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The 2021 flood event in the Dutch Meuse and tributaries from a hydraulic and morphological perspective

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Abstract

In July of 2021, large areas in the catchment of the Meuse River in Belgium, the Netherlands and Germany were affected by extreme rainfall and floods. This paper presents the hydraulic and morphological data that were collected during and after the flood. The data were analysed to understand the hydraulic and morphological functioning of the Meuse River in the Netherlands during the flood event. The data showed that measured peak discharges in the upstream part of the Meuse and regional tributaries were the highest ever recorded. However, as the flood had a very short duration, peak attenuation played an important role, resulting in discharges and water levels in downstream reaches that were lower than during previous floods. Furthermore, the implementation of river widening and floodplain lowering measures as part of the Meuse Works programme contributed to a reduction in peak water levels along the Meuse. The analysis also showed that flood forecasts in the upstream part of the Meuse in the Netherlands depended heavily on rainfall forecasts and rainfall-runoff modelling and underestimated the peak water levels up to 36 hours before the flood actually peaked. Further downstream, the lead time increases and forecasts are based on discharge levels that are measured in upstream parts of the catchments. This results in more accurate estimates. The floods have also resulted in unprecedented morphological changes. The armour layer in the riverbed of the 'Common Meuse', consisting of very coarse gravel, was mobilised and layers of fine sand quickly eroded. This resulted in multiple scour holes with depths of 3 to 15m, especially in a reach which was hardly or not at all widened in the room for the river programme called Meuse Works. In this reach, the flow velocities were high and even higher than prior to the Meuse Works.

Keywords

Floods July 2021, Fact Finding, Hydraulics, Peak Attenuation, Morphodynamics

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1 Introduction

In July 2021, large areas in the province of Limburg in the Netherlands were affected by extreme rainfall. The rainfall originated from a strong and persistent ‘cut-off’ low that covered the north-east of France, western Germany, eastern Belgium and the southeast of the Netherlands. The rainfall peaked between 13 and 15 July (Kreienkamp et al., 2021). Heavy rainfall over a period of 1-2 days in combination with wet conditions already before the event resulted in severe floods (Kreienkamp et al., 2021). Large areas in Belgium, Germany and the Netherlands were flooded, which led to high damages (He et al., 2021). In Germany, 184 people died (Thieken et al., 2022), making it one of the worst flood disasters in recent European history (Barredo, 2007). In the Netherlands, there were, fortunately, no casualties.

The flood is considered an extreme event with an enormous impact. This paper aims to present facts and understanding of the floods that occurred in the Netherlands, based on a hydraulic and morphological perspective. Data on river discharges, water levels and morphological changes (bathymetric and topographic) were collected and analysed to understand the hydraulic and morphological functioning of the Meuse River in the Netherlands during the flood event. This paper also aims to present, in a structured way, data that have been collected and make them available for further use by other researchers (see supplementary information).

This paper starts with context on the way floods are managed in the Netherlands, information about the study area and a description of available data. Next, the results are presented in three separate sections and comprise the dynamics of the 2021 flood wave in the Netherlands, the flood from a historical and statistical perspective and a description of the morphological changes that occurred. The implications of the key findings are discussed, including some challenges faced while performing the study and recommendations are made for follow-up studies and possible improvements in flood management. Concluding remarks are presented at the end of this paper.

2 Context

2.1 Flood risk management in the Netherlands

Roughly two-thirds of the Netherlands is vulnerable to flooding from the sea, major lakes or major rivers, which led to a system of primary flood defences and a governance structure to regulate flood risk levels. Along the Meuse River, the protection standards (in terms of failure probability) of the surrounding primary flood defences vary from 1/100 to 1/10,000 per year. The primary flood defences are maintained by the water board and financially supported by the national government. In flood-prone areas along the smaller rivers in the Netherlands, including the tributaries of the Meuse river in Limburg, flood defences are barely present and protection levels are lower. In these unembanked areas, safety standards indicate the maximum permissible probability of flooding as a result of insufficient discharge capacity. Most urban areas in the south of Limburg have a safety standard of 1/25 per year. The water board is responsible for complying with these standards. This safety level in Limburg deviates from other regional water systems in the Netherlands, where surrounding urban areas are protected against flood up to approximately 1/100 per year regional flood events.

Next to limiting the flood probability, flood risk can also be reduced by limiting the flood impact. This can be done by ensuring good options for evacuation and crisis management. By preparing for potential flooding, responding to the threat of flooding and taking action after flooding (which was also done during and after the 2021 flood), the impact of floods can be reduced. The success of crisis management relies among others on accurate forecasts and real time information of the flood occurring. Water levels in rivers play a crucial role in managing floods as they affect the flood impact and determine the hydraulic load on flood defenses. Understanding and monitoring water levels is essential for predicting and mitigating flood risks.

2.2 Study area

The Meuse catchment is located in Western Europe. It covers an area of approximately 33,000 km^2, including parts of France, Luxembourg, Belgium, Germany, and the Netherlands. The Meuse River has a total length of about 950 kilometres from its source in France to the estuary Hollands Diep in the Netherlands. About 250 kilometres of the river

Meuse is in the Netherlands. The Meuse is a rain-fed river (de Wit et al., 2001) where large fluctuations in river discharge occur, responding rather quickly to precipitation in upstream parts of the river basin. The basins response to precipitation is fast, primarily caused by the presence of large tributaries with relatively impervious subsoils in Belgium. In general, discharges in the Meuse River are low during summer when evaporation rates are higher, while the amount of precipitation is evenly distributed throughout the year (Tu, 2006). Although most floods in the Meuse basin occur in winter, the 2021 summer floods indicate the strong natural variability of the weather.

In France and Belgium, the Meuse is a typical low mountain river with a relatively steep slope. In the Netherlands, the Meuse River can be divided into six sections by riverkilometre (rkm): the Upper Meuse (*Bovenmaas*, 3-15 rkm), Common Meuse (*Gemeenschappelijke Maas*, 16-55 rkm), Lake Meuse (*Plassenmaas*, 56-93), Sand Meuse (*Zandmaas*, 94-164 rkm), Embanked Meuse (*Bedijkte Maas*, 165-200 rkm) and Tidal Meuse (*Getijdenmaas*, 201-247 rkm). The Common Meuse forms the border between Belgium and the Netherlands. It has a relatively steep slope of about 0.5 m/km. It is a free-flowing, dynamic gravel-bed river that is not suited for navigational purposes. Near Roermond, large lakes are present in the floodplain of the Meuse. Here, the Meuse River shows a sharp transition from a gravel-bed to a sand-bed river where the slope decreases from about 0.5 to about 0.1 m/km (Murillo-Muñoz and Klaassen, 2006). The downstream part of the Meuse River (downstream of rkm 165) is embanked over its entire length and from Lith (201 rkm) onwards, the North Sea tide influences the hydro- and morphodynamics, altering the river characteristics once again.

This paper focuses on the Dutch part of the Meuse, which enters the Netherlands near Eijsden. Some of the main tributaries of the Meuse in the Netherlands (from upstream to downstream) are the Geul, Geleenbeek, Roer, Swalm, Neerbeek and Niers. In this paper, we focus on the catchments of the Geul, the Geleenbeek and the Roer (see Figure *1*), as these were the catchments where most of the flooding took place and damages occurred. Their contributing areas are 338 km^2, 203 km^2 and 2245 km^2, respectively. Hardly any flood defences have been constructed in the tributaries. Along the Meuse River, about 400 kilometres of flood defences have been constructed that protect cities and villages.

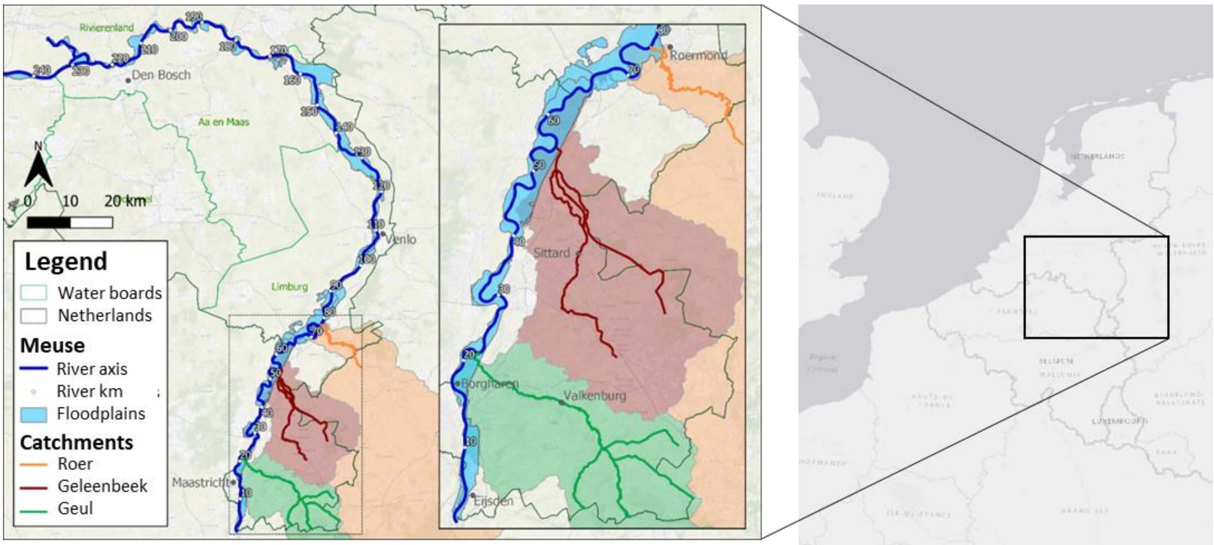

Figure 1: Geographic map that shows the Dutch part of the Meuse River and the main tributaries that are analysed in this paper.

3 Data collection and approach

This study presents an analysis of hydraulic (water level and discharge) and morphological data collected during and after the 2021 flood event. These observations are placed in a historical context using data from previous floods. Moreover, in this study, the data collected is compared to model results to evaluate the hydraulic and morphological functioning of the river system. This evaluation helps to determine whether the observations align with our pre-existing expectations. In this paragraph, a description of both the data collected and the models employed in this study is provided.

3.1 Available discharge and water level data

In the Netherlands, Rijkswaterstaat (Executive agency of the Dutch Ministry of Infrastructure and Water Management) is responsible for monitoring discharges and water levels in the major water bodies, like the sea, rivers, canals and lakes. There is a monitoring network that consists of more than 450 locations (Rijkswaterstaat, 2023). Water levels are continuously measured using accurate automatic boat-driven shaft encoders and measurements at 35 monitoring sites along the Dutch Meuse are used in this study, retrieved from the Rijkswaterstaat WaterInfo website (Rijkswaterstaat, 2021a). These measurements are available for the entire flood period and water levels are given relative to the ordnance level NAP. The water board Waterschap Limburg is responsible for the monitoring network of water levels in the tributaries, During the flood, several monitoring sites failed and in total 46 sites show reliable measurements. These data are retrieved from Waterschap Limburg (2021).

Discharge estimates are derived from cross-sectional flow velocity profiles with an Acoustic doppler current profiler (ADCP). These measurements are carried out at several permanent locations along the Meuse and during the 2021 floods multiple discharge measurements were carried out with ADCPs mounted on (un)manned boats. These additional measurements are available for the Meuse and the Roer. There are no discharge measurements available for the Geul and Geleenbeek. Therefore, water level measurements in combination with hydrodynamic model results are used to estimate peak discharges during the flood.

