C.J.M. Frijns

Comparison of the flood extent on the River Meuse

1993, 1995 and 2021

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By

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Rijkswaterstaat

Preface

This master thesis is the result of my final work in obtaining the master degree in Civil Engineering at Delft University of Technology with the specialisations River Engineering, Coastal Engineering and Ports and Waterways. This research has been performed with the support of Delft University of Technology and Rijkswaterstaat. The performed research would not be achieved without the contribution of many people who I would like to thank.

Firstly, I would like to thank my committee members. I want to thank my daily supervisor Robert Slomp for the many meaningful conversations, his endless knowledge and his motivation to help when necessary, Martine Rutten and Robert Lanzafame for all their valuable feedback and expertise. My expressions of gratitude go out to Matthijs Kok for chairing my MSc thesis committee and finding an interesting thesis topic for me.

Secondly, I want to thank the colleagues from Rijkswaterstaat for their enthusiasm and willingness to help. Even though I was not able to see anybody a lot in real life, it felt like I could still reach out to ask questions.

Thirdly, I would like to thank also Martine Rutten and Bas Jonkman for creating the project group Limburg floods 2021. I found the COVID-pandemic with its social distancing and working from home demotivating. Therefore, I was always looking forward to see our Delta futures lab group every few weeks. It was very motivating and nice to be able to see still a few students in the COVID- pandemic. Furthermore, everyone working on other parts of the same event gave me new insights for my own thesis.

Fourthly, I want to thank the Delft University of Technology for all the experiences and lessons learned over the course of my Master degree. I am grateful for the people I have met and the opportunities that were made possible through the university.

Lastly, I want to thank my family and friends for their continuous support during my study.

C.J.M. Frijns

Delft, June 2022

Contents

Abbreviations

AHN3	Actueel Hoogtebestand Nederland 3
CEST	Central European Summer Time
ENW	Expertise Netwerk Waterveiligheid
GRADE	Generator of Rainfall and Discharge Extremes
HWBP	Hoogwaterbeschermingsprogramma
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LKW	Lateraal Kanaal West
MIM	Ministerie van Infrastructuur en Milieu
MVW	Ministerie of Verkeer en Waterstaat
NAP	Normaal Amsterdam Peil
PUC	Publicatieplatform UitvoeringsContent
Rkm	River kilometers
RWS	Rijkswaterstaat
VNBM	Vlaams Nederlands Bilaterale Maascommissie
WWTP	Waste Water Treatment Plant

Nomenclature

Symbol	Description	Unit
A_c	Area of the wetted conveyance cross-section	m^2
B	Width of the main channel	m
B_c	Width of the floodplain	m
c_{HW}	Propagation speed of the flood wave	m/s
c_f	Friction coefficient	-
g	Gravitational coefficient	m/s^2
h	Water depth	m
i_b	Slope of the river bed	-
P	Wetted perimeter	m
Q_d	Diffusive discharge	m^2/s
Q_e	Kinematic discharge	m^2/s
R	Hydraulic radius	m
s	Distance	m
U_u	Velocity of uniform flow	m/s

Summary

Major flooding occurred on the Meuse River in 1993, 1995 and 2021, causing significant damage to regions in NL, BE, DE. The flood events of 1993 and 1995 occurred in the winter, while that of 2021 occurred in the summer. There are large differences in the characteristics of these floods separated by nearly three decades; not only the seasons differ, but the topography of the river bed and the shape of the flood wave have also changed. Since 1995 dikes and flood-routing measures have been constructed along the river. Although all these projects are not yet completed, the flood event of July 2021 indicates that the Meuse projects are producing the expected results.

This research aims to understand the effect of the shape of the flood wave during a high-discharge event, the impact of the different types of flood protection along the river and the interaction between the main river and its tributaries. Flood wave characteristics play an important role: the width illustrates the duration of the event, while the height indicates the maximum water level that can be expected.

Before the flood events of 1993 and 1995, the Limburg Meuse River valley was not heavily engineered. The natural landscape created a river valley with the river on the lower elevation points, and the towns were built on the higher plateau. However, many villages were still inundated in 1993 and/or 1995 despite their elevated locations. This created the need to protect the villages located in the flood prone areas and therefore 150 km of dikes are raised immediately after the flood of 1995 on the Dutch part of Limburg. After the flood a plan that was partly designed after the flood in 1993 was elaborated and finalised in 1995. This plan included raising of the dikes and flood routing measures to create more room for the river, as the raising of dikes had the drawback of reducing 40% of the river flood plain volume. In 2021 this resulted in a higher water level than the flood of 1995 because of the decrease in conveyance width. Thus, flood-routing measures are an important method for reducing flood risk by increasing the effect of peak attenuation.

After an analysis comparing inundation maps, five flood prone areas were identified and investigated, namely: Maastricht, Bunde and Meerssen, Maaseik-Roosteren, Roermond and Venlo as shown in Figure 1. Four of them, Maastricht, Maaseik, Roermond and Venlo, are big cities in the Meuse valley, whereas the villages Bunde and Meerssen and the city Roermond are confluence points where the tributaries meet the Meuse river. The tributaries the Geul and the Roer had higher discharges in 2021 than the designed discharge of the flood defences. Furthermore the peak of the flood waves of the main channel and the tributaries arrived at the confluence points simultaneously. At Bunde the siphon design capacity was also lower than the measured discharge. This combination of factors increased the water levels and created a backflow in the tributaries.

The flood prone areas are also the main bottlenecks in the River Meuse at Maastricht, Roosteren - Maaseik and Herten/Roermond. A bottleneck is a point in the river caused by a reduction of discharge capacity. The shared characteristic of these three bottlenecks is the lack of space to create more room for the river. The city of Maastricht, because it is built surrounding the river and there is almost no room left to give back to the river floodplain. While the area between the village of Roosteren and the city Maaseik may appear to provide enough room, it makes a sharp turn between the two urban areas which reduces flow velocity and results in a lower discharge capacity. The village of Herten was built into the floodplain which abruptly reduces the total width of the river and causes a local reduction of the discharge capacity.

Theoretical predictions of flood wave behaviour derived by scenario-based simulations with hydraulic models (i.e., report of peak attenuation, evaluation of the Grensmaas and the tool Box of building blocks) were compared with measurement data, water levels, discharges and inundation maps in order to assess if intended effect of certain measures correspond with the measured effect of the flood events of 2021.

The report of peak attenuation commissioned by RWS evaluated the effect of peak attenuation on the Dutch part of River Meuse in 2019. The study simulated a sharp flood wave similar to the flood wave of 2021, while the shape of the average flood wave was similar to the flood waves of 1993 and 1995. This study allowed a comparison to be made between the different flood events even though the topography of the river bed changed significantly in the preceding decades. It can be concluded that a sharper shape of

the flood wave will increase the effect of peak attenuation. Furthermore, the increase in the width of the flood plains (800 m) from the Grensmaas to Maasplassen (1100 m) changed the kinematic wave to a dissipative wave.

Figure 1: The Limburg River Meuse

The four most important flood-routing measures of the Box of Building Blocks are the deepening of the main channel from Eijsden till Borgharen by two meters, the potential high-water channel at Borgharen and Itteren, the high-water channel at Kotem (Flemish side) and the delta program project Ooijen-Wanssum.

None of the dike sections along the river, designed for an event with return period of 300 years, experienced a dike failure in 2021 because the flood routing measures increased the flood system discharge capacity to a total return period from 50 years to 250 years. Although the flood routing measures are important to reduce the flood risk, the main reason flooding did not occur was that the dikes protected the urban areas and dikes are an important component of flood safety, especially on the villages, Visserweert, Aasterberg, Thorn and Wessem, Buggenum and Well Dorp, which would have been flooded if there were no dikes.

The shape of the flood wave has a large impact on the behaviour of the flood wave, however it is outside the scope of human engineering due to issues such as cost, complexity and system complexity. Therefore implementation of flood protection measures at a specific location are most favourite in improving the flood safety of a river. In addition, it is important to create a new measurement station just downstream of the project Ooijen-Wannsum to get a good estimation of the effect of the Ooijen-Wannsum project, for example, a suitable location would be near Arcen.

1

Introduction

1.1 Background information

The Meuse River is the second largest river in the Netherlands. The catchment area of the river Meuse is stretched out over five countries: France, Luxembourg, Belgium, Germany, and the Netherlands. The river has a length of 874 km from the source in France to the Rhine-Meuse estuary in the Hollands Diep (Dutch Deep) in the Netherlands (Burgdorffer, 1994). The river catchment has a total area of circa 33.000 km^2. The surface area of the Dutch Meuse catchment area is about 7.700 km^2 and about 500 km^2 of this is water (MIM, 2015).

The Meuse is a rain-fed river characterized by relatively high floods and low baseflows (Berger, 1992). Especially the precipitation in the Ardennes determines the river discharge. The precipitation here flows quickly in the smaller rivers and streams into the rocky bottom of the Meuse. As a result, the water levels can fluctuate greatly in a short period.

The origin of the river Meuse flows through a relatively flat area in France with a permeable substrate, which generates a relatively slow response time to precipitation. While the tributaries in Belgium, partially the Ardennes, the river basin is hilly with a rocky subsoil. This creates larger slopes than in France. As a result, little water can be stored and the drain reacts quickly to precipitation (Burgdorffer, 1994). Figure 2 shows the river Meuse with all its tributaries in height difference in NAP.

