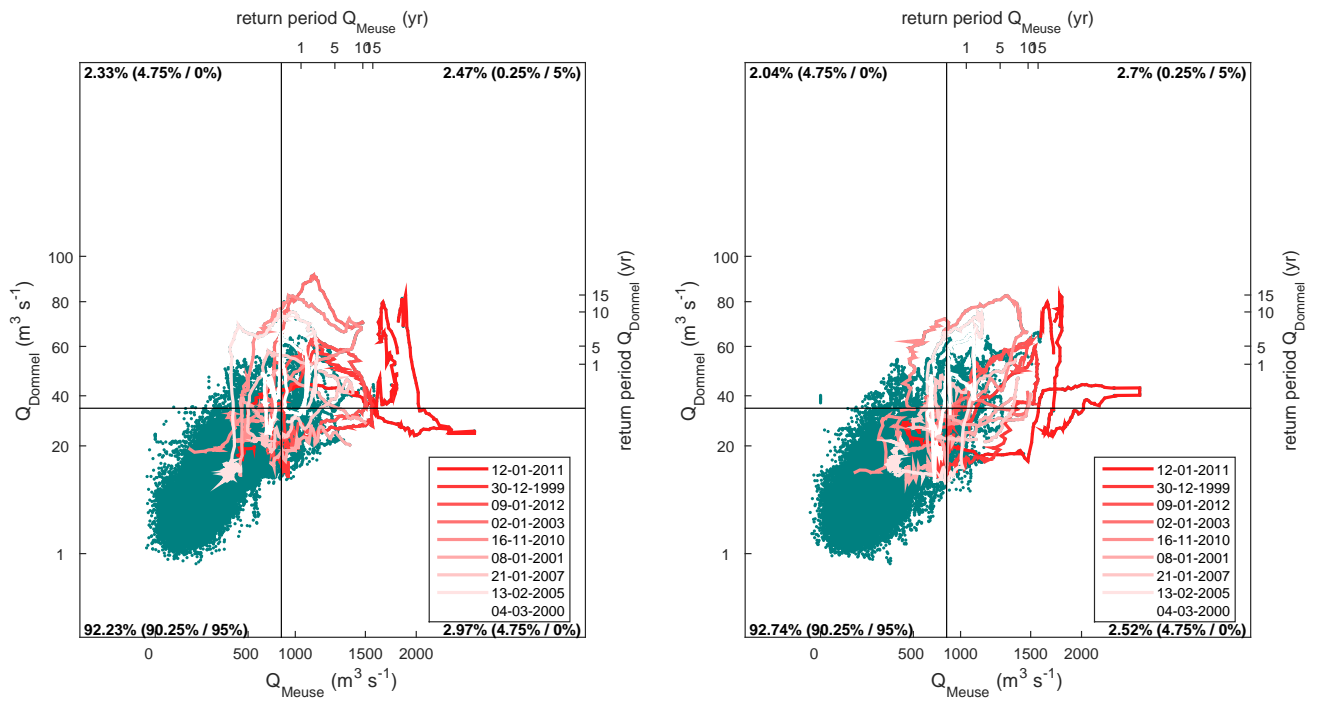
Figure 10. Gumbel distribution of the discharge of the Dommel and the Meuse from 1996 to 2015. The red lines show the discharge a week prior and a week after the analysed discharge peaks at Megen and follow a clockwise hysteresis. The discharge of the flood event of 1995 was 2.825 m^3 s^{-1} for the Meuse and 100 m^3 s^{-1} for the Dommel. The figure is divided in quadrants in a way such that 95 % of discharge values at the Meuse are located at the left-side of the vertical line and that 95 % of discharge values at the Dommel are located below the horizontal line. The numbers in the corners successively indicate the percentage of samples in each quadrant and the percentages that would result from complete randomness and exact (1-to-1) correlation. The latter two are in brackets.