3.2 Hydrodynamic models used

Throughout this paper, several hydrodynamic models are used to compare with the observations and interpret the flood event. The following models were used in the forthcoming analyses, with paragraph numbers provided to indicate where each model is mentioned:

- For the statistical analyses of the wave form, model results from the GRADE project are used (Hegnauer et al., 2014). This project uses the 2D hydrodynamic WAQUA model beno17_5-v1 (De Jong & Visser, 2018) (Paragraph 4.3).
- For the longitudinal changes in peak discharge, during three major floods, 2D WAQUA models are used that best represent the state of the Meuse during these floods: j93_5-v1 (for flood 1993), j95_5-v1 (for flood 1995) and j19_5-v1 (for flood 2021). (Paragraph 4.3)
- Before and during the flood event, flood forecasts were made for several locations along the Meuse that were published by Watermanagement centre Netherlands (WMCN). Hydrodynamics in these forecasts are computed with 1D SOBEK model j19_5-v1. (Paragraph 4.4)
- The measured peak water levels along the Meuse are compared to model results in which the model best represents the actual state of the river, which is described by the 2D WAQUA model j19_5-v1. (Paragraph 5.2.1)
- For the estimation of water levels and their exceedance probabilities of each regional tributary, we used model results obtained from the waterboard. These are coupled SOBEK 1D2D models that are forced by extreme rainfall events and discharge boundary conditions. (Paragraph 5.2.2)

A description and further references to all the official Rijkswaterstaat models of the Dutch Meuse are given in the factsheet (Rijkswaterstaat, 2021b).

4 Flood wave dynamics of 2021 floods in the Netherlands

4.1 Peak discharges

Between 11 and 15 July 2021 unprecedented amounts of rainfall occurred in large parts of the Meuse and Rhine catchment areas. This resulted in record-breaking peak discharges near St. Pieter, a hydrodynamic monitoring station located along the Meuse River near the border between the Netherlands and Belgium. However, it is not only the peak discharge near St. Pieter that is important for the height and timing of the peak water levels downstream along the Meuse, but also the shape of the flood wave (the duration of the flood) and the volume and timing of the discharge from the tributaries in the Netherlands.

The peak discharges in the Meuse and larger lateral inflows are shown on the map in Figure *2*. The discharges mentioned in this figure were estimated based on the data available. The discharge in the Meuse River at St. Pieter is estimated at 3310 m^3/s (Van der Veen & Agtersloot, 2021). The Meuse River enters the Netherlands near Eijsden. Between Eijsden (rkm 3) and St. Pieter (rkm 11) a lock complex on the Canal de Lanaye connects the Albert Canal to the Meuse. Although these locks do not usually discharge during flood events, this discharge was increased to an estimated 200 m^3/s to compensate for the higher water levels resulting from the maintenance to the Monsin Weir in the Meuse at Liége. In this way a part of the Meuse discharge was diverged via an alternative route to the Netherlands (see Figure *2*).

Peak discharges are estimated at around 135 m^3/s in the Geul near Valkenburg and 270 m^3/s in the Roer near Stah respectively (Deltares, 2022). The peak lateral inflows of these tributaries into the Meuse were lower due to peak attenuation along the tributaries. The peak inflow from the Geul coincided more or less with the peak discharge in the Meuse River, while the flood peak at the Roer occurred after the discharge peak in the Meuse River. There are no discharge measurements available at the downstream part of the tributaries and therefore the timing is based on water level time series (see paragraph 4.2)

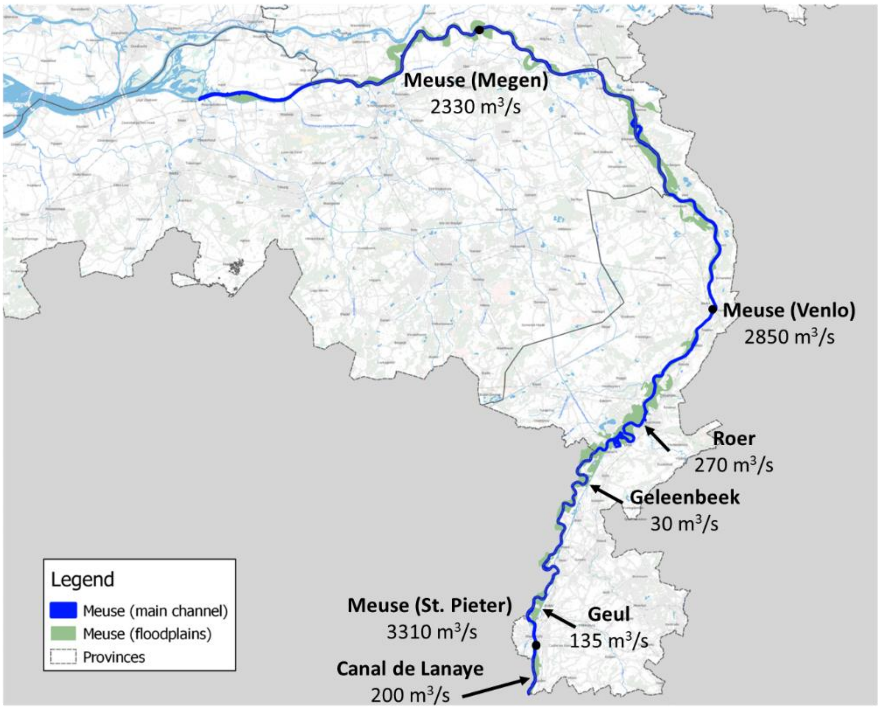

Figure 2: A geographic map that shows the peak discharge levels along the Meuse River during the 2021 floods. The peak inflows of the largest tributaries are indicated by arrows, which are upper limits since peak attenuation downstream of gauging stations lowered the peak discharge at the confluence with the Meuse. The discharge levels along the Meuse, Geul and Geleenbeek are based on water levels that are translated to discharge levels by using rating curves in combination with a hydrodynamic model. The Roer peak discharge was measured with an Ott Qliner (uses ultrasound to measure the water speed and depth of rivers and in this way measures the discharge).

4.2 Development of peak water levels

Along the Dutch section of the Meuse (between Eijsden and Keizersveer, see Figure S1 for a map of the monitoring sites), the total propagation time of the flood wave was 113 hours (almost 5 days), where the propagation speed varies along the Meuse (high propagation speed upstream and lower further downstream). The peak reached Eijsden (number 1 in Figure *3*) on 15 July at 22:00, Roermond (nr. 16) on 17 July at 06:00, Venlo (nr. 22) on 17 July at 16:00 and Keizersveer (nr. 35) on 20 July at 17:00 (moments rounded off to the nearest hour). According to Asselman et al. (2022) a flood wave in the Meuse with an average shape and duration takes about 80 hours to travel from Eijsden to Keizersveer. The 2021 flood wave had a very short duration, which resulted in slower flood propagation in comparison with floods with an average duration (about 115 hours instead of 80 hours to propagate from Eijsden to Keizersveer), which is relevant for possible evacuations and emergency measures. The highest water level measured at other stations and the associated times can be found in

Table S1.

Figure *4* shows the highest water levels measured in the tributaries and the moment when they were measured. The peak water levels along the Geul and Geleenbeek occurred in the evening of Wednesday 14 July and the morning of Thursday 15 July (see Figure *4*). The catchment of both tributaries lies primarily in the Netherlands and have small time of concentration. As a result, the peak water levels occur rapidly after the heavy rainfall. The highest water levels in the upstream section of the Geul (station 13 Epenermolen and 14 Cottessen) occurred later than at the measuring stations located downstream. This can be explained by the observed double peaked flood wave in the Geul catchment (see Figure S4). In the upstream part of the Geul catchment, the second flood peak was higher than the first, whereas in the more downstream parts of the Geul the first peak was higher. The Dutch Roer covers the last 22 kilometres of a river that is approximately 165 km long (the largest catchment of the tributaries considered) which means that it took some time for the flood wave to reach the Dutch part of the Roer. Consequently, the highest water levels at the Roer were not measured until later on (between the evening of Friday 16 July and the morning of Saturday 17 July). Peak water levels in the downstream part of the Roer near the confluence with the Meuse peaked earlier than further upstream in the Roer, because the high water levels in the Meuse peaked earlier and influence the water levels in the Roer via backwater curves. The highest water level measured and the associated times at the stations along the tributaries can be found in Table S3.

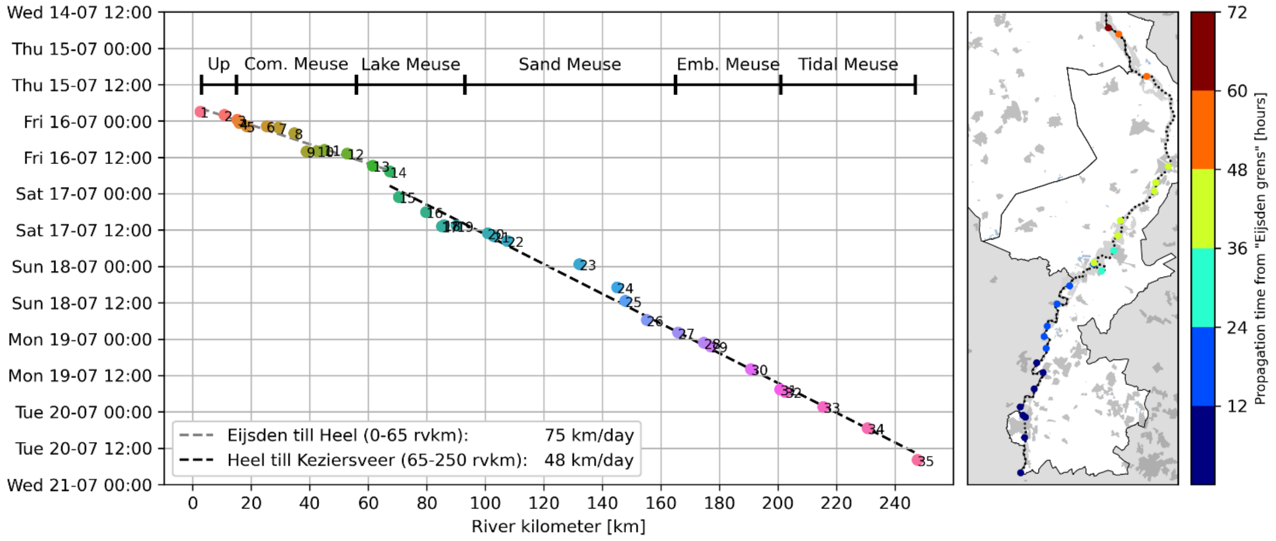

Figure 3: Timing of peak water levels along the Meuse during the 2021 flood. In the left graph, the propagation speed of the flood wave is indicated for two different trajectories.

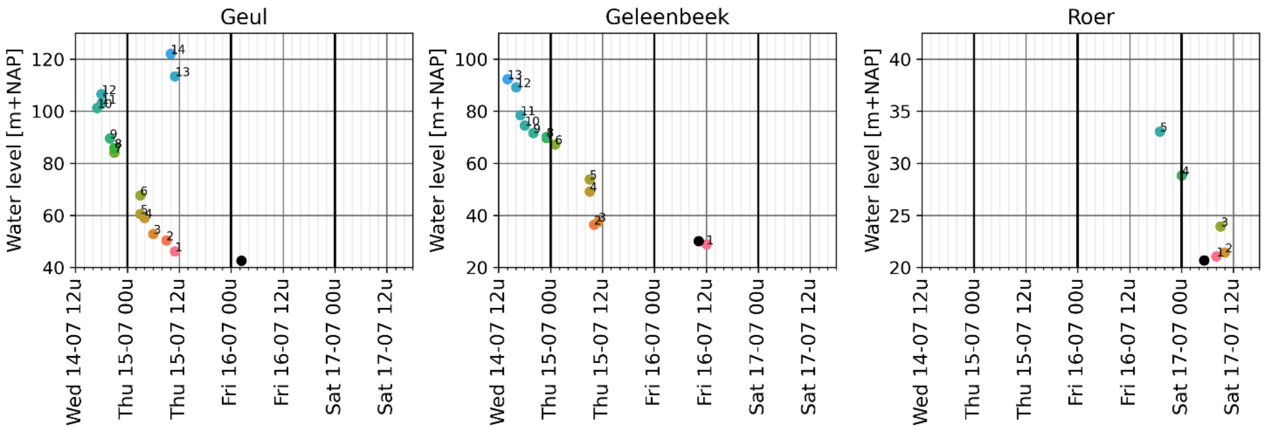

Figure 4: Timing and height of the peak water levels along the Geul, Geleenbeek and Roer. The stations associated with the numbers can be found in Table S3, S4 and S5. The black dots indicate the moment and the height of the water level at the measuring station in the Meuse close to the confluence of the tributary in the Meuse.