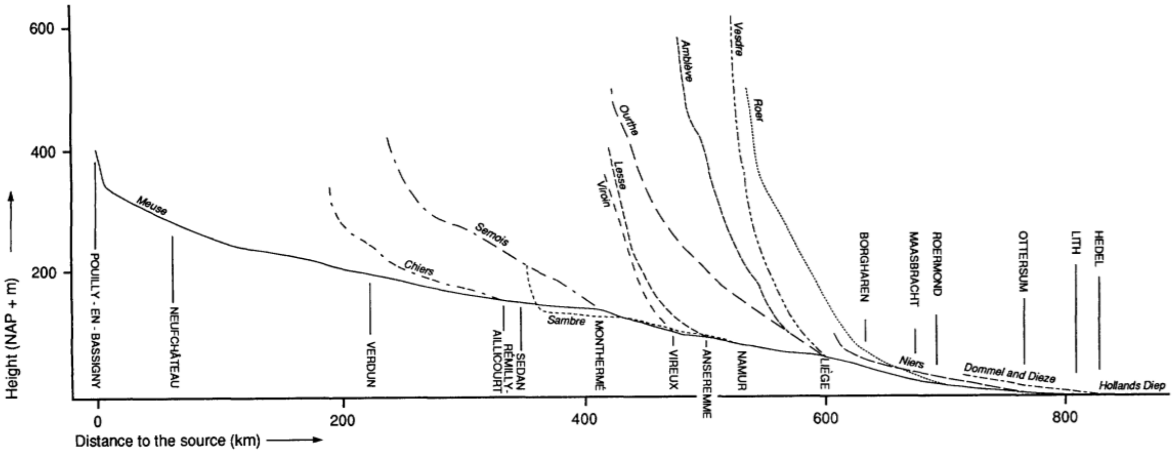

Figure 2: Longitudinal profile of the Meuse River of its main tributaries (Berger, 1992)

The upper reaches of the Meuse, the first 150 km in the Netherlands is defined as the Limburg part of the Meuse River. The protection of the houses follows into three categories: village on a terrace, houses located on a small island, or village located near a ford (Boers & Pille, 2009).

The Dutch River basin of the Meuse in figures (MIM, 2015):

- Catchment area: 7700 km^2 (including coastal zone)
- Highest point 323 m (Vaalserberg)
- Meuse discharge at Eijsden average: 230 m^3/s
- Meuse discharge at Eijsden highest measured: approximately 3300-3400 m^3/s (2021)
- Normative discharge at Eijsden: 3800 m^3/s

1.2 Problem definition

Historically, the last major flood events of the Meuse happened in 1993 and 1995. However, in July 2021 the river dikes along the Meuse were again threatened with high water levels due to a large amount of precipitation and flooding in Belgium and the Netherlands. Following the flood events of 1993 and 1995, the national government, provinces, water boards, and municipalities created five projects to prevent this from happening again:

- 'het Deltaplan Grote Rivieren', which resulted in circa 150 km of new dikes (MVW, RWS, 1995)
- Maaswerken (relocating dikes and reinforcement and river-widening projects (RWS, 2021)
- Delta Program projects
- Flood protection projects in Dutch called Hoogwaterbeschermingsprojecten (HWBP)
- River-widening projects along with HWBP

Even though not all the Meuse projects are completed and the HWBP and river-widening projects along with HWBP are still in the planning phase, the flood event of July 2021 gives a good indication whether the Meuse projects are producing the expected results. This thesis will give a global evaluation of the measures that the Dutch and the Belgians have taken to protect the province of Limburg against the river Meuse since 1995. Are the measures that have been taken logical and how large is the impact of certain measures.

Figure 3: The Limburg part of the Meuse

1.3 Research purpose

The purpose of this research is to understand the effects of the form of the flood wave during a high-discharge event. Furthermore, to understand the impact of the different types of flood protection along the river.

1.4 Scope limitations

It is important to define the scope of the research, as it helps to give the researcher focus by providing limitations to the research topic. The scope of the project is defined as:

- The research area is the Limburg part of the Meuse River, from Eijsden till Mook.
- The strength of the flood protections are not investigated in this research. There were no failures of dikes in the 2021 flood. Furthermore there were almost no flood protections in 1993 and 1995.

- Only the hydrodynamic behaviour of the flood is investigated. The primary focus was on the water levels.
- The difference in friction coefficient in summer and winter is an interesting topic but it will only be discussed globally.

1.5 Research question

The main research question is: what are the hydrodynamic differences between the high-waters levels on the Meuse in Limburg in 1993, 1995, and 2021, and how can these differences be explained?

The research question is broken down into sub-questions:

1. What are the similarities and differences between the hydrodynamics on the floods in 1993/1995 and 2021?
2. What impact did the protective and flood routing measures have on the behaviour of the flood?
3. What are the bottlenecks in the Limburg part of the Meuse River?
4. What protective measures have the largest impact?

1.6 Thesis outline

Chapter 2 provides the necessary existing theory on fundamental aspects regarding the characteristics of the Meuse, the theory of flood events, the flood protection measures and the flood-prone areas. Chapter 3 explains the research methods and the research process. In chapter 4, the data of the high-water events of 1993, 1995 and 2021 and the measures taken after the flood events will be compared. Chapter 5 will compare the intended effect and the measured effects. Chapter 6 provides a discussion and conclusion on the results of this study. The recommendations are described in chapter 7.

2

Fundamental aspects

This chapter provides an overview of the existing literature about fundamental aspects regarding the characteristics of the Meuse, theory of floods events and flood protection measures.

2.1 The characteristics of the river

2.1.1 The hydrology of the Meuse

High discharges occur almost always in winter and spring because the Meuse River is a rain-fed river. The average annual precipitation of the river basin in the Netherlands is approximately 750 mm, while the rainfall in the higher parts of the Ardennes is circa 1200 mm. Commonly, 60% of the total precipitation in the Meuse catchment evaporates, indicating that only 40% of the precipitation discharges into the river basin. Precipitation is relatively constant over the whole year, but evaporation is higher in the summer than in winter due to the warmer weather. In the summer the evaporation can be 100 mm/per month, while the evaporation is close to zero in the winter. This creates a seasonal variation in the discharge regime, as shown in Figure 4 (de Wit, et al., 2001).

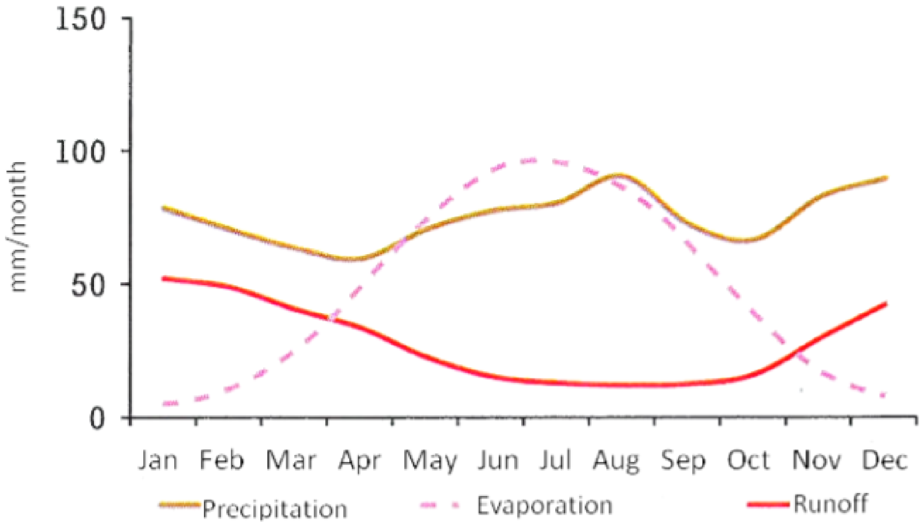

Figure 4: Precipitation, evaporation and run-off of the river Meuse (de Wit, Van regen tot Maas, 2008)

On average, the Meuse discharges 340 m^3/s during the high-water season (between 1 November and 1 April) with a corresponding water level of 39.50 m above NAP (TAW, 1994). Once every three years, the discharge can go up to 1800 m^3/s, but under very extreme weather conditions, the Meuse can accommodate more than 3300 m^3/s. These extreme conditions occur on average once every 250 years (RWS, 2018).

2.1.2 Confluence point

In geography, a confluence occurs where two or more flowing bodies of water join together to form a single channel. A confluence can occur in several configurations: at the point where a tributary joins a large river (main stem) or where two streams meet to become the source of a river of a new name or where two separated channels of a river re-join at the downstream end.

River confluences are important points in the alluvial network. It is often represented with abrupt changes in discharge, grain size and channel geometry.

2.1.3 Hydraulic radius

The hydraulic radius is used as an indication of the flow's efficiency. The definition of the hydraulic radius is that the cross sectional area of flow divided by the wetted perimeter as shown in Figure 5. The greater the hydraulic radius, the more water can flow through the channel. The formula for the hydraulic radius is:

$$R = \frac{A}{P}$$

Where R is the hydraulic radius [m], A is the cross-sectional area [m^2] and P is wetted perimeter in [m].