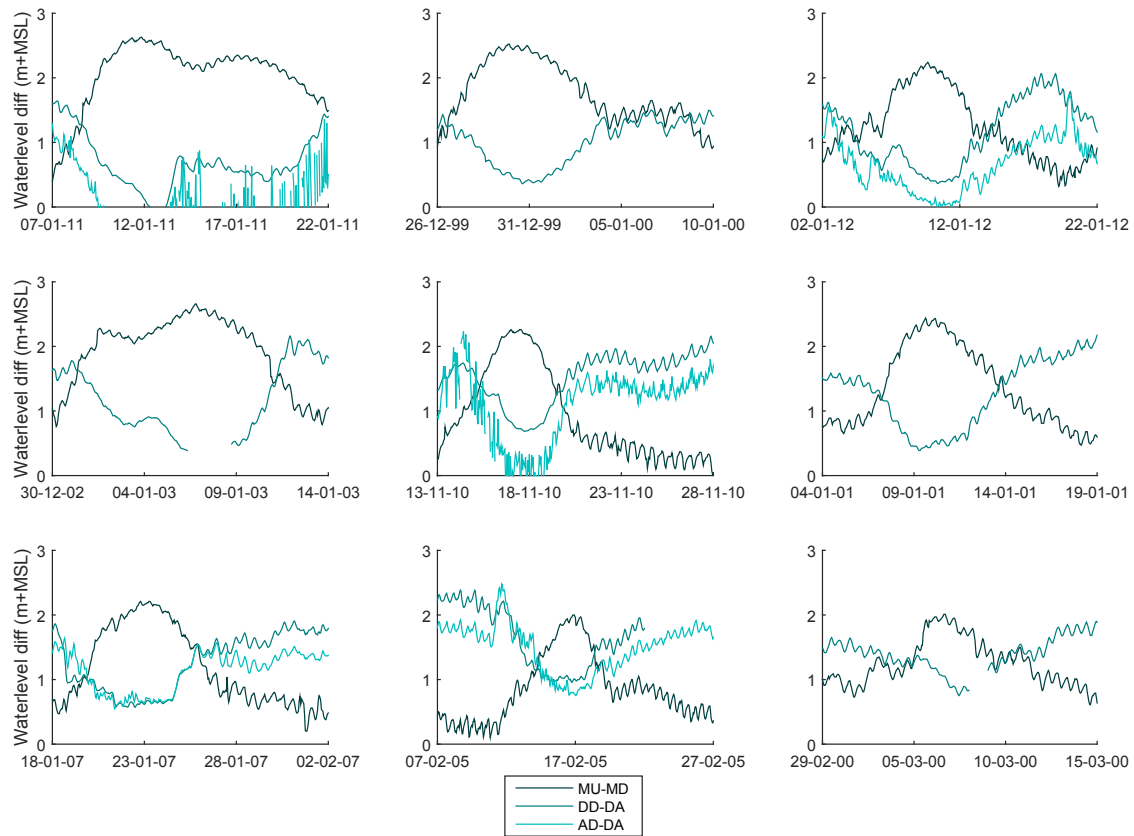
Figure 11. Water level differences of the Meuse, Dommel and Aa rivers during the nine highest discharge peaks in the Meuse. Note that the water level difference of the Meuse (MU-MD) increases, while the differences of the Dommel (DD-DA) and Aa (AD-DA) decrease during the discharge peak.