4.3 Peak attenuation along the Meuse

Although record high discharges were measured at the upstream gauging station near St. Pieter, flood water levels in more downstream reaches were much lower compared to those of previous floods with comparable peak discharge at St. Pieter. Peak attenuation probably played a major role in this. Peak attenuation is the gradual decrease of the peak discharge when a flood propagates downstream. The rate of peak attenuation depends on the river geometry, such as river slope and floodplain width and available storage areas (floodplain, wetlands, lakes and reservoirs). High hydraulic roughness of the channel and the floodplain also enhances peak attenuation. The peak discharge decreases due to peak attenuation and water levels in the lower reaches of the river remain lower. Peak attenuation can have a significant effect on peak discharges along the Meuse in the Netherlands but depends strongly on the shape of the flood wave (De Jong & Asselman, 2019; Asselman et al., 2022).

The flood wave that entered the Netherlands in 2021 had a very sharp peak compared to historic flood waves. Figure 5 compares the normalised flood wave with the historical floods of 1993 and 1995. Because the peak discharge in all cases is equated to 1, differences in the form of the flood wave are clearly visible. The graph also shows statistical flood wave shapes as derived from the database of flood waves from the GRADE project (Hegnauer et al., 2014) by aligning the peak discharges and calculating the percentiles of the relative discharge per day. The median wave shape, as well as the 2.5% and 97.5% percentiles, are shown. The graph shows that the 2021 flood was of extremely short duration, as it was sharper than the 2.5% percentile. Two days before the flood peak, the river still had regular summer discharges (lower than 300 m^3/s).

The deformation of the sharp peaked flood wave can be derived from measurements. The analysis in the supplementary information (paragraph 9.1.3) shows that the duration of the flood peak (the period that water levels are within 0.05 m of the peak water levels) increased in a downstream direction: 4 hours near St. Pieter (rkm 11) and 9 hours near Roermond (rkm 80). Similarly, the rate at which the water level increased around the peak became lower and lower (from 10 cm per hour near Maastricht to 5 cm per hour near Roermond), indicating an increasingly flatter flood hydrograph while travelling downstream.

Figure 6 shows observed changes in peak discharge during the three major floods of 1993, 1995 and 2021. The 1995 flood had a very long duration and hence resulted in little peak attenuation. In fact, the peak attenuation was less than the increase in peak discharge caused by the tributaries. The 2021 flood had an extremely short duration and resulted in strong peak attenuation, which exceeded the increase in peak discharge due to inflow from the tributaries. Due to the strong decrease in peak discharge during the 2021 flood, water levels at the downstream reaches of the Meuse River were up to 1 m lower than would be expected using an average flood wave shape.

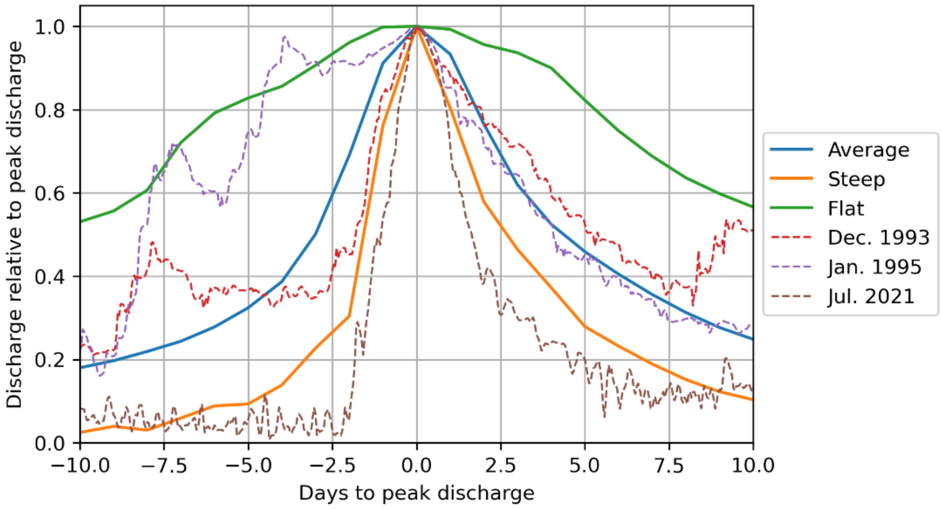

Figure 5: Comparison of the normalised flood wave of July 2021 with the floods of 1993 and 1995. The average/median wave form (50% percentile), sharp/steep (2.5% percentile) and flat (97.5% percentile) are shown for comparison (Asselman et al., 2022). The peak discharges near St. Pieter equalled 3039 m^3/s in 1993, 2745 m^3/s in 1995 and 3310 m^3/s in 2021.

The overall presence of storage capacities along the Meuse decreased between 1995 and 2021 (Asselman et al., 2022). As a result of the shape of the flood wave, the peak attenuation during the 2021 flood wave was still stronger than the floods in 1993 and 1995 despite the straightening of rivers and loss of floodplain area. Storage areas provide a significant contribution to the peak attenuation along the Meuse. Especially in the so-called Lake Meuse reach around the city of Roermond (rkm 60-87) the suddenly wide floodplains and large lakes attenuate flood waves, in particular the short and peaked ones (see Figure 6 and Asselman et al., 2022).

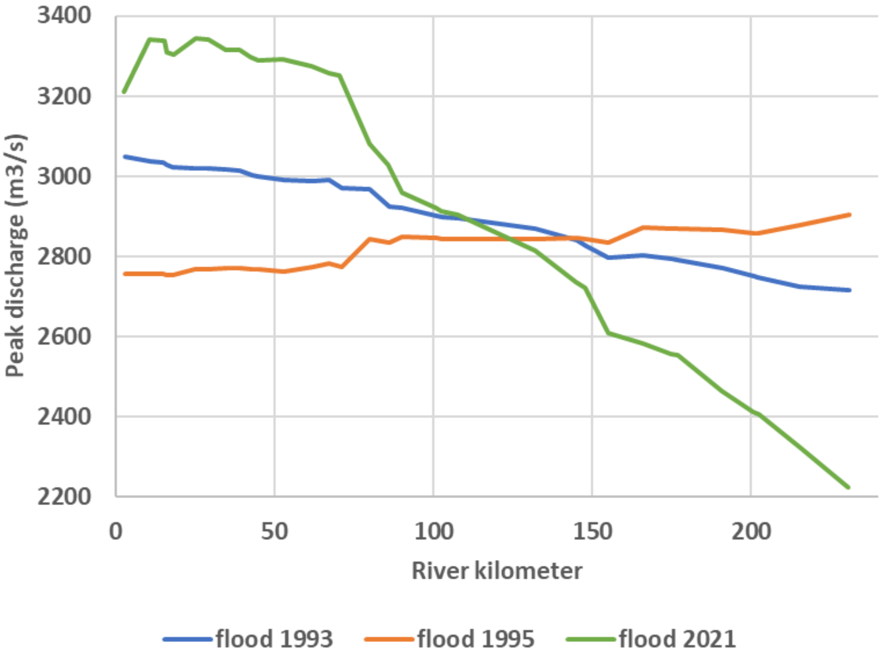

Figure 6: Longitudinal changes in peak discharge along the Meuse River in the Netherlands, observed during three major floods.

4.4 Evaluation of flood forecasts along the Meuse

The July 2021 flood was a complex transboundary event, spanning multiple rivers and countries in Western Europe, with different flood forecasting and early warning systems (Kreienkamp et al., 2021). The commonly used practice for flood forecasting is to record real-time rainfall data, using rain gauges or radar images, and then apply the measured rainfall to forecast discharge levels using a rainfall-runoff model (Werner et al., 2013). For catchments with a relatively low hydrological time of concentration, flood forecasting with real-time rainfall data can be insufficient for announcing flood warnings at the required lead time for taking emergency measures (Amernath et al., 2016) and forecasted rainfall can be used instead. The flood early warning system of the Meuse uses forecasted rainfall data and can make flood forecasts up to 14 days ahead. After forecasting discharge levels at one or several locations in the catchment, the water levels are calculated using a hydrodynamic model. In this paragraph, the forecasted peak discharge levels at St. Pieter and forecasted peak water levels along the Meuse are evaluated, by analysing the forecasts at several moments in time. The WMCN (Watermanagement centre Netherlands) is responsible for preparing and releasing the forecasts (or flood messages) based on an ensemble of model results, which are used in this analysis.

The first flood message that was released by WMCN on the 14th of July in the morning, 36 hours prior to the discharge peak at St. Pieter. Extreme rainfall between 13th and 15th of July was already forecasted in some members of the ensemble on the 11th of July (Cornwell, 2021) with high peak discharge levels at St. Pieter forecasted several days later, but this forecast was not released. One day before the discharge at St. Pieter peaked, the forecasted peak discharge was about 400 m^3/s lower than the actual peak discharge. This discharge increase is equivalent to an increase in water levels of about 10 – 60 cm higher along the Meuse depending on the location (assuming an average-shaped flood wave) or a decrease in exceedance probability of the discharge level near Eijsden of a factor 3, so from an exceedance probability of 1:30 per year to 1:100 per year, based on available discharge frequency lines (Hegnauer et al., 2014). Figure *7* shows how the forecasted peak discharge changed over time. It shows that in the evening of July 14, a peak discharge was expected of about 2600 m^3/s, with a 90% confidence interval of 1900 to 2900 m^3/s. This was well below the peak discharge of 3310 m^3/s that occurred ultimately. The accuracy of the predicted peak discharge increased over time, as more measurements came available from upstream stations.

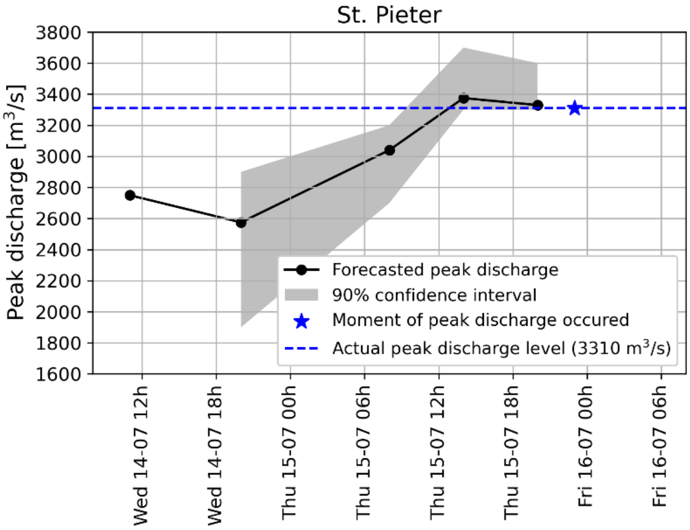

Figure 7: Development of the forecasted peak discharge levels at different moments in time.

Figure *8* shows the forecasted water levels at different moments in time. The accuracy of these forecasts (in this study defined as the difference between forecasted peak water levels and actual peak water levels) and how this changed in time were analysed. Due to uncertainties (or inaccuracies) in the forecasted peak discharge levels at St. Pieter, the forecasted water levels at the stations in the upstream part of the river (until station Elsloo) were still one metre too low 36 hours before the water level actually peaked at these locations. Further downstream, the forecasted water levels were more accurate, since the amount of discharge in the Meuse River was more certain. In other words: due to the fast response of the catchment, the forecasted peak discharge and water levels in the upstream part of the Meuse River in the Netherlands depend heavily on the accuracy of the rainfall forecasts and rainfall-runoff modelling. Further downstream the lead time increases and forecasts are based on discharges that are measured in upstream parts of the catchments. This results in more accurate estimates.