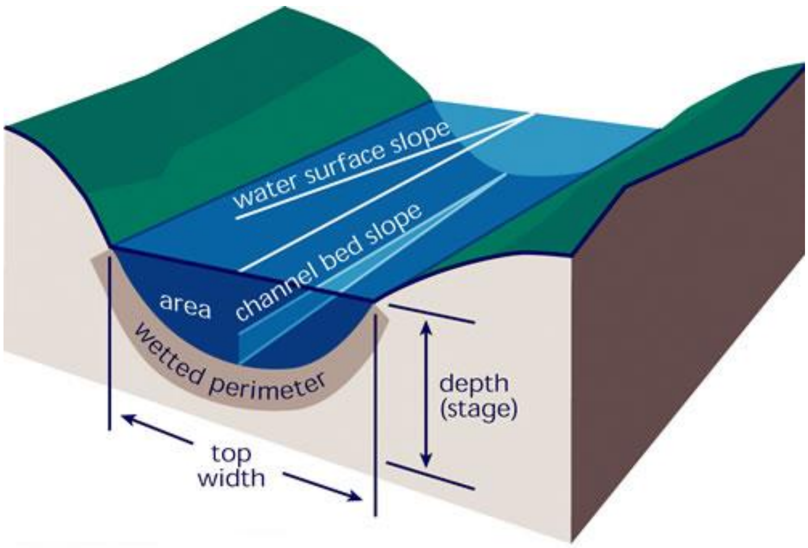

Figure 5: Definition of hydraulic radius (Coolgeography, 2022)

2.1.4 Measurement stations

The number of measurement stations and the locations to measure the water level in 1993, 1995 and 2021 changed. In 1993 and 1995, there were 23 measurement stations to register the water level, while in 2021 there were 27 measurement stations. The VNBM (Vlaams Nederlands Bilaterale Maascommissie), a commission which is explained in 2.3.2.2. Grensmaas project, decided to build measurement stations that would be used for Belgium and the Netherlands. Therefore some measurement stations were moved a few hundred meters and new measurement stations were built. The measurement stations Uikhoven, Eisden Mazenhove, Meeswijk veer, Negenoord-Oost and Herenlaak were new measurement stations. While the measurement station at Dilsen Stokkem was dismantled and a new measurement location was established at Rotem Maas 900 m further downstream. The measurement station the Spaanjerd was created after 1995 and the location at Stevensweert 1.2 km downstream was dismantled as shown in Figure 6.

The water levels at the measurement station differ between the different flood events. Six of the stations (Linne beneden, Roermond boven, Kessel, Belfeld beneden, Arcen and Gennep) only measured every eight hours in 1993 and 1995 as shown in Appendix A. In July 2021 the measurements were taken every 10 minutes for all the measurement stations. Five stations (Elsloo, Roermond boven, Belfeld beneden, Venlo and Sambeek beneden) have been relocated to a maximum of 700 m. The measurement station at Neer was created after 1995 and the location at Kessel 3.8 km downstream was dismantled. Further a new measurement station was built at Buggenum after 1995. The measurement station Arcen was also dismantled, but no measurement station is built to replace it.

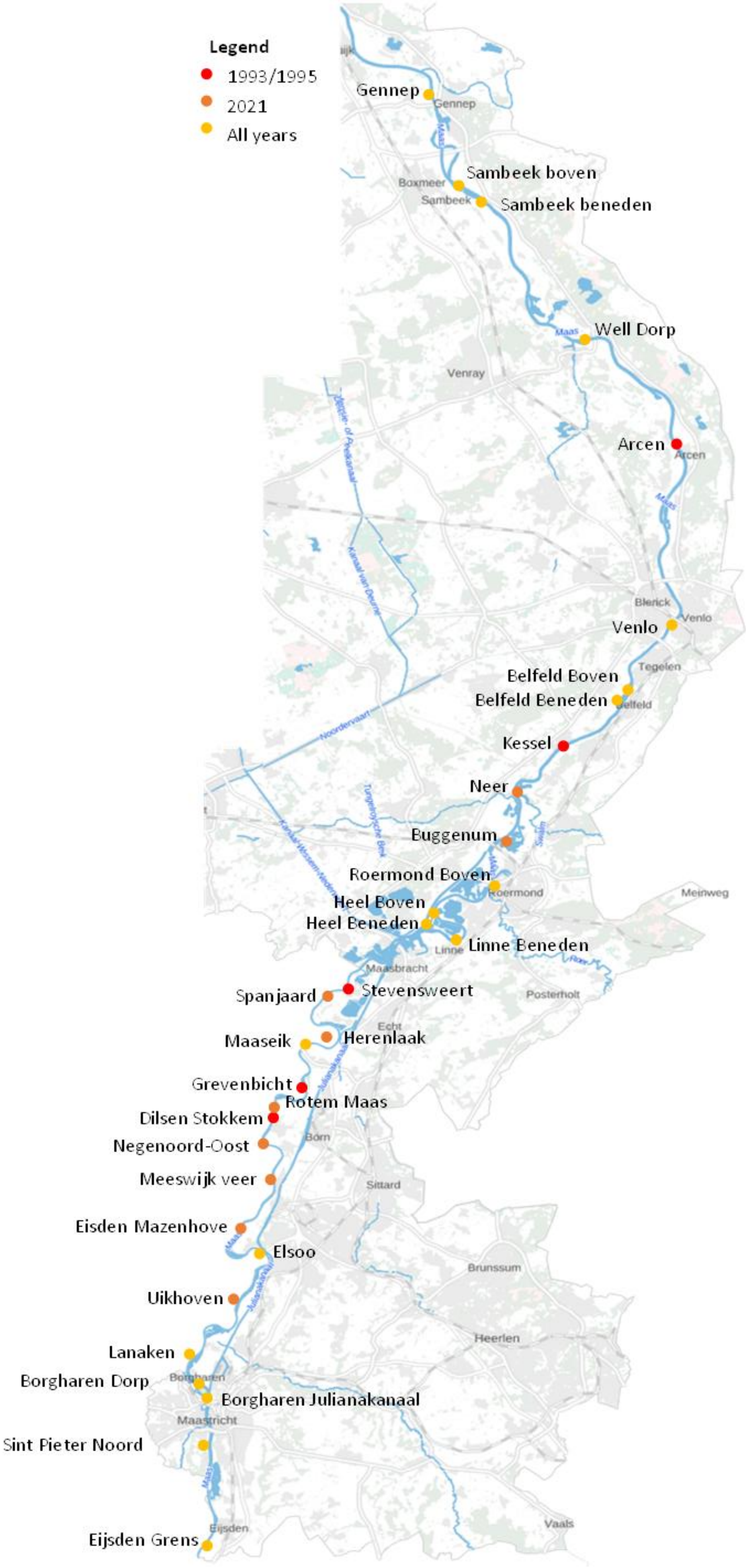

Figure 6: Locations of measurement station between 1993 and 2021

2.2 The behaviour of the flood wave

2.2.1 The definition of the flood wave

The definition of a flood is that the amount of precipitation in the river basin is high for a short period. In the Netherlands, the term is defined as that the discharge is greater than the critical discharge in the River Meuse (Berger, 1992). However, since 2017 there is no formal design discharge value anymore. A new approach to flood safety is implemented in 2017, the WBI2017 (TAW, 2000). This means that previously flood protections was designed with probability of exceedance and the new approach is the failure probability per dike segment.

The change in evolution and the dynamics of the flood wave differs significantly between the upper and lower reaches of the river. In the upper reaches, the change is quick because of the relatively steep slopes and small catchment area (for example, in the Ardennes). This results in rapid variations in the flow rate and the water levels. In the lower part of the river, the changes are slow. In most cases, it takes several days due to the large catchment area, mild slope and tributaries. The peak run-off from all the different tributaries will not happen simultaneously. Therefore, it can be concluded that the maximum of their sum is less than the sum of the individual maxima. Furthermore, the internal dynamics of the flood wave cause the wave to flatten and elongate as it propagates downstream (Battjes & Labeur, 2017).

To calculate the speed of the high-water wave in the lower part of the river, the following formula is used:

$$c_{HW} = \frac{1}{B}\frac{dQ_u}{dd} = \frac{3}{2}\frac{B_c}{B}\ U_u$$

where c_{HW} is the propagation speed of the flood wave [m/s], B_c is the width of the floodplains [m], B is the width of the main channel [m] and U_u is the velocity of uniform flow [m/s].

When the flood plains are submerged, B is much larger than B_c, leading to a difference in velocity in the main channel and the flood plains. The effect of bottom friction on the flow velocity is largest close to the river bed. For a higher water depth, the influence of bottom friction on the flow velocity is smaller. The bottom resistance in the flood plains will also be more prominent than in the main channel. Therefore, the water moves slower in the flood plains than in the main channel.

In the first part of the Meuse river, the kinematic wave model is a good approximation. From Roermond onward, the river width and the bed slope will be better represented by the diffusive wave model. The river width will roughly change from 800 m to 1100 m and the bed slope from $4x10^{-4}$ to 0.8×10^{-4}.

Both the kinematic wave and the diffusive wave models are quasi-steady approximations of the shallow-water equations; the local acceleration term is neglected in the momentum equation. In addition, the kinematic wave model is based on the assumption that the flow is also quasi-uniform, meaning the discharge depends on the local depth and the bed slope only. This leads to the following formula for the kinematic wave model:

$$Q_e = A_c\sqrt{\frac{gRi_b}{c_f}}$$

where Q_e is the kinematic discharge [m^2/s], A_c is the area of the wetted conveyance cross-section [m^2], g is the gravitation constant [m/s^2], R is the hydraulic radius [m], i_b is the slope of the river bed [-], and c_f is the friction coefficient [-].

In the diffusive wave model, the latter simplification is not made and the discharge is therefore dependent on the actual water level gradient, including the depth gradient. This leads to a so-called hysteresis; in the rising stage the discharge is larger than the discharge for the same flow depth in the falling stage. There is no unique relation between the flow depth and the discharge. This causes damping and flattening of the diffusive wave.

The diffusive flood wave is described as (Battjes & Labeur, 2017):

$$Q_d = A_c \sqrt{\frac{gR}{c_f}} \sqrt{i_b - \frac{\partial R}{\partial s}} = Q_e \sqrt{1 - \frac{1}{i_b} \frac{\partial R}{\partial s}}$$

where Q_d is the diffusive discharge [m^2/s], Q_e is the kinematic discharge [m^2/s], i_b is the slope of the bed, R is the hydraulic radius [m], and s is the distance in [m].

In contrast, the kinematic wave will retain its shape (although it may deform since the wave speed c_{HW} depends on the local water depth). As the flattening of a kinematic wave proceeds, the influence of the depth gradient, causing the kinematic behaviour, becomes less and less important and will ultimately disappear leading to a dissipative wave.