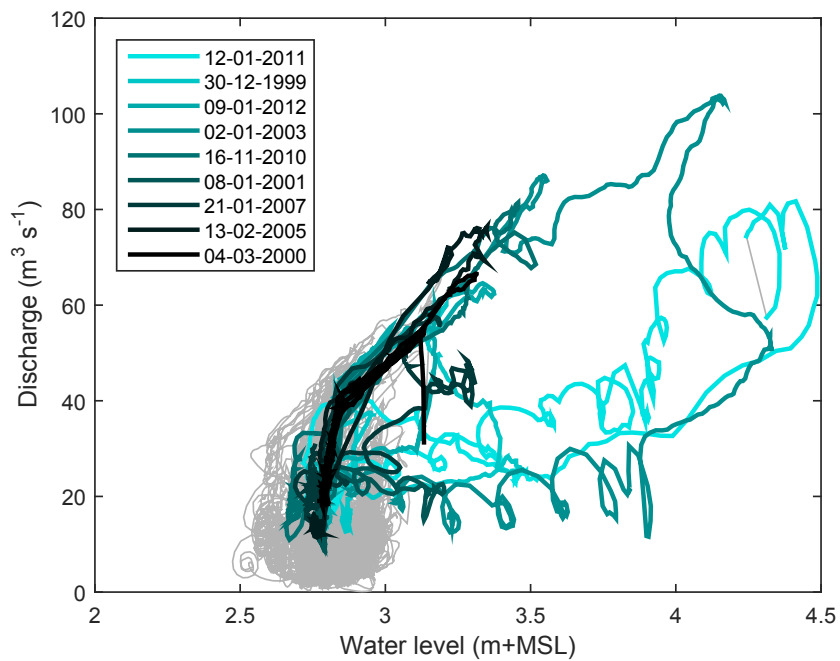
Figure 12. The stage-discharge relation of the Dommel river at measuring station DD (Figure 1). Note that stage and discharge have been measured independently, and that strong non-uniqueness and hysteresis effects can be seen.
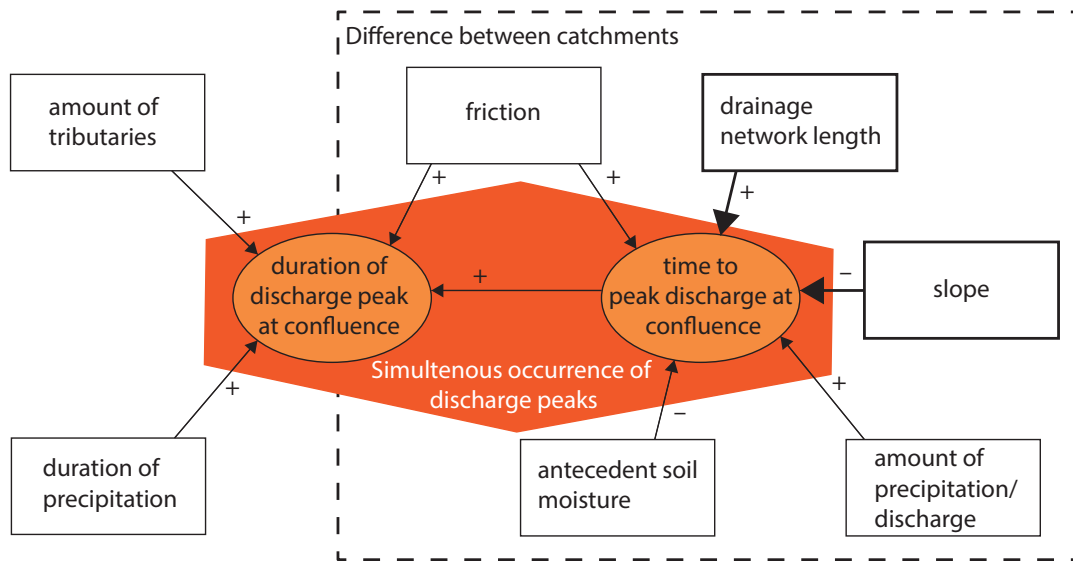
Figure 13. Conceptual framework of processing controlling simultaneous occurrence of discharge peaks at confluences. When discharge peaks coincide at confluences indicated by the orange polygon, the time to discharge plus the duration of the discharge peaks should overlap. The arrows indicate the factors influencing the time to discharge and/or duration of the discharge peak. The plus signs indicate positive effect and the minus signs indicate negative effect of the factors. The drainage network length and the slope have a larger influence on time to discharge than the other factors. For the time to discharge is it crucial to understand the difference between the catchment areas joining at the confluence, which is indicated by the dashed box.