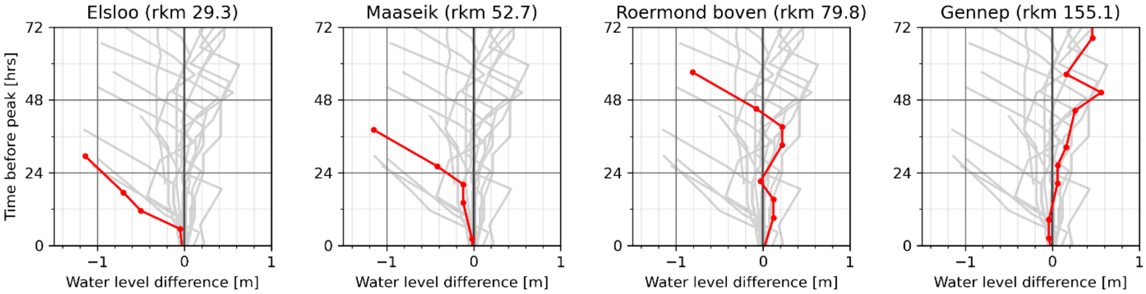

Figure 8: The development of the forecasted water levels at different lead time for several monitoring stations (red lines). The grey lines in the back represent the forecasted water levels at all monitoring stations to indicate the water level differences between forecasted and observed.

5 The floods from a historical and statistical perspective

5.1 Peak water levels that occurred along the Meuse

The 2021 floods were a rare event with the highest discharge level ever measured near St. Pieter. However, at many measuring stations, the water levels were lower than during the floods in 1993 and 1926 (see Table 1). The 1993 and 1995 floods initiated actions to reduce flood risk along the Dutch part of the Meuse River, also known as Meuse Works programme (WHM, 1998 and Looy van and Kurstjens, 2022). These actions include both measures to reduce peak water levels (e.g. water retention and river widening) and measures to reduce the impact of floods (e.g. improved flood forecasting and construction of embankments). The steep-shaped flood wave and the measures carried out within the Meuse Works programme resulted in lower water levels at many locations along the Meuse during the 2021 floods compared to previous floods (see Figure 9). At several measuring locations such as Eijsden, Maaseik and Well Dorp, the water levels during the 2021 floods were higher than during the floods in 1993 and 1995. This increase in flood water levels is still to be explained. The propagation of the historical flood waves varies since the shape of the flood wave, river geometry and roughness were different. The 2021 flood wave travelled in 90 hours from St. Pieter to Lith, while in 1993 and 1995 the travel time was 86 and 54 hours, respectively.

Table 1: Peak water levels (in m +NAP) for several measuring stations along the Meuse for various historic floods. In 1926, fewer measuring stations were in place than there are today so, at a number of stations the peak water levels are missing.

rkm	*name*	*Jan **1926***	*Dec **1993***	*Jan **1995***	*July **2021***
		3175 m^3/s	*3039 m^3/s*	*2745 m^3/s*	*3310 m^3/s*
2.6	Eijsden	-	50.45	50.16	50.64
16	Borgharen Dorp	46.1	45.9	45.71	45.23
52.7	Maaseik	-	29.5	29.44	30.17
67.3	Heel boven	23.6	22.81	22.69	22.78
85.1	Heel beneden	21.55	20.52	20.59	20.49
107.5[i]	Venlo	18.8	18.35	18.55[i]	18.01
132.1	Well Dorp	-	15.34	15.43	15.48
145.0[ii]	Sambeek boven	14.53	13.92	14.02	13.77
177.0[iii]	Grave beneden	10.95	10.39	10.45	9.47
203.3	Lith Dorp	7.75	6.32	6.54	5.79

i for the floods in 1926, 1993 and 1995, the location of Venlo measuring station was rkm 108.1

ii for the floods in 1926, the location of Sambeek boven measuring station was rkm 145.9

iii for the floods in 1926, 1993 and 1995, the location of Grave beneden measuring station was rkm 176.0

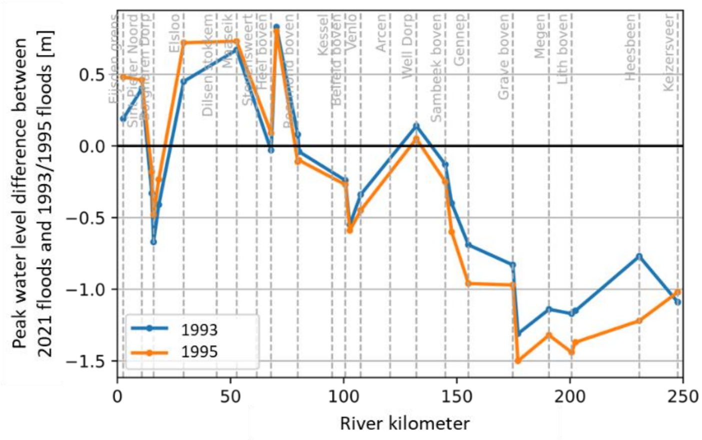

Figure 9: Water level differences between the measured peak water levels during the 2021 floods and the floods of 1993 and 1995. Many stations are missing because they did not exist in the 1990s, or have been demolished or relocated today.

5.2 Probabilities of exceedance of peak water levels

5.2.1 Meuse River

Statistical analyses of historical water levels measured along a river are complicated due to inhomogeneities in the time series as a result of e.g. flood plain excavations and bed erosion of the main channel. In practice, for water management and flood risk analyses along the Meuse, probabilities of exceedance of water levels are estimated using probabilistic and hydraulic models, like Hydra-NL (Geerse, 2011). Statistical analyses are carried out to obtain the probability distribution of peak discharge levels. Hydrodynamic models, that represent the current or future state of the river, are used to calculate the corresponding water levels along the river. By combining the probability distribution of discharge levels and calculated water levels, the exceedance probability (or return period) of maximum water levels can be obtained. In this study, we compared the 2021 measured peak water levels to model results that best represent the actual state of the river (Rijkswaterstaat, 2020). Model simulations for a flood wave event with average wave shape, a peak discharge level with a probability of occurrence of 1:100 years and average discharges from tributaries provides information (see Figure *10*) on the physical (differences with simulated water levels) and statistical characteristics of the 2021 flood event. This comparison shows that:

- In the upstream part of the Dutch Meuse the difference in water level increases from –0.2 m at *Eijsden* to +0.5 m at *Elsloo*. This is partly explained by the large lateral inflows from the Canal de Lanaye and the river Geul. However, these causes do not fully clarify the large water level differences. The discrepancies between models and measurements of water levels can arise from several factors, different schematisation of construction sites in the flood plains and differences in vegetation in the flood plains and morphological changes in the main channel (paragraph 6.1.1), which can affect bathymetry and roughness parameterisation. The role of these differences to the discrepancies needs to be investigated through further research.
- Downstream from the station Heel Boven (nr 14 in Figure *10*) the water level difference declines significantly again. This is the result of the higher peak attenuation due to the steep wave shape in 2021. The large inflow of the river Roer (at *Roermond boven*) does not compensate for this. Further downstream, the overall picture shows a further deviation from the modelled water levels up to –1.0 m as a result of the large peak attenuation. The weir at Sambeek was being refurbished and not all gates could be opened in time and backwater curves may influence the upstream peak water levels near Well Dorp. The exact contribution of each component is still unknown.

Overall, the exceedance probabilities of the water levels along the Common Meuse seem to be more extreme than 1:100 per year. Further downstream, the probability of exceedance increases (less extreme) becomes equal to or less than 1:50 in a year near Venlo and even more frequent near Gennep. Locally the observed water levels were higher than expected from model results, probably because of differences between the actual situations and the model schematisation (e.g. maintenance at weirs or other roughness parameters).

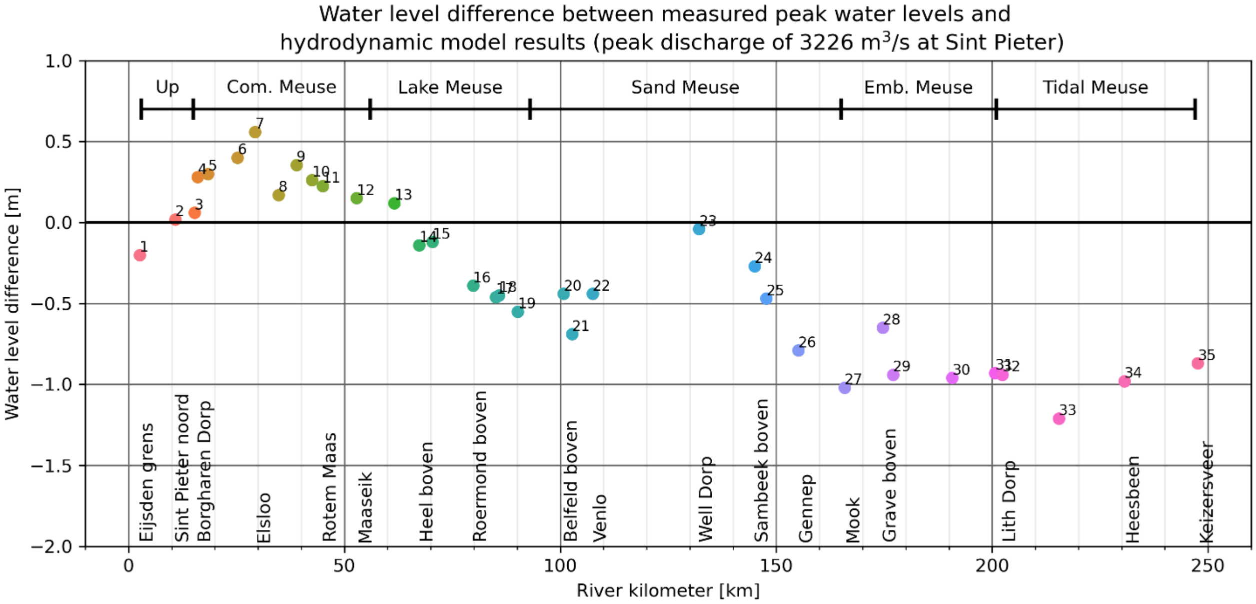

Figure 10: Difference in peak water level, compared with a model simulation for a probability of occurrence of 1:100 years. The model simulation uses an average wave shape, average lateral inflows and models the flood season (winter) 2020-2021. Model data from Rijkswaterstaat (2020).

5.2.2 Regional tributaries

The water board Limburg determines flood probabilities and the probabilities of exceedance of peak water levels and corresponding inundation patterns, based on statistical information on peak discharge levels and calculated water levels by using a hydrodynamic model. The peak water levels that occurred during the flood are compared with expected water levels with different return periods (e.g. 10, 100 or 1000 years). The probabilities of exceedance of the water levels that occurred in the main tributaries can be summarised as follows:

- Along the Geul, the observed peak water levels were several decimetres up to a maximum of one metre higher than the water levels calculated with a probability of exceedance of 1:100 per year (in the current climate). For the Geul River no modelled water levels with a probability of exceedance of 1:1000 per year were available. However, the probability of exceedance of the water levels that occurred are estimated to lie between 1:100 and 1:1000 per year.

- In the catchment of the Geleenbeek, the probabilities of occurrence vary along the various (sub)streams. At the Caumerbeek in Heerlen, the observed peak water levels were approximately 1-2 metres higher than the water levels calculated with a probability of exceedance of 1:100 per year. Along the section of the Geleenbeek upstream, near Brommelen and Laar, the water levels roughly correspond to the water levels with a probability of exceedance of 1:100 per year. Further downstream near Daniken, Munstergeleen and Susteren (see Table S4 for the geographic locations), the probability of exceedance lies between 1:10 and 1:50 per year. Locally, there are outliers between observations and expected water levels from model results (both high and low probabilities of exceedances) which may be due to for example blockage of the flow profile by debris, different precipitation runoff (difference in soil infiltration) or interaction with the municipal sewer.

- While the Geul and Geleenbeek are steep and respond rapidly, the Dutch part of the Roer has a relatively gentle slope and a longer response time. A comparison of the water levels that occurred along the Roer with the calculated water levels of 1:100 and 1:1000 per year shows, that the observed water levels predominantly fall in between.