2.2.2 Peak attenuation

Peak attenuation is the phenomenon that describes how the peak discharge or the water height changes as it propagates in the downstream directions, keeps flattening; Peak attenuation occurs along all rivers but the degree of flattening of the peak discharge depends on factors such as the depth of the river, the slope, and the width of the winter bed (de Jong & Asselman, 2019). The degree of peak attenuation depends on the height of the discharge wave (peak discharge) but much more firmly on the discharge wave. As a result, the discharge wave decreases and water levels in the river's lower reaches will decrease as well.

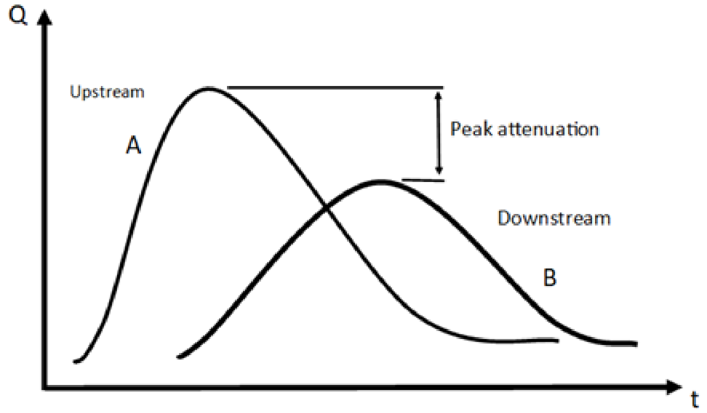

Figure 7: Schematization of the effect of peak attenuation on a flood wave moving downstream

This differs from the diffusive wave approximation because even in a canal, a diffusive wave can occur, while for peak attenuation, the river's topography changes the flood wave.

Peak attenuation has a positive effect on flood risk further downstream. The peak discharge wave is reduced with corresponding lower water levels. For the development of the flood risk management plan it is important to assess the effect of all the interventions along the river.

However, the most critical factor is the storage capacity of the water along the river. This makes retaining storage capacity vital to increase peak attenuation and lower water levels downstream. Moreover, it is difficult to determine the exact effect of a storage area since the effect is strongly dependent on the shape of the discharge wave and the height of the peak discharge (de Jong & Asselman, 2019).

2.3 Human interventions

2.3.1 Types of Human interventions

Over the course of the last century most of the rivers around the world have changed drastically by large-scale engineering. Rivers have been dammed, embanked, straightened and large amounts of water have been abstracted for irrigation. There are two types of human interventions of river engineering protecting the urban areas by constructing and raising flood protection or creating room for the river.

2.3.1.1 Room for the River

"Room for the River" is a program created by Rijkswaterstaat and is meant to take measures to widen and deepen the river, which can help in decreasing the water levels and lowering the pressure on the dikes. The crest heights of the dikes are not only allowed to be increased again to comply with the new design safety standards (Silva, Klijn, & Dijkman, What research has taught us, 2001), so Rijkswaterstaat has been looking for alternative options. Programs such as the Maaswerken also allow for old landscapes to be restored to act as "natural water sponges" if a flood occurs (Alberta WaterPortal, 2015).

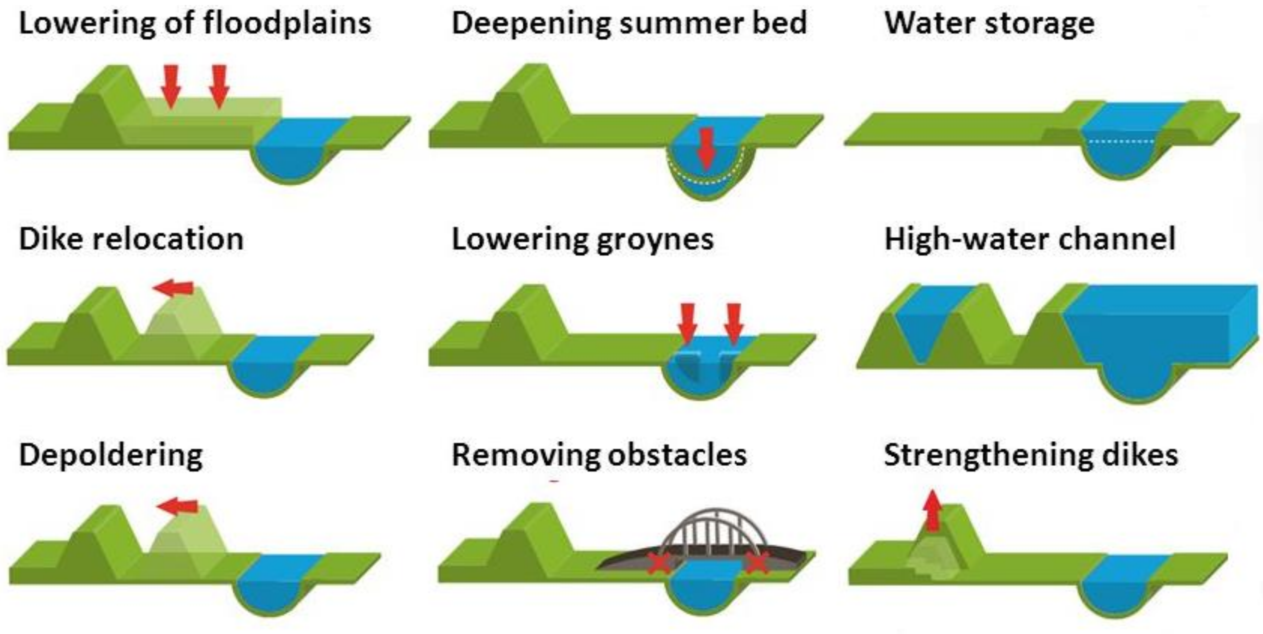

Figure 8: Types of room for the river projects (Schindler, et al., 2016)

Different measures following the "Room for the River" approach are (Silva, Dijkman, & Klijn, 2001) as shown in Figure 8:

- Lowering flood plains: excavating parts of the floodplain will increase the discharge capacity of the floodplains.
- Deepening the summer bed: by deepening the main channel, more water can be transported in a high-water event.
- Retention reservoir: an existing dike will be lowered, and a new dike ring will be built surrounding the planned retention reservoir. Excess water can easily overflow over the lowered dike into the retention reservoir if a high-water event occurs. This will lead to a smoothening of the peak discharge wave, and the peak of the flood wave will be stored temporarily in the retention reservoir. The retention area can have a different function when it is not used for excess water.
- Locally setting back dikes or on a large scale: relocating the dike inland will widen the floodplain and therefore increase the discharge capacity of the floodplain.
- Lowering of the groynes: groynes stabilize the location of the river and create a fixed water depth. However, during a high water event it will form an obstruction and as a result the water velocity will decrease. If the groynes are lowered the flow rate in the river will increase.
- Creating a by-pass or a high-water channel: reintroducing the old part of the river when it was still a meandering river. Branching off from the main river to discharge excess water via a separate route.
- Removing hydraulic obstacles (if possible): removing or modifying barriers in the riverbed, such as houses or factories, will increase the discharge capacity of the flood plain.
- Strengthening of the dikes: dikes will only be strengthened if there is no room to the create a room for the river project.

2.3.1.2 Retention areas

Retention areas, one of the room for the river measures, are primarily intended for water storage in situations with an excess of water (flood risk management and flooding). Still they can also fulfil a function for infiltration into the groundwater (Pötz, 2013).

The measures defined by Rijkswaterstaat can be categorized in the following groups: reduction of the flow of (excess) water, storage of (excess) water along the rivers, and discharge of (excess) water via rivers (Silva, Dijkman, & Klijn, 2001).

To prevent flooding in the urban area further downstream during heavy rainfall and high river water levels, retention areas can be constructed upstream to slow down the water. These retention areas often also have natural functions or serve as meadow areas. Any buildings in these areas must, of course, be water-resilient or have to be easily removable. Another way to realize additional retention areas is to excavate parts of the floodplain so that the river gets more space during high water. However, the area will not be flooded earlier than currently because the height of the inlet or the sluice gate has to be opened and that will not change. This does not mean that the area is wet all year round. Between April and November, the area can be used regularly in the dry periods.

Retention areas are areas that are temporarily flooded to store water when the top of the flood wave passes the high-water inlet. As a result, less water needs to be drained by the river in parallel and downstream of such an area, flattening the discharge wave. After the peak of the flood wave has passed and the water levels on the river have dropped again, the water is discharged back into the river at such a rate that high-water levels will not occur again (Berkhof, 2016).

The inlet of a storage or retention area is usually adjusted for a standard high-water wave. In contrast, the high-water waves, in reality, will almost always have a different shape. The storage or retention area is designed for the discharge (criteria from before 2017); therefore, the discharge has to be high to enter the inlet. Retention is also sensitive for 'series' applications (multiple retention areas in succession). If floodplain measures are applied to successive sections, the individual effect can be added together to get a picture of the combined effect quickly. This is different for retention areas since each will slightly cap the high-water wave. If the first retention area worked less than expected, the water level at the next retention area would be higher or lower than planned, making that area less effective (de Jong & Asselman, 2019).

2.3.2 History of the Meuse projects

Following the flood events of 1993 and 1995, the national government, provinces, water boards, and municipalities created five projects:

1. ‘het Deltaplan Grote Rivieren’, which resulted in circa 150 km of dikes (MVW, RWS, 1995)
2. Maaswerken (relocating dikes and reinforcement and river-widening projects (RWS, 2021))
3. Delta Program projects
4. Flood protection projects in Dutch called Hoogwaterbeschermingsprojecten (HWBP)
5. River-widening projects along with HWBP

The flood protection projects and the river-widening projects are still in the planning phase. They still have to be designed in detail and/or constructed. As a result, only a global overview is given on the HWBP projects, and the river-widening projects along with HWBP and therefore, not discussed in this report.