6 Morphological changes

6.1 Main channel of the Meuse River

During a flood, the flow velocities in the Meuse increase and along with these, the bottom shear stress and the sediment transport capacity. When the sediment transport capacity in alluvial bed material varies from location to location, it leads to erosion and sedimentation. The sediment transport capacity mainly depends on the flow velocities and the composition of the sediment. The higher the flow velocities and the finer the sediment, the larger the sediment transport will be. During the flood, the weirs in the Meuse River in the Netherlands and Belgium were fully opened. That means that during this flood, they provided minimal obstruction with respect to the transport of sediment.

Directly after the floods, the monitoring department of the Directorate-General for Public Works and Water Management (RWS CIV) carried out multi-beam soundings of the main riverbed. The differences were compared with earlier soundings and provide a clear picture of the morphological changes as a result of the flood. The largest morphological changes occurred along the so-called Common Meuse between the Borgharen weir (rkm 15.4) and Roosteren (rkm 52.4). For that reason, the Common Meuse will be discussed separately below.

6.1.1 Common Meuse

During the floods, at least 22 scour holes of 3 to 15 metres deep developed along the Common Meuse within a short section from rkm 34 to 40. Four of those scour holes were more than ten metres deep. Figure 11 shows the reach with most scour holes and a detail of the erosion hole at the location of the Berg-Meeswijk ferry. The scour holes caused severe damage to river infrastructure such as bank protection (rkm 34.65, 37.9 and 38.2), a ferry landing (rkm 38.9) and crossing pipelines (rkm 36.27). It should be noted that the scour holes developed in or just beside the main channel of the Meuse. Directly after the flood the damage to aprons downstream from the weirs still had to be verified but no major damage due to erosion occurred there or at the location of other structures such as bridges or sluices.

The deep scour holes developed as a result of the following combination of circumstances:

1. Very high flow velocities along the Common Meuse up to 4-5 m/s locally, see Figure 12. Locally, these velocities were even higher than during the floods of 1993 and 1995 as a consequence of non-continuous river widening measures that have been carried out along the Common Meuse (Meuse Work Programme).
2. The local presence of fine sands under a thin layer of gravel. After the armour layer was mobilised and broke up, the thin layer of gravel underneath was also mobilised, and the underlying fine sand was able to erode quite easily (see Figure 13).

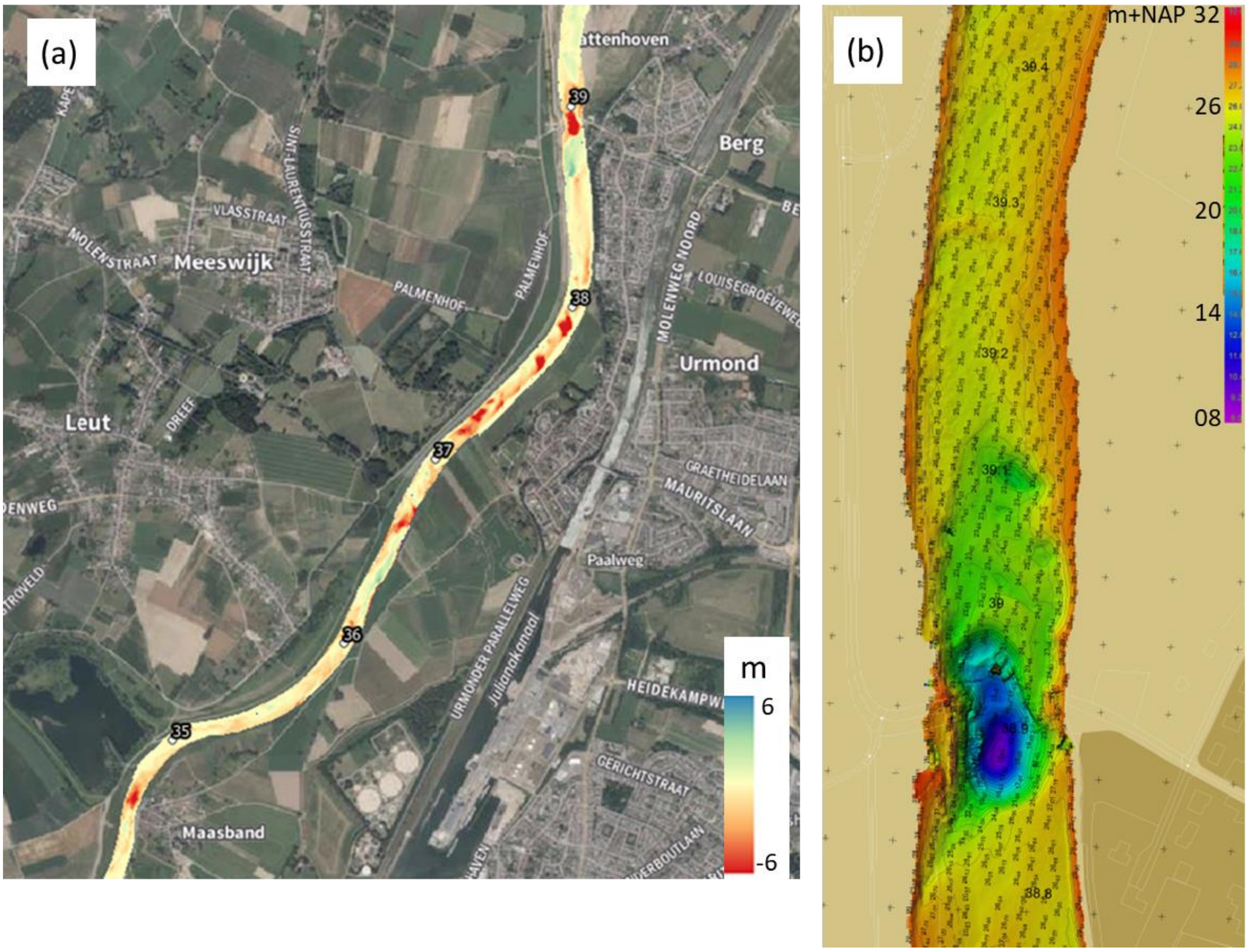

Figure 11: Bed level changes Common Meuse (a) between Maasband (rkm 34) and Nattenhoven (rkm 39.5) and (b) detail of scour hole near the ferry crossing of Berg (source: RWS CIV). Purple colours in figure b indicate low bed levels and red high. Water is flowing from the bottom to the top of the map.

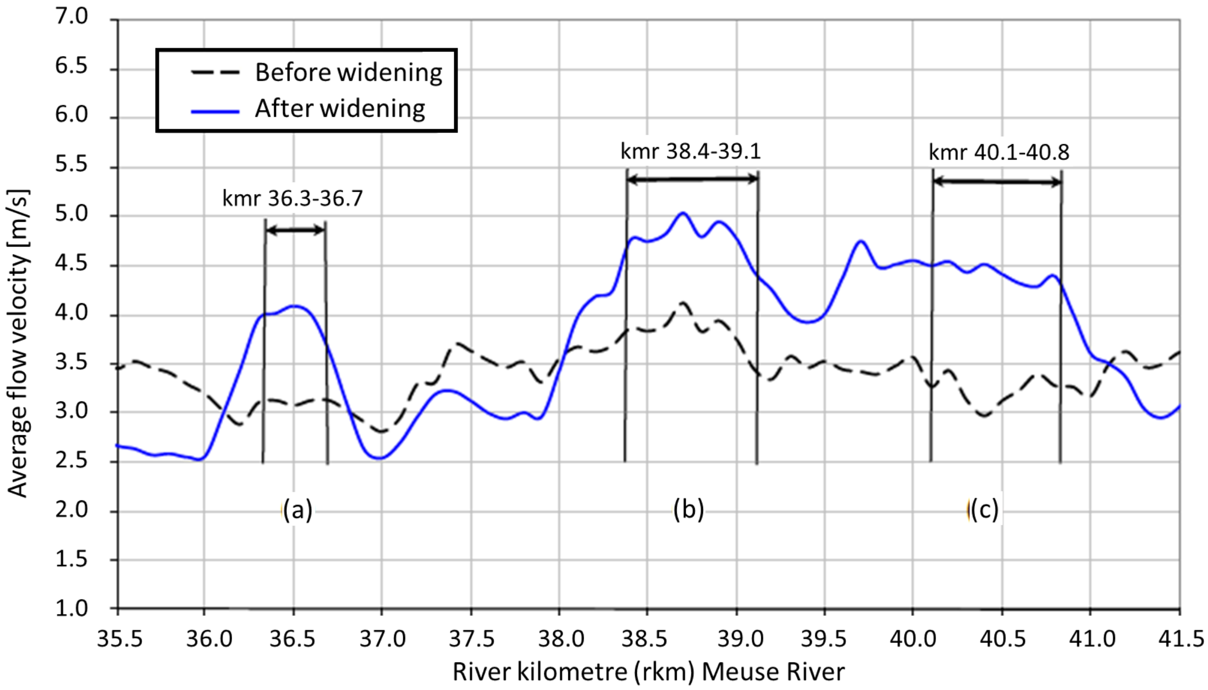

Figure 12: Simulated cross-sectional average flow velocities for a flood discharge of 3,275 m^3/s before the river widening measures carried out since 1995 and after implementation of these measures. At the locations of (a) Urmond, (b) Berg/Nattenhoven and (c) Obbicht no river widening was planned, so at these locations flow velocities have clearly increased. Source: Meijer & Vieira da Silva (2007).

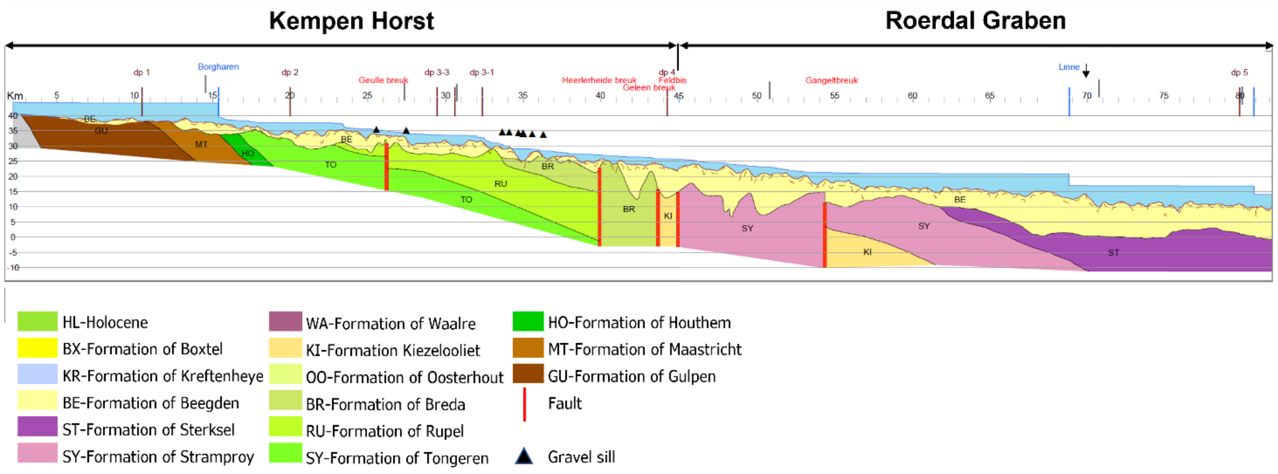

Figure 13: Geological profile of the Meuse valley between the border with Belgium (rkm 2) and rkm 80. The Kempen Horst (tectonically slowly rising area) and Roerdal Graben (slowly sinking) are indicated as well as the different layers of sediment. In the Kempen Horst the thin gravel containing formation of Beegden (yellow) and underlying formations of Breda (Miocene) and Rupel (Oligocene) in green containing fine marine sands are typical. Source: Meijer et al (2011).

Besides the erosion in the above-mentioned section, sand accumulation occurred in the main channel further downstream in the Common Meuse. Near Grevenbicht and Roosteren more than 2 metres of sand accumulated in the main channel.