2.3.2.1 Deltaplan grote rivieren

The national government, provinces, water boards, and municipalities created the “Deltaplan Grote Rivieren” (MVW, RWS, 1995). The objectives specifically for the Meuse was to complete new dikes as much as possible in 1995 with an extension period to 1996 and for the other components, the time horizon from 2010 to 2015 will be brought forward considerably.

Commission Boertien-II recommends the following adjustments (MVW, RWS, 1995):

- Grensmaas (combined gravel extraction, nature development, winter and summer bed lowering) resulting in lower high-water levels
- Zandmaas (combined summer bed reduction, mainly sand extraction, limited nature development on the Meuse between Roermond and Mook) resulting in lower high-water levels
- Dikes: the implementation of an extra 60 km of dikes to protect habited areas where the water level-lowering effect of the Grensmaas and Zandmaas is still insufficient (see Appendix B.1 Dike reinforcement)
- Administrative measures in the area of spatial planning to prevent future new damage
- Sewage adjustments and other small-scale measures in the municipal sphere

The dikes (as shown in Appendix B.2 All dike sections) constructed since the flood of 1995 caused a reduction of the flood plains of the river by 40% (Slomp, 2021). This will lead to higher water levels in the main channel after construction of the dikes.

2.3.2.2 Maaswerken

The Maaswerken are the improvements of the flood protection along the river Meuse. The implementation of the Maaswerken program takes place in three sub-programmes, namely, the Maasroute, Zandmaas and the Grensmaas. With 52 locations along the total length of 22 km of the Meuse (RWS, 2021).

The program the Maaswerken was created in 1997 by the former Ministry of Transport and Water Management, the former Ministry of Agriculture, Nature and Food Quality and the Province of Limburg. The Maaswerken has four main objectives: to give the river space, make the Meuse more navigable, more nature and mineral extraction (RWS, 2019). Only the Zandmaas and the Grensmaas are relevant for the flood safety of the province Limburg. The Maasroute program improves the navigability by sea transport of the Meuse River.

2.3.2.2.1 Grensmaas project

The Grensmaas is the unnavigable part of the Meuse between Maastricht and Roosteren with a length of 43 kilometres. The Meuse is the only gravel river in the Netherlands. In this area, work is being done to protect against high water by widening the flow channel and lowering the floodplains (RWS, 2021). This section of the river is called Grensmaas because the river is the border between Belgium and the Netherlands. The border is creating difficulties with executing a joint flood safety program. The VNBM, Vlaams Nederlands Bilaterale Maascommissie, has been created for this purpose. The commission aims to be a bilateral and integral consultation forum at a high official level to improve the structure of the Flemish-Dutch cooperation regarding the Meuse. In the project ,three objectives for high water safety were drafted. The VNBM created the first objects, stating that there should be no deterioration compared to the design water level from 1995 at a discharge level of 3275 m^3/s at Borgharen. Furthermore, both governments formulated their objective for flood protection. The Flemish objective is to design the height of the dike for a design discharge of 3000 m^3/s + 0.5 m. While the Dutch objective is that the freeboard is 0.5 m concerning the design water level based on the discharge level of 3275 m^3/s at Borgharen (Meijer & Agtersloot, 2021). Therefore, the Dutch have a higher safety standard than the Flemish.

The Flemish have completed all the projects, while the Dutch are still working on a few projects as shown in Figure 9.

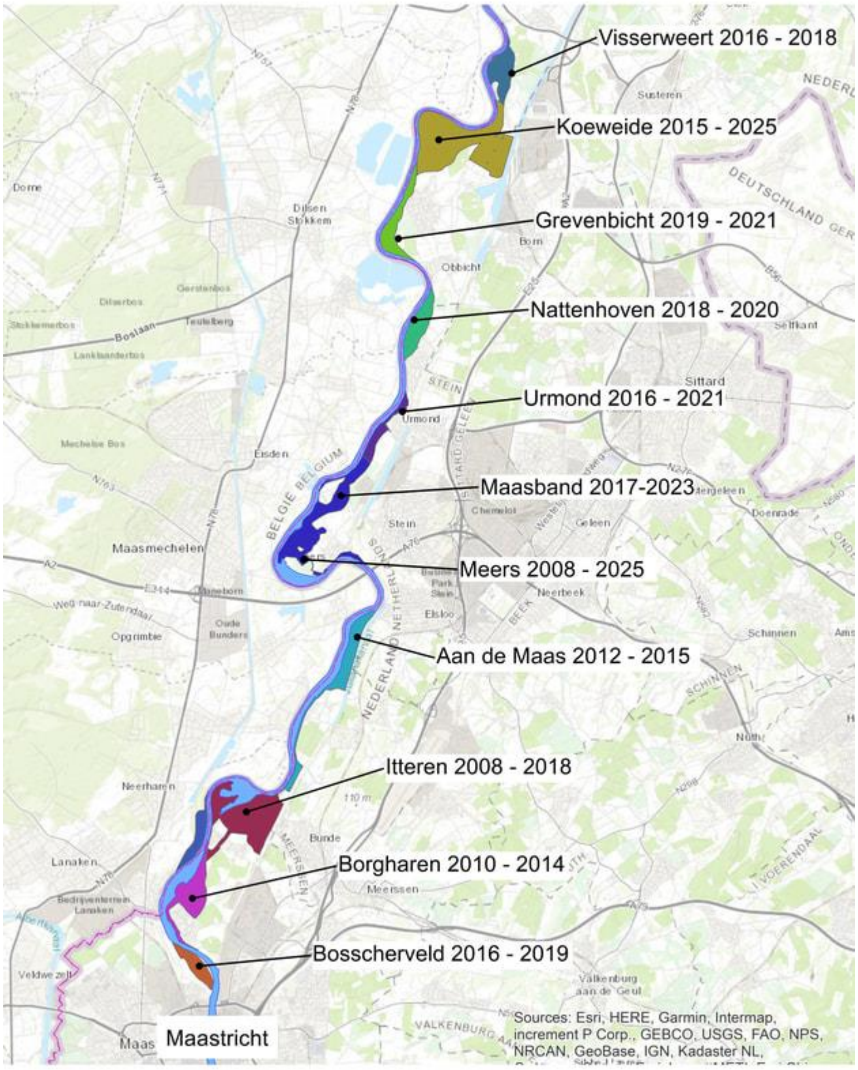

Figure 9: The Dutch project locations for the Grensmaas (Living Lab Grensmaas, 2021)

The expected effect of the water level of the Grensmaas will be between 60 and 80 centimetres lower than before the river widening. Even at the city of Maastricht the water level will reduce circa 20 centimetres (Consortium Grensmaas BV, 2021).

2.3.2.2.2 Zandmaas project

The part of the Meuse between Maasbracht and Den Bosch is called the Zandmaas. In the beginning of the 19th century they began to extract gravel and sand in the areas now called Maasplassen. Several flood protection projects are being carried out in the Zandmaas. The initiators and implementers differ per project (RWS, 2021).

The project of the Maaswerken has also widened the river and strengthened dikes in this part of the Meuse. This resulted in retention areas for the Meuse to store and drain more water, resulting in water levels dropping in a flood event. During the realization of the flood protection measures in the Zandmaas area, 20 million m^3 of sand was extracted on various stretches. By selling a large part of the extracted sand (13 million m^3), a big part of the project's costs has been funded. The extraction of sand along the Meuse offers good opportunities to combine flood protection with the development of existing and new nature. In total, 427 ha of new nature has been made possible by Maaswerken. Where there is no room for the river, for example, in urban areas right next to the main river, the dikes will be strengthened and raised (RWS, 2018).

The measures taken in the Zandmaas are (RWS, 2018):

- Construction and reinforcement of dikes (water defences): 40 kilometres of flood defences have been constructed and adapted in the urban areas around Roermond, Venlo, Gennep, Mook and Middelaar. Most of these projects were completed in 2007.
- Dike reinforcement: dikes are being built in more rural areas and strengthened. The Limburg Water Board is currently involved with the so-called prioritized dike improvement.
- Deepening and widening the riverbed: a few meters of the riverbed will be excavated so that the water level will drop significantly. In Swalmen-Beesel the river has been widened. Deepening of the main channel took place on the three routes Grave-Ravenstein, Gennep-Grave, and Venlo-Arcen.
- Construction of high-water channels: high water channels lie parallel to the Meuse to be used as additional side channels. They form a kind of inlet that flows with the river at high-water, resulting in a discharge with an accelerated rate. This measure will reduce the water level at high water, which can still be felt tens of kilometres upstream. A high-water channel has been constructed in Lomm and two channels have been constructed in Well and Aijen, which are located in sequence. The area developments around Lomm and Maaspark Well are more comprehensive, but they are not ready yet. The expected water level effect of Well – Aijen high water channel is approximately 28 cm lower at rkm 133 (Agtersloot, 2021). While, the predicted water level reduction is on average 29 cm by Lomm (Meulenbroeks, 2013).
- Creation of a retention area: a retention area with two basins has been created in Maasgouw and Leudal. Excess water can flow from the Meuse and the Lateral Canal in a basin during high water. As a result, the water level drops downstream by an average of ten centimetres. The Northern Basin is located at Horn and the southern basin at Heel.

2.3.2.3 Deltaprogram project

The Maaspark Ooijen-Wanssum project was finished in July 2021 just before the flood. The created high-water channels from an old river arm as shown in Figure 10.

Figure 10: Maaspark Ooijen-Wanssum (Ooijen-Wanssum maaspark, 2021)

The high-water channel has four levels of water inflow. The first level is that at a water level of 12.9 meters above NAP at Broekhuizenvorst will flow into the high-water channels. More water will flow into a larger area at 13.6 m NAP in the second level. In the third level, this means the Ooijen and Wanssum channel flows along with the main river and more water will flow into the old river arm at 14.5 m above NAP. All the high-water channels will flow at the last level at 15.5 m above NAP. The project will create a drop in the water level to a maximum of 35 cm in the Meuse River. The influence will be visible upstream up to the city of Roermond (Ooijen-Wanssum maaspark, 2021).

2.3.2.4 HWBP projects

In the Flood Protection Program (HWBP) context, fifteen dike improvement projects are being carried out in the Northern Meuse Valley. This project is in addition to tackling another eighteen dikes from the Maaswerken in the Limburg program. By reinforcing 51.9 kilometres of the dike, more than 60.000 people are protected and this project should be completed by 2024 (Witteveen+Bos N.V., 2019).

To prevent circumventing of water due to higher design standards- dikes have to be extended into the high ground. This means the construction of 12 to 19 kilometres of new flood defences. In addition to dike improvement, a dike relocation is also being explored for five dike sections, Thorn – Wessem, the design of a retention area and in Baarlo – Hout – Blerick, the exploration will be expanded with a high water channel. Furthermore, possibilities are being explored for stream and water system recovery at five locations. Dike route Kessel follows a special route. As a result of the exploration, the process is initiated here to remove this dike section from the Water Act (HWBP, 2021).

Table 1: HWBP projects (Programmabureau Hoogwaterbescherming, 2018) (HWBP, 2021)

	Length	Dike section	Failure mechanism	Completed
Thorn – Wessem	5.3 km	79	Crest height, piping, macrostability, grass cover	2026
Heel	3.6 km	78	Piping, stability, grass cover	2023
Willem-Alexanderhaven Roermond	1.2 km	76	Crest height	2025
Bruggenum	1.3 km	75	Crest height, piping, stability	2025
Beesel	1.1 km	73	Crest height, piping, stability	2023
Belfeld	1 km	71	Crest height	2025
Steyl - Maashoek	235 m	68	Crest height, piping, heave	2025
Baarlo – Hout Blerick	4.8 km	68	Crest height, piping	2026
Blerick – Groot Boller	1.2 km	69	Crest height	?
Venlo - Velden	6.8 km	68	Crest height	?
Arcen	5.2 km	68	Crest height, piping, inner stability	2027
Well	5.7 km	60	Crest height, piping, macro stability	2026
Nieuw Bergen	1.8 km	57	Crest height, piping, stability	2025
Lob van Gennep	16 km	55	Crest height, piping, stability	2026

2.4 Flood prone areas

In this chapter, the most flood-prone areas along the Meuse River in the Dutch province Limburg will be discussed. The total analysis is presented in Appendix C. There are four large and important cities (Maastricht, Maaseik, Roermond, and Venlo) along the Limburg part of the Meuse River. With such old large cities along a river, there is not a lot of extra space for “Room for the River” projects, and therefore, almost only dike reinforcement projects can be implemented. Next to the four main cities, confluence points were important in the flooding of 2021.

2.4.1 Maastricht

The city of Maastricht is a big city located around the Meuse and is a bottleneck when implementing preventive measures for flooding. Even though Maastricht has not been flooded in each of the three floods (see Figure 11 left side), all the water is pushed through the city centre, creating a risk. Currently, there is only one main channel without any flood plains (see Figure 11 right side).

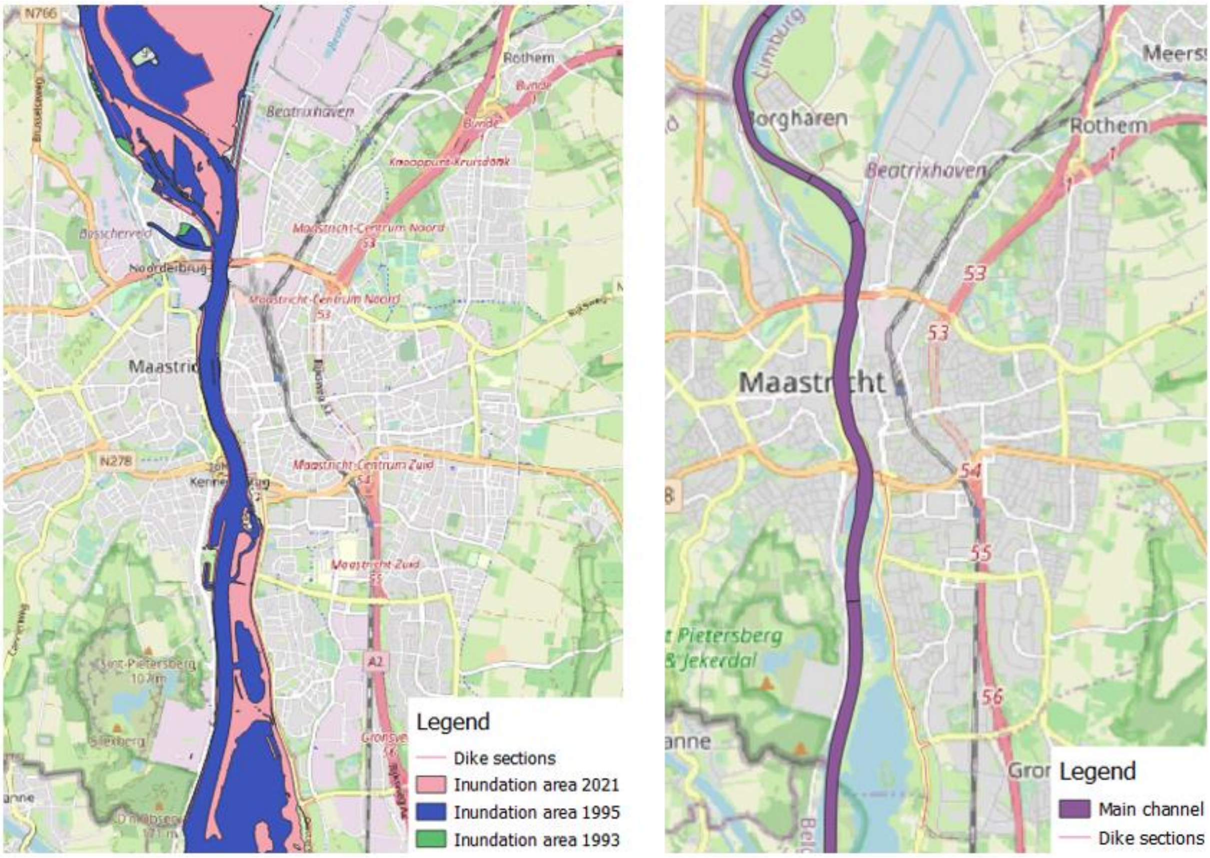

Figure 11: A map of Maastricht with the inundation areas of the different floods (left side) and with the dike sections and the main channel (right side)

Bosscherveld is one of three locations – next to Itteren and Borgharen – within the municipal boundaries of Maastricht where the Grensmaas project is being carried out. The island Bosscherveld in the Meuse is located North of Maastricht and will change into gravel after excavation. In times of high-water the area will be inundated.

Another measure in the Grensmaas project is to deepen the main channel by 2 m from the border to the Borgharen weir (Wijbenga, 2021). The hydraulic radius is calculated to get a clearer view of the bottleneck. The dimensions of the river which are shown in Appendix D. The formula for the hydraulic radius is:

$$R = \frac{A}{P} = \frac{B_z * (h_z + 2)}{B_z + 2 * h_z} = \frac{150 * (7.5 \ + \ 2)}{150 + 2 * 7.5} = \frac{1425}{165} = 8.64\ m$$

Where R is the hydraulic radius [m], A is the cross-sectional area [m^2] and P is wetted perimeter in [m].

The safety priority level of the dike sections is displayed in bolt lines in different colours in Figure 12. The green line shows a safety level of 1/300 years, yellow a safety level of 1/1000 years, and orange for 1/3000 years. The green/blue bandwidth is the total areas that will be inundated by a discharge of 4000 m^3/s.

Buildings are displayed as green or red in the potential floodplains, where red means unprotected, while green buildings are behind a dike.

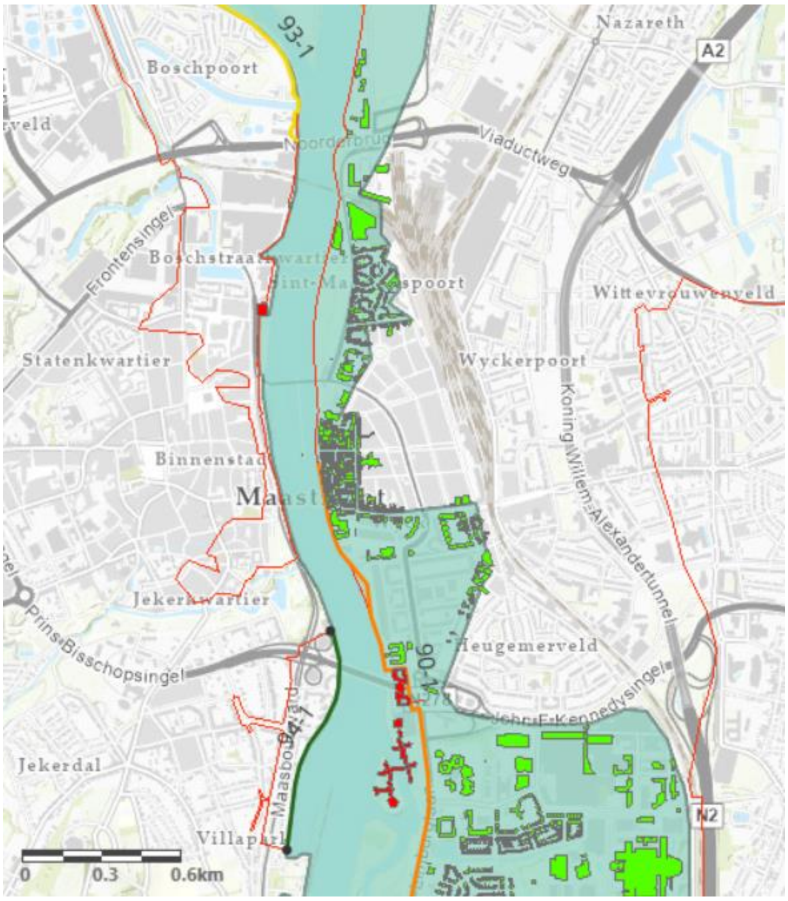

Figure 12: City centre of Maastricht (Rozier, 2021)

2.4.2 Bunde and Meerssen

The Geul is a right-bank tributary to the River Meuse, and the location of the confluence is at Bunde. It flows from the siphon at Bunde into the main channel. For modelling the discharge for the tributary the Geul at Meerssen the value 61 l/s/km^2 is used (Acima, Rura-Arnhem, 2018), while the observed discharge was 100 m^3/s. This means that the discharge capacity of the siphon was less than was needed. However, the local people were convinced that the maintenance of the siphon was less than desirable. There were no pictures taken before the flood event, so it is unclear if the siphon was working fully at the beginning of the flood event. In the end, the amount of debris was at least a problem during the flood (ENW, 2021).