6.1.2 Embanked Meuse

After the floods, multibeam soundings were also carried out by RWS-CIV in the Upper Meuse (reach upstream of Borgharen weir) and downstream from the Common Meuse. The morphological changes are much smaller than along the relatively steep Common Meuse, where the flow velocities are much higher. The changes are local in nature and mainly occur close to bridges and weir complexes, consisting of limited local bed erosion and sedimentation downstream. the morphological changes did not cause any stability problems for structures.

6.2 Banks and floodplains of the Meuse

6.2.1 Bank erosion

The consequences of the high flow velocities can be seen on the banks along the complete Meuse River. In August 2021, Wageningen University (WUR), in partnership with RWS, carried out fieldwork in order to map the sand deposits on the flood plains of the Meuse (see also below). When fresh bank erosion was found, the locations were noted and positions of top and toe of eroded banks were recorded. Naturally, that overview is not complete and does not provide complete information on the magnitude of the erosion, but it does confirm the idea that bank erosion occurred at many locations. The analyses of aerial photographs will provide a more complete overview of all the locations of erosion. During the field work it was found that the bank erosion along the Common Meuse was the largest. The steep edges of the new banks show that the banks consist largely of clayey material, incorporating horizontal layers of sand and gravel. This coarser material therefore also ended up in the Meuse River and may have been deposited downstream. But also along more downstream river reaches multiple locations of bank erosion were found, as can be seen for the Embanked Meuse River (Figure 14).

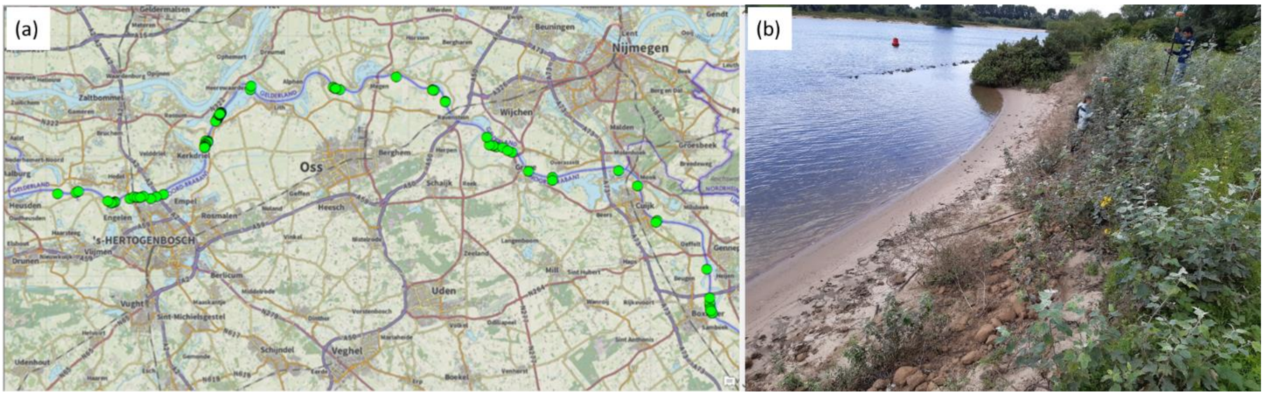

Figure 14: (a) bank erosion locations along the embanked Meuse from Boxmeer (rkm 150) to Ammerzoden (rkm 226) and (b) example of bank erosion location near 's-Hertogenbosch at a location downstream from the A2 highway bridge.

6.2.2 Flood plain sedimentation

From 16 to 27 August, a team from WUR visited the flood plains of the Meuse in order to map the sand deposits on the flood plains. The survey showed that especially in the Common Meuse large deposits of fine sand were found, as shown in Figure *15*. The locations of the scour holes are also shown on the map and it can be seen that large sand deposits near Negenoord and Grevenbicht (map (b)) were found downstream from the scour holes. Large sand deposits were also found near Bosscherveld, upstream of the scour holes. This sand was probably transported from Belgium in suspension or eroded in the river reach upstream between the border and weir Borgharen.

The sand deposits found on the flood plains downstream from the Common Meuse are less thick and cover less area. The volumes deposited along the Embanked Meuse also appear to be somewhat lower than found in 1995 (Sorber, 1997). According to expectations, the main reasons for this are that (1) the peak discharge in the Embanked Meuse during the 2021 flood was significantly lower than in 1995 and (2) the duration of the flood was much shorter than in 1995. The fact that the banks and floodplains were heavily vegetated in the summer (natural or crops) may have caused less flow and sediment transport towards the flood plains.

Most of the deposits were found on inner convex banks and low-lying flood plains, for example near the lowered floodplains of Ooijen-Wanssum.

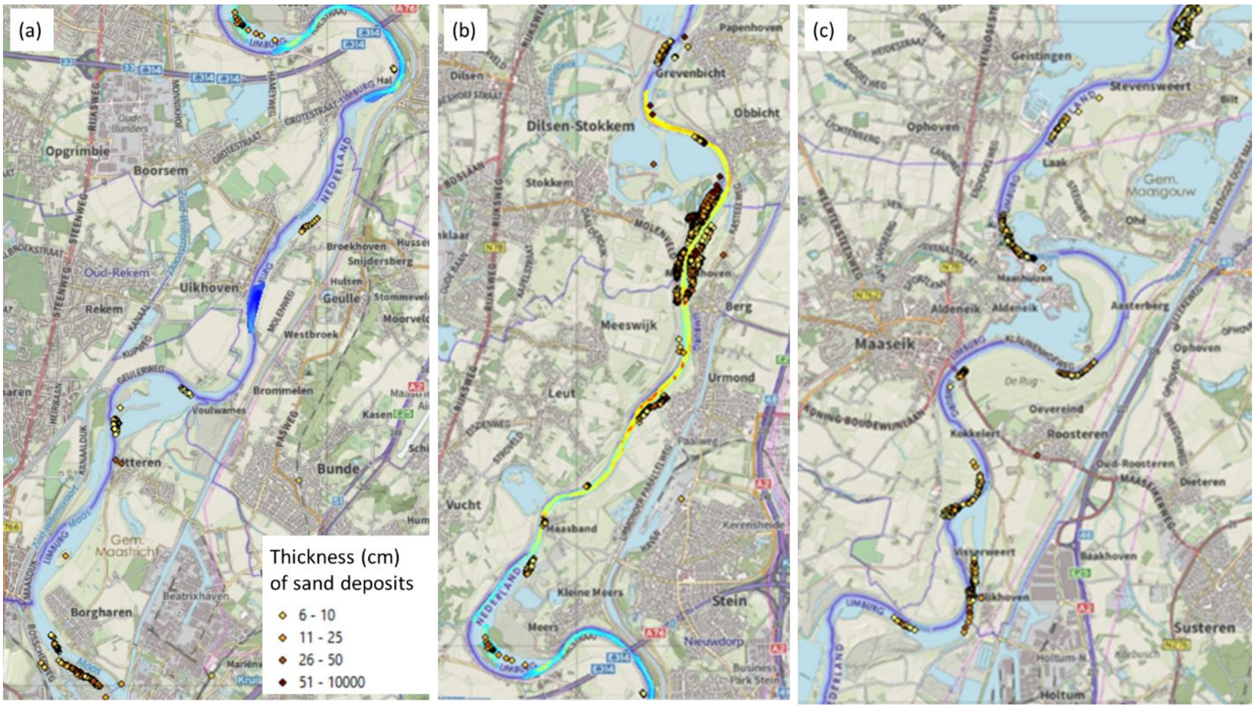

Figure 15: Sand deposits measured in the Common Meuse (a) reach Maastricht-Meers, (b) reach Meers-Grevenbicht and (c) reach Grevenbicht-Stevensweert. The colours in the circles indicate the thickness of the deposits, where the darkest colour is related to sand deposits over 0.5 m thick. The volume of sand deposits in this part of the Meuse River amounted to approximately 75% of the sand deposits found along the complete Meuse River in the Netherlands.

6.3 Tributaries of the Meuse

In the tributaries, high discharges and widespread flooding occurred. However, the LiDAR recordings of the Limburg Water Authority (16 and 17 July 2021) do not indicate major riverbed changes (e.g. bend cutoffs or bank erosion) and there were no reports of major morphological events.

Some major morphological changes were noted in the Old Meuse just downstream from the culvert under the Juliana Canal which conveys the water of the Geleenbeek towards the Old Meuse, see Figure 16.

Figure 16: Morphological changes in the Old Meuse showing bank erosion and bar development. Photo looking in upstream direction.

7 Discussion

This paper aims to provide a comprehensive analysis of the floods that occurred in the Netherlands in 2021 from a hydraulic and morphological perspective. The presented data and analyses are structured to provide a thorough understanding of the flood event. The majority of analyses were conducted immediately after the flood, with some limitations regarding data availability.

Future research can improve our understanding and management of floods. In this paper, we provide some recommendations for future studies. First, our hydrodynamic models were not entirely able to reproduce the water levels that occurred along the Meuse and its tributaries. This may indicate that certain processes are not captured well enough in the models or that model schematizations are invalid. Secondly, until now, statistical analyses on the exceedance probability of certain discharge levels have been limited to the winter months, as very high discharges were expected to be more likely during this period. However, the occurrence of the 2021 flood event in the summer months has shown that this assumption may need to be adjusted. Overall, this study provides valuable insights into the flood that occurred in the Netherlands in 2021, highlighting the need for ongoing research to improve our understanding and management of flood events.

8 Conclusions

The peak discharge in the Meuse River near St. Pieter and a number of tributaries is the highest discharge ever measured. The probability of exceedance of the peak river discharges and corresponding peak water levels observed at different locations along the Meuse River in the Netherlands is approximately 1:100 per year in the upstream reaches near St. Pieter. The methodology that is used in the Netherlands to derive hydraulic loads to assess and design primary flood defences takes floods of this magnitude into account, but assumes that they only occur in the winter and not in the summer. This assumption may have to be changed as it affects the water levels and possible the flood impact.

Although the peak discharge in the Meuse River at St. Pieter was the highest discharge ever measured, water levels downstream of Roermond were lower than during previous floods. The implementation of river widening and floodplain lowering measures as part of the Meuse Works programme contributed to a reduction in peak water levels along the Meuse compared to previous floods. Furthermore, hydraulic models already suggested that peak attenuation plays an important role in the Meuse River in the Netherlands, resulting in lowering discharges and water levels in downstream reaches, and the discharge and water level data collected during this flood have confirmed this. Furthermore, Previous model studies also showed that floods with a short duration have much longer travel times. This was also confirmed by the measurements of the 2021 flood. Due to its exceptionally short duration, the 2021 flood had a travel time that was approximately 50% longer than floods with a more average duration. The analysis also showed that the standard hydraulic models were not able to reproduce the water levels accurately at all locations. This might be due to differences in hydraulic roughness (the models assume a winter situation with less vegetation on the floodplains), but could also indicate errors in the models. This needs to be investigated further.

The analysis also indicated that forecasts became accurate during a late stage, when the rainfall already became runoff. The flood forecasts in the upstream part of the Meuse in the Netherlands depended heavily on rainfall forecasts and rainfall-runoff modelling. The peak discharge levels and water levels were significantly underestimated up to 36 hours before the flood actually peaked. Further downstream, the lead time increases and forecasts are based on discharges that are measured in upstream parts of the catchments. This resulted in more accurate estimates.

The flood resulted in large-scale morphological changes. At several locations in the Common Meuse the breaking up of the armour layer resulted in scour holes of 3 to 15 metres deep. This has shown that locations where there are layers of fine sand close to the surface provide a great risk, as the scour holes caused damage to ferry landings and increased risk of breaching of crossing pipelines. The armour layer was mobilised because of high flow velocities up to 4-5 m/s locally, which occurred in river reaches that were not or hardly widened in the room for the river programme Meuse Works. The morphological changes that have occurred during the 2021 flood therefore also emphasise the importance of a morphological assessment of future river widening plans, so as to prevent large gradients in flow velocities and sediment transport capacity.

Acknowledgement

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9 Supplementary information

9.1 River Meuse

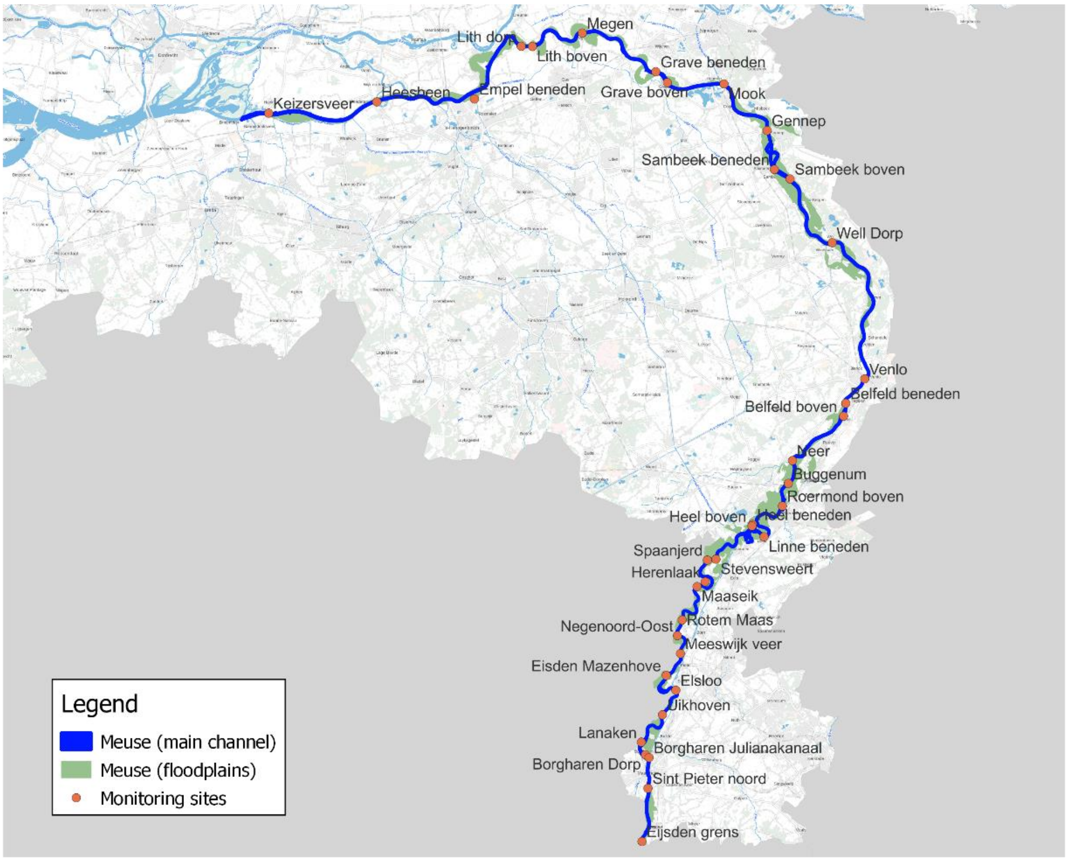

Figure S1: Monitoring sites where water levels are measured along the Meuse River.

9.1.1 Highest water levels measured

Table S1 shows the data obtained from Waterinfo (Rijkswaterstaat, 2021a), where the height and moments of the peak water level are determined based on the 10-minute time series of measured water levels. In addition to the date-time of the peak water level, the table also indicates over which period the water level was only 5, 10 or 20 cm below this peak. In order to keep the table concise, only the times are indicated for this period and not the duration in minutes or hours. All times are given in UTC+2. The projection of the x-y coordinates is EPSG:28992 Amersfoort / RD New.

Table S1: Overview of the measured peak water levels and their timing at different monitoring sites along the Meuse, including geographic information.

Nr	Station name	x	y	Maximum (m+NAP)	Moment peak water level	Time period max-0.05m	Time period max-0.10m	Time period max-0.20m
1	Eijsden grens	175916.5	307627.8	50.64	2021-07-15 21:50:00	20:30 - 02:00	17:40 - 07:10	14:30 - 14:20
2	Sint Pieter Noord	176793.1	315453.5	48.12	2021-07-15 22:20:00	20:50 - 03:20	18:30 - 09:00	15:40 - 15:30
3	Borgharen Julianakanaal	176965.9	319978.1	46.09	2021-07-15 23:40:00	21:10 - 05:00	17:40 - 12:40	13:30 - 20:50
4	Borgharen Dorp	176423	320396.1	45.23	2021-07-16 01:20:00	23:20 - 05:40	19:40 - 11:00	16:30 - 17:30
5	Lanaken	175820.1	322235.8	44.56	2021-07-16 02:00:00	23:50 - 06:50	19:50 - 12:50	15:30 - 20:10

6	Uikhoven	178932.7	326257.8	42.61	2021-07-16 03:20:00	00:40 - 06:50	20:10 - 13:00	16:20 - 20:30
7	Elsloo	180899.9	329869.9	40.95	2021-07-16 02:30:00	00:10 - 07:20	19:40 - 13:30	16:10 - 20:50
8	Eisden Mazenhove	179494.7	332052.3	37.77	2021-07-16 05:40:00	03:10 - 08:30	00:30 - 13:00	21:30 - 18:20
9	Meeswijk veer	181586.1	335265.5	34.05	2021-07-16 11:30:00	05:50 - 13:00	03:20 - 19:40	22:40 - 01:50
10	Negenoord-Oost	181132.9	337893.1	32.81	2021-07-16 10:10:00	08:20 - 13:40	04:30 - 20:40	23:40 - 02:30
11	Rotem Maas	181834	340197.4	32.42	2021-07-16 10:10:00	08:10 - 15:20	05:00 - 21:20	02:10 - 02:50
12	Maaseik	184023.9	345116	30.17	2021-07-16 11:10:00	08:40 - 16:30	05:40 - 22:50	02:10 - 04:30
	Herenlaak	185227.6	345827.9	27.01	2021-07-16 13:10:00	11:00 - 19:40	07:30 - 00:40	03:00 - 07:50
13	Stevensweert	186812	349143.9	25.57	2021-07-16 15:40:00	11:40 - 21:20	07:10 - 03:50	00:20 - 11:50
	Spaanjerd	185551.1	349012.8	25.14	2021-07-16 13:50:00	11:10 - 22:30	06:20 - 06:00	23:40 - 15:30
14	Heel boven	192109.9	354025.1	22.78	2021-07-16 15:40:00	13:20 - 02:50	09:30 - 09:10	04:10 - 17:20
15	Linne beneden	193890.5	352440.4	21.88	2021-07-17 01:10:00	21:00 - 06:30	15:00 - 12:10	09:50 - 20:00
16	Roermond boven	196595.3	356958.6	20.68	2021-07-17 06:10:00	03:20 - 14:10	22:50 - 20:00	18:00 - 02:40
17	Heel beneden	192203.9	354253.1	20.49	2021-07-17 11:30:00	04:10 - 16:30	23:50 - 21:00	19:10 - 03:10
18	Buggenum	197470.7	360279	20.30	2021-07-17 12:30:00	05:30 - 16:10	00:30 - 21:40	19:40 - 04:00
19	Neer	198076.5	363639.5	20.10	2021-07-17 08:30:00	05:30 - 17:00	01:00 - 22:00	20:10 - 04:30
20	Belfeld boven	205601.9	370173.1	18.89	2021-07-17 13:10:00	09:30 - 19:20	04:20 - 01:20	22:50 - 08:10
21	Belfeld beneden	205929.1	372066.3	18.45	2021-07-17 14:30:00	11:50 - 19:40	06:00 - 01:40	00:50 - 08:40
22	Venlo	208721.3	375664.2	18.01	2021-07-17 15:40:00	11:30 - 21:30	05:40 - 03:30	00:10 - 11:10
23	Well Dorp	203915.8	395685.5	15.48	2021-07-17 23:20:00	18:30 - 06:50	11:50 - 14:50	04:30 - 01:40
24	Sambeek boven	197722.4	405051.8	13.77	2021-07-18 08:50:00	03:00 - 17:50	19:40 - 02:30	12:10 - 14:00
25	Sambeek beneden	195404.9	406451.2	13.33	2021-07-18 11:30:00	06:20 - 19:50	00:00 - 04:30	15:50 - 14:50
26	Gennep	194354.4	412179.3	12.34	2021-07-18 17:30:00	12:30 - 01:10	04:30 - 09:20	21:20 - 19:50
27	Mook	187991.6	419024.8	10.78	2021-07-18 21:00:00	16:20 - 07:10	10:50 - 14:30	01:50 - 00:10
28	Grave boven	179657.2	419221.7	9.95	2021-07-19 01:30:00	18:00 - 10:00	12:30 - 18:50	03:20 - 04:50
29	Grave beneden	177964	420830.2	9.47	2021-07-19 02:30:00	22:30 - 11:10	15:40 - 19:10	07:00 - 05:10
30	Megen	167124.4	426506.4	7.63	2021-07-19 07:30:00	04:20 - 18:40	20:50 - 03:50	09:10 - 15:10
31	Lith boven	159777	424531.4	5.97	2021-07-19 15:00:00	10:30 - 02:40	01:40 - 12:30	14:40 - 00:00
32	Lith Dorp	158140	424560	5.79	2021-07-19 17:00:00	11:30 - 03:50	03:10 - 14:00	15:40 - 01:30
33	Empel beneden	151248.6	416819.8	4.86	2021-07-19 23:10:00	16:50 - 08:20	08:00 - 18:30	21:20 - 05:40
34	Heesbeen	136870	416380	3.27	2021-07-20 05:30:00	02:20 - 12:10	13:50 - 00:50	22:20 - 13:30
35	Keizersveer	120950	414720	1.54	2021-07-20 16:40:00	03:10 - 05:20	02:30 - 19:30	23:20 - 00:00

9.1.2 Historical perspective

Table S2: Comparison of the measured peak water levels during the 2021 flood with previous floods in 1993 and 1995.

Riverkilometre	Station name	1993	1995	2021
2.6	Eijsden grens	50.45	50.16	50.64
10.8	Sint Pieter Noord	47.72	47.66	48.12
15.2	Borgharen Julianakanaal	46.42	46.27	46.09
16.0	Borgharen Dorp	45.90	45.71	45.23
18.3	Lanaken	44.97	44.79	44.56
24.8	Uikhoven			42.61
29.3 [2]	Elsloo	40.50	40.23	40.95
34.8	Eisden Mazenhove			37.77
38.9	Meeswijk veer			34.05
42.5	Negenoord-Oost			32.81
43.9	Dilsen stokkem	32.95	32.92	
44.0	Rotem Maas			32.42
44.9	Grevenbicht	32.80	32.73	
52.7	Maaseik	29.50	29.44	30.17
55.0	Herenlaak			27.01
60.4	Spaanjerd			25.14
61.6	Stevensweert	25.36	25.30	
67.9	Heel boven	22.81	22.69	22.78
70.3	Linne beneden [1]	21.05	21.08	21.88
79.7 [2]	Roermond boven [1]	20.60	20.79	20.68
80.3	Heel beneden	20.53	20.59	20.49
85.8	Buggenum			20.30
90.1	Neer			20.10
94.9	Kessel [1]	19.66	19.74	
100.7	Belfeld boven	19.13	19.16	18.89
102.7 [2]	Belfeld beneden [1]	19.00	19.04	18.45
107.5 [2]	Venlo	18.35	18.46	18.01
120.5	Arcen [1]	15.80	16.93	
132.1	Well Dorp	15.34	15.43	15.48
144.9	Sambeek boven	13.90	14.02	13.77
147.7 [2]	Sambeek beneden	13.72	13.92	13.33
155.1	Gennep [1]	12.95	13.22	12.34
165.8	Mook			10.78
174.7 [2]	Grave boven [1]	10.51	10.65	9.95
177.0 [2]	Grave beneden	10.39	10.58	9.47
190.7	Megen	8.30	8.48	7.63
200.7 [2]	Lith boven	6.54	6.81	5.97
202.4	Lith Dorp	6.32	6.54	5.79
215.4	Empel beneden			4.86
230.6	Heesbeen	3.26	3.71	3.27
247.6	Keizersveer	2.28	2.21	1.54