The area of Bunde is the lowest point on the right side of the Juliana Canal. The Juliana Canal acts as a dike to protect Bunde and Meerssen from the Meuse River. This has created a (semi) natural polder. The water run-off of the surrounding area will flow into the polder and cause fluvial flooding to Bunde and Meerssen.

Furthermore, the peak of the Geul and the peak of the Meuse River arrived at Itteren almost simultaneously in 2021. This created a backflow in the Geul since it could not even discharge the maximum capacity of the siphon into the main river. Therefore, the water in the Geul overflowed its banks. However, due to the Juliana Canal, the water could not flow back into the Meuse, creating an issue for the inhabitants of Bunde and Meerssen, while it was supposed to be a protection. Therefore, the water couldn't be drained naturally. The area remained flooded for approximately a week.

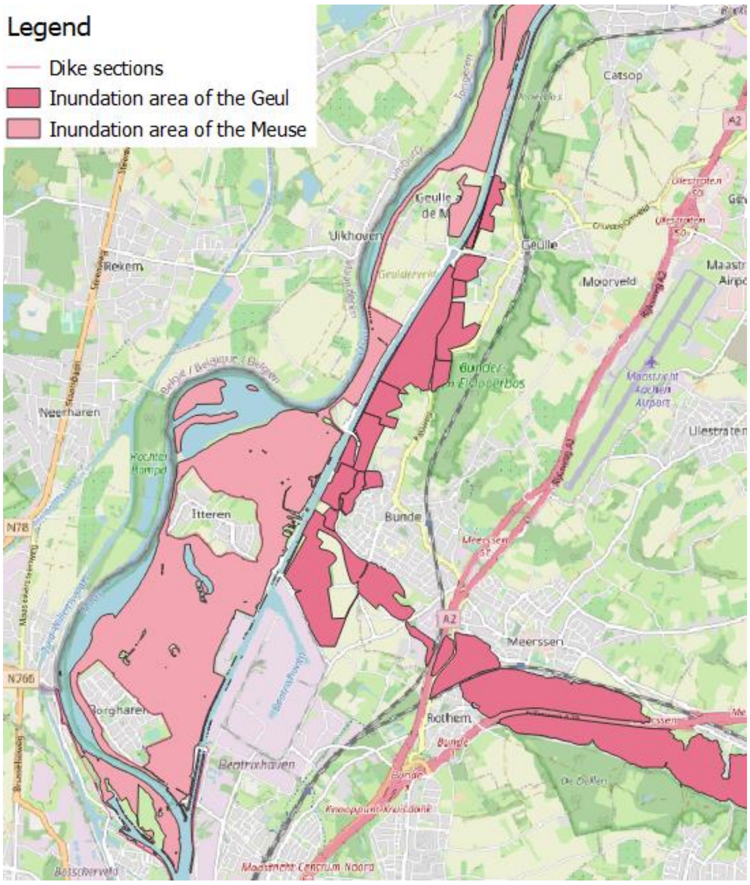

Figure 13: Inundation area of the Geul and the Meuse in July 2021

2.4.3 Maaseik

The Flemish city of Maaseik is a big city located on the left side of the Meuse and is a bottleneck for implementing preventive measures for flooding. Even though the city of Maaseik has not been flooded in each flood events (see Figure 14 left side), all the water is pushed through the bend to the city, creating a risk. The bend near the town of Maaseik is very sharp. The dike section 83 was built to protect the village of Roosteren on the Dutch side. The village of Roosteren was inundated in 1993. The dike section has protected Roosteren from the flood of 2021. However, this dike section has significantly limited the flood plains of the river.

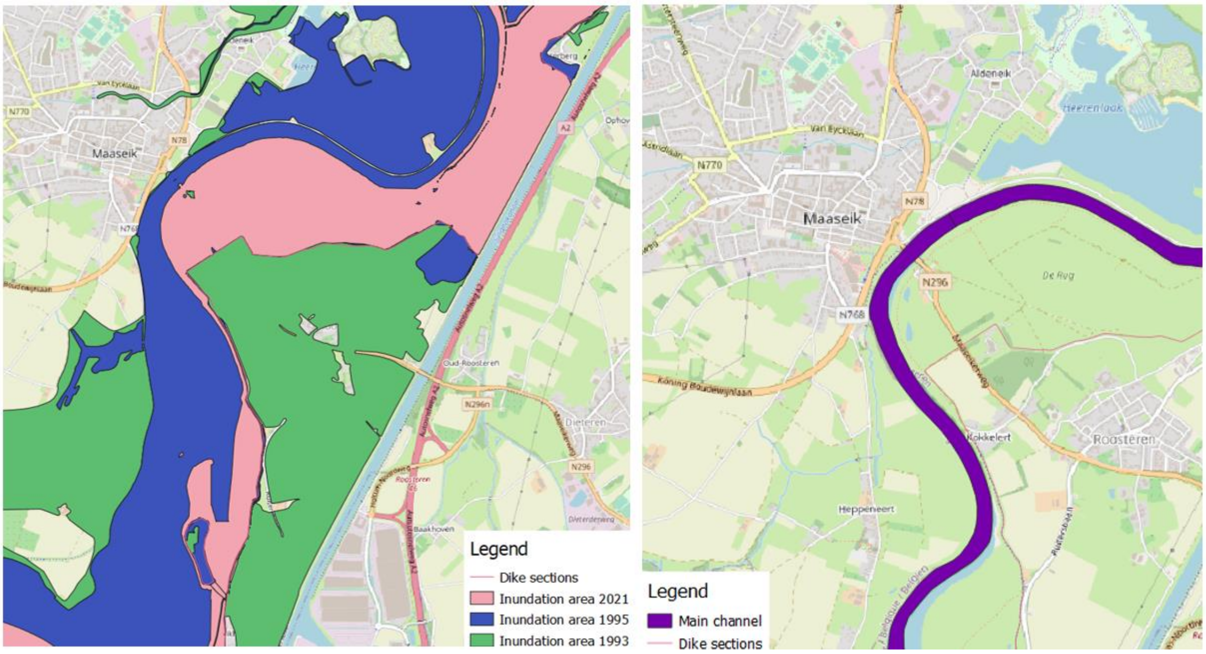

Figure 14: A map of Maaseik and Roosteren with the inundation areas of the different floods (left side) and with the dike sections and the main channel (right side)

The safety priority level of the dike sections is displayed in bolt lines in different colours in Figure 15. The green line gives a safety level of 1/300 years. The green/blue bandwidth is the total area that will be inundated by a discharge of 4000 m^3/s. Buildings are displayed as green or red. The red buildings are unprotected from the water, while the green buildings are behind a dike.

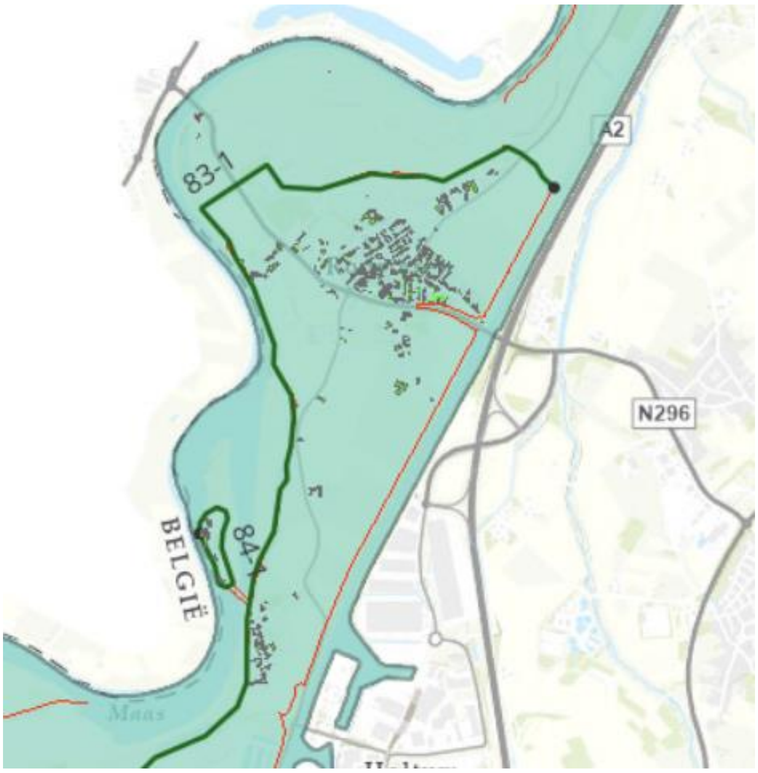

Figure 15: The Dutch safety levels at Roosteren (Rozier, 2021)

The dike section 83 makes a sharp angle at the words 83-1 in Figure 15. This can lead to flow separation and reduce the discharge capacity under the bridge between Maaseik and Roosteren. There is a farm on the right side of the Maaseikerweg, from the right side above the town Kokkelert till the dike it is farmland.