9.1.3 Peak attenuation

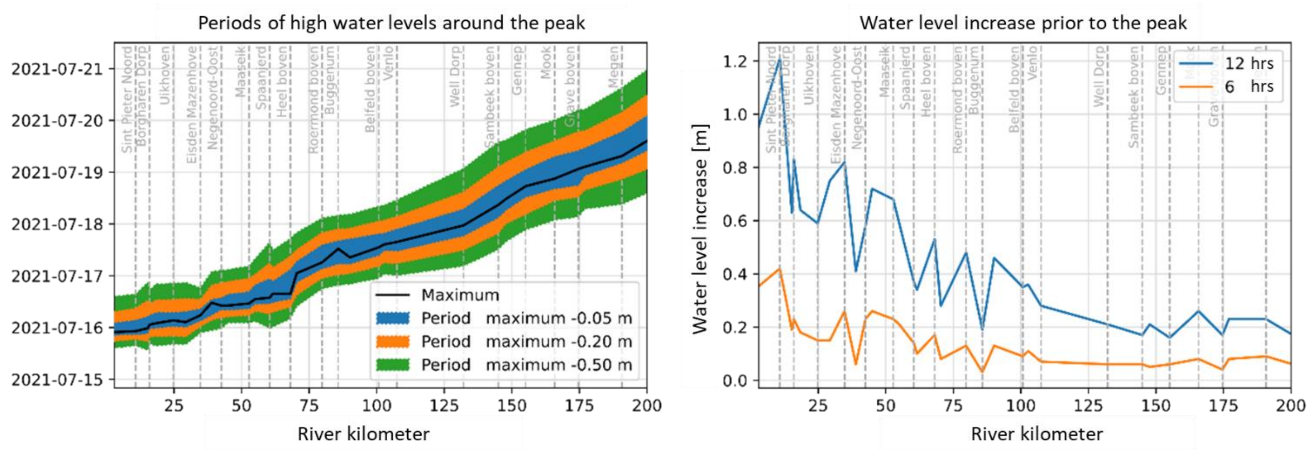

Figure S2: Left: Timing of the maximum water level and the period during which the water level nearly reached this height. Right: Increase in water levels in the last hours up to the water level peak.

9.2 Tributaries

9.2.1 Highest water levels measured

Table S3: Water level measurements in the Geul catchment (consisting of three river branches).

nr	Station name	X	Y	Maximum (m+NAP)	Moment peak water level
	Geul				
1	Meerssen Maastrichterlaan	178824.9	322436.1	46.16	2021-07-15 11:00:00
2	Rothemermolen	179879.9	321378.1	50.43	2021-07-15 09:00:00
3	Grote Molen	181145.9	321278.1	52.95	2021-07-15 06:00:00
4	Geulhemmermolen	182945.9	319982.1	59.09	2021-07-15 04:00:00
5	Geulhem	183464.9	319925.1	60.56	2021-07-15 03:00:00
6	Valkenburg Wiegert	185965.9	319659.1	67.71	2021-07-15 03:00:00
7	Wijlre	190422.9	316266.1	84.07	2021-07-14 21:00:00
8	Wijlre Brand bierbrouwerij	190616.9	315686.1	85.94	2021-07-14 21:00:00
9	Samenvloeiing Geul Gulp Selzerbeek Eyserbeek	191050.9	314601.1	89.59	2021-07-14 20:00:00
10	Mechelen	192534.9	311792.1	101.31	2021-07-14 17:00:00
11	Commandeursmolen	192693.9	311490.1	102.88	2021-07-14 18:00:00
12	Volmolen Hurpesch	192460.9	310763.1	106.63	2021-07-14 18:00:00
13	Epenermolen	192542.9	309318.1	113.37	2021-07-15 11:00:00
14	Cottessen	193598.9	307725.1	122.04	2021-07-15 10:00:00
	Gulp				
1	Gulpen Azijnfabriek	190541.9	313924.1	91.93	2021-07-14 20:00:00
2	Euverem	189462.9	312872.1	104.99	2021-07-14 20:00:00
3	Beutenaken	188169.9	310728.1	124.05	2021-07-14 18:00:00
4	Instroom molentak Broekermolen	188441.9	309065.1	137.23	2021-07-14 18:00:00
5	Slenaken	188522.9	309008.1	138.24	2021-07-14 17:00:00
	Eyserbeek				
1	Meetgoot Eys	193201.9	315190.1	102.74	2021-07-14 18:00:00
2	Eys	194191.9	315221.1	111.62	2021-07-14 17:00:00
3	Simpelveld Oude Molen	196199.9	316069.1	131.35	2021-07-14 16:00:00
4	Simpelveld	197519.9	316322.1	141.18	2021-07-14 16:00:00

Table S4: Water level measurements in the Geleenbeek catchment (consisting of two river branches).

nr	Station name	x	y	Maximum (m+NAP)	Moment peak water level
	Geleenbeek / Caumerbeek				2021-07-16 12:00:00
1	Oud Roosteren	186152.9	343256.1	28.92	2021-07-15 10:00:00
2	Millen Meetgoot	188837.9	337307.1	36.49	2021-07-15 11:00:00
3	Millen	188971.9	337049.1	37.59	2021-07-15 09:00:00
4	Munstergeleen	188208.9	332162.1	49.18	2021-07-15 09:00:00
5	Daniken	186893.9	330107.1	53.91	2021-07-15 01:00:00
6	Kathagen	190598.9	326546.1	67.3	2021-07-14 23:00:00
7	Laar	191608.9	325233.1	69.68	2021-07-14 23:00:00
8	bovenstrooms RWZI Hoensbroek	192361.9	325162.1	70.2	2021-07-14 20:00:00
9	Brommelen	191944.9	324475.1	71.59	2021-07-14 18:00:00
10	benedenstrooms Buffer de Dem	193612.9	325590.1	74.5	2021-07-14 17:00:00
11	benedenstrooms Buffer Kopkesmolen	194590.9	324371.1	78.46	2021-07-14 16:00:00
12	bij instroom Oude beek	196163.9	323786.1	89.18	2021-07-14 14:00:00
13	bij instroom Palenbergerbeek	196986.9	323707.1	92.33	2021-07-16 12:00:00
	Rode Beek				
1	Susteren	187676.9	341129.1	29.62	2021-07-14 20:00:00
2	Stuw AR Millen bovenstrooms	189349.9	337218.1	37.39	2021-07-15 10:00:00
3	bovenstrooms N274	196089.9	332446.1	52.78	2021-07-15 11:00:00
4	Schinveld Putbergstraat	196469.9	330881.1	57.83	2021-07-14 12:00:00
5	benedenstrooms buffer Breukberg	196449.9	330422.1	59.88	2021-07-14 12:00:00

Table S5: Water level measurements in the Roer catchment.

nr	Station name	x	y	Maximum (m+NAP)	Moment peak water level
1	Hambeek	197088.9	355270.1	21.07	2021-07-17 08:00:00
2	Roermond Andersonweg bij stuw Hoge Bat	198123.9	351201.1	21.44	2021-07-17 10:00:00
3	St. Odiliënberg	202926.9	350932.1	23.95	2021-07-17 09:00:00
	Bosbeek voor instroom Roer	203617.9	349638.1	27.60	2021-07-17 03:00:00
4	Vlodrop	205246.9	345611.1	28.84	2021-07-17 00:00:00
5	Stah	197088.9	355270.1	33.05	2021-07-16 19:00:00

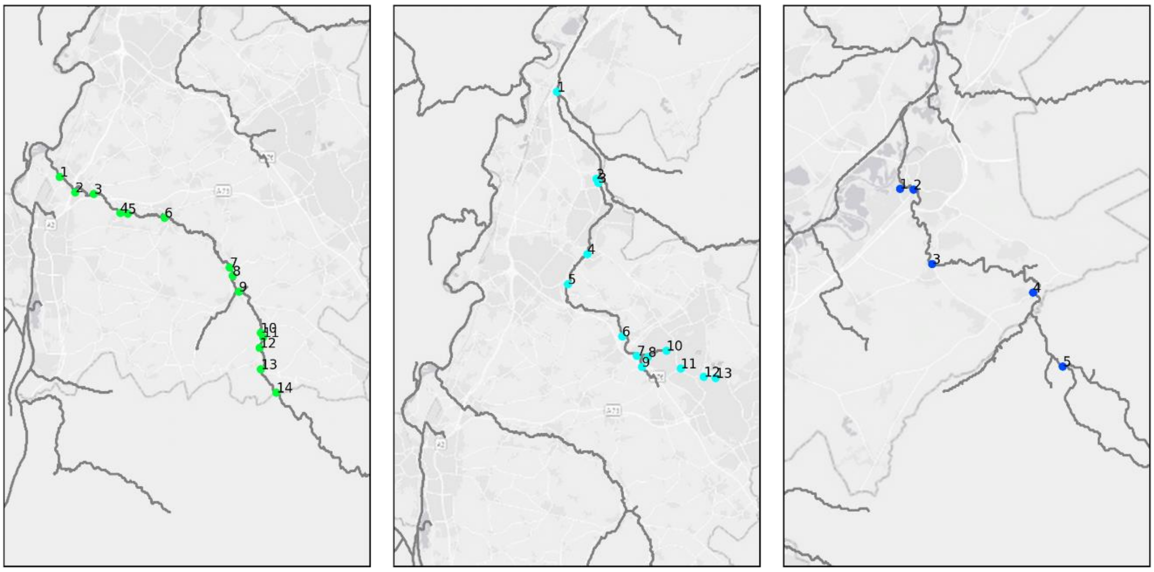

Figure S3: Measurement locations where only the locations along the main river in the catchments are shown. From left to right: the Geul, the Geleenbeek and the Roer.

9.2.2 Water level time series

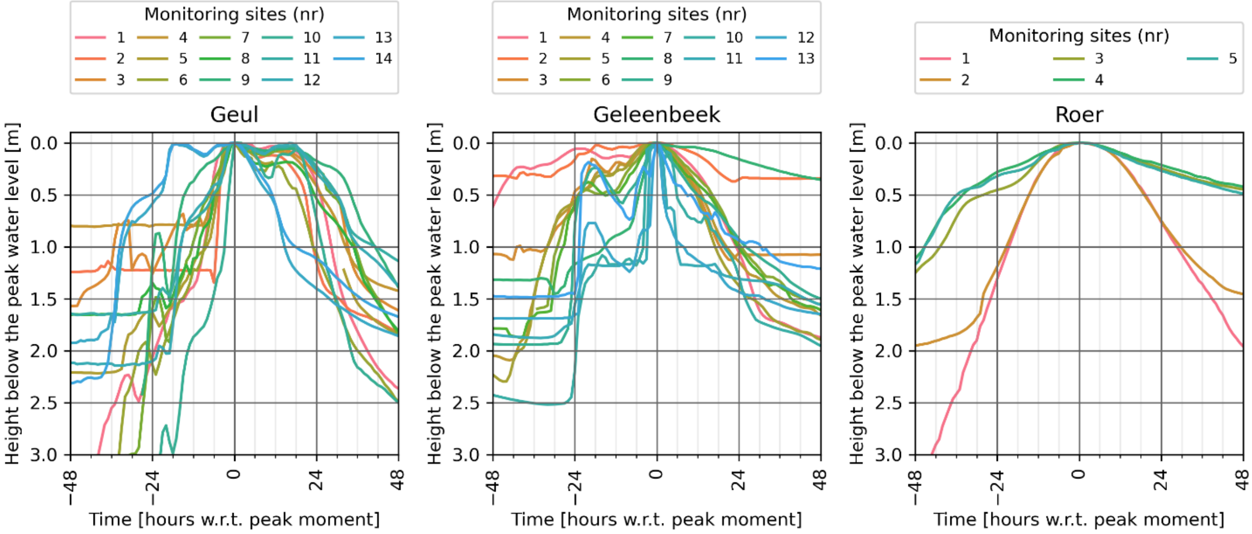

Figure S4: Time series of water level heights relative to the peak level at each location within the three catchments, measured in hours from the peak moment.