An option would be to relocate a section of the dike to create a more natural bend to reduce the amount of turbulence in the river bend.

The discharge measured at measurement station of Maaseik 3791 m^3/s (as shown in Figure 16) was even higher than all upstream, namely 3260 m^3/s at Eijsden-grens, 3310 m^3/s at St. Pieter and Borgharen – Dorp 3284 m^3/s (van der Veen & Agtersloot, 2021). The difference in discharge between St. Pieter and Maaseik is 481 m^3/s. Geul (100 m^3/s) and Geleenbeek (35 m^3/s), flowing into the main channel cannot explain the significant increase in discharge even with the tributaries.

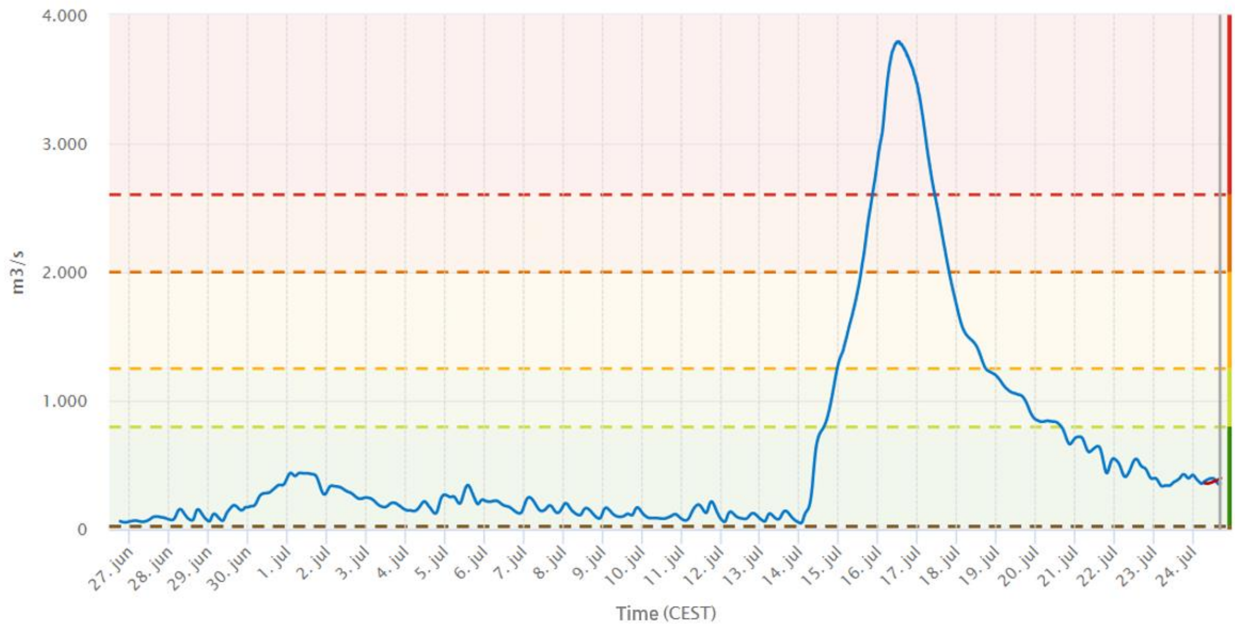

Figure 16: The discharge measurements against the time at the measurement station Maaseik (Rijkswaterstaat waterinfo, 2021)

In principle, every widening location is a risk location for sedimentation. This could endanger the high-water objective again in the long term. Sedimentation was already visible in the relatively small river bend between Roosteren and Maaseik. It was predicted to be a bottleneck before the flood event of 2021. The project Roosteren was already realised in 2007; therefore, there was a lot of sedimentation. The future planned projects Heerenlaak and Contelmo will predictably reduce the water levels. However, this will not be enough to reduce the bottleneck completely (Meijer & Agtersloot, 2021).

2.4.4 Roermond

Roermond lays only on the right side of the river (see Figure 17 right side). While the village Horn lies on the left side. The part of the Meuse near Roermond differs from Maastricht and Venlo due to the Maasplassen (see Figure 17 right side). The Maasplassen are artificial lakes created by mining gravel that was deposited naturally over the past centuries by the Meuse. The gravel extraction was phased out after 1990, although gravel is still being mined in a few places on a much smaller scale. A new purpose for the gravel holes was found in water recreation and with a bonus of retention areas. The Maasplassen are located in both Belgian and Dutch Limburg from Maaseik till Roermond, and their combined surface is approximately 30 km^2.

Since the Maasplassen can store part of the excess water, the height of the peak will be less in Roermond than Maastricht. Furthermore, the lakes for example Hatenboer lie between the Lateraalkanaal and the Meuse River. The discharge is split between the Lateraalkanaal and the river Meuse, connected to the Maasplassen. Therefore, it can be concluded that the city of Roermond is less of a bottleneck than Maastricht. However, small parts of a sub municipality of Roermond, Herten, was flooded in 1993 and 1995 (see Figure 17 left side) and a large part of Herten was flooded in 1993. After these floods, the dike sections were constructed to protect Herten. The dike sections have protected the inhabitants from the flood of July 2021, so this can be marked as a success (see Figure 17 right side).

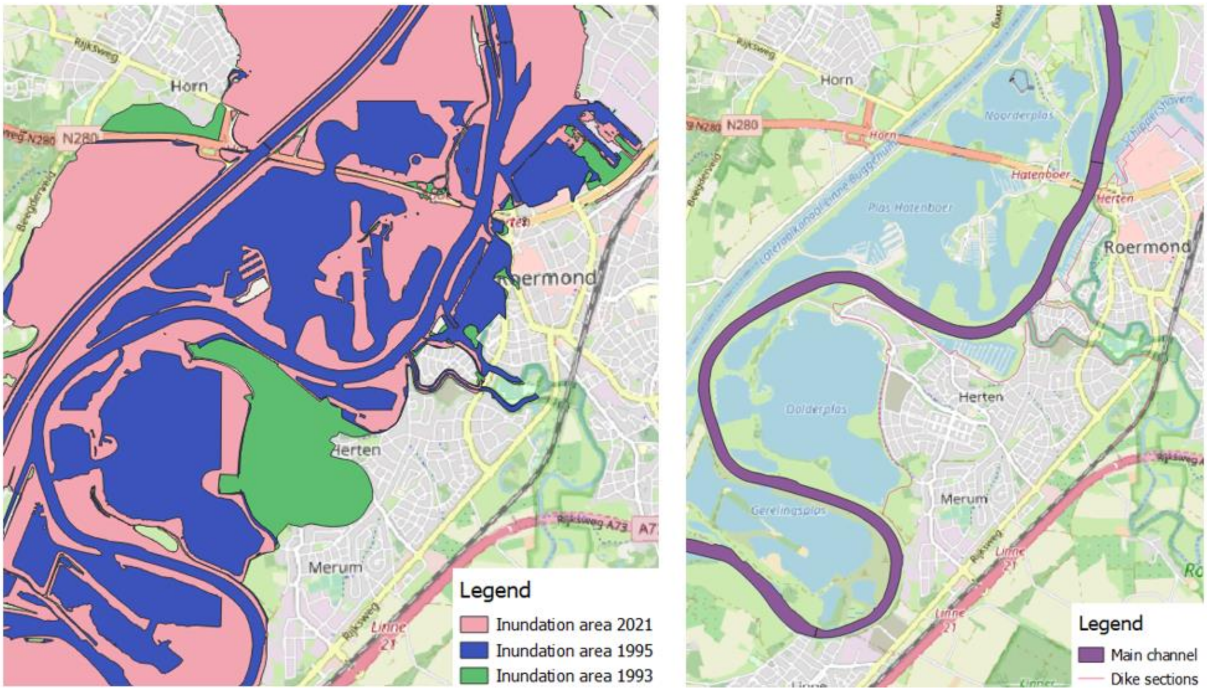

Figure 17: A map of Roermond with the inundation areas of the different floods (left side) and with the dike sections and the main channel (right side)

The cross-section next to the city centre of Roermond equals the width of the main channel times the depth of the main channel plus the characteristics of the floodplain from the Maasplassen. The dimensions of the river are used in Appendix D. The formula for the hydraulic radius is:

$$R = \frac{A}{P} = \frac{B_z * h_z + (B_{w,2} - B_z) * h_{w,2}}{B_{zw2} + 2h_z} = \frac{150 * 7.5 + (1100 - 150) * 2.9}{1100 + 2 * 7.5} = \frac{3880}{1115} = 3.84\ m$$

Where R is the hydraulic radius [m], A is the cross-sectional area [m^2] and P is the wetted perimeter in [m].

When calculating the discharge of the Meuse, the tributaries have an important effect on the height of the discharge. To model the discharge for the Roer at measuring point Stah the value 45 l/s/km^2 is used (Acima, Rura-Arnhem, 2018).

However, the newly created dikes at Herten extent far into the floodplain, creating a great reduction in the width of the floodplain and resulting in a bottleneck at Roermond.

The Roer, which Roermond is named after, flows through the city and flows into the river Meuse. The discharge of the Roer in 2021 was also higher than usual, with a maximum of 270 m^3/s (ENW, 2021). As a precaution, the Safety Region of North-Limburg evacuated everyone who lived in the orange area, as shown in Figure 18. Hambeek is located between the neighbourhood of Herten and the city centre of Roermond, and in hindsight, it was unnecessarily evacuated. However, this is where the Roer meets the Meuse and the chance of flooding in the estuary is high. If the water had not been able to flow into the Meuse river, the neighbourhood would have been inundated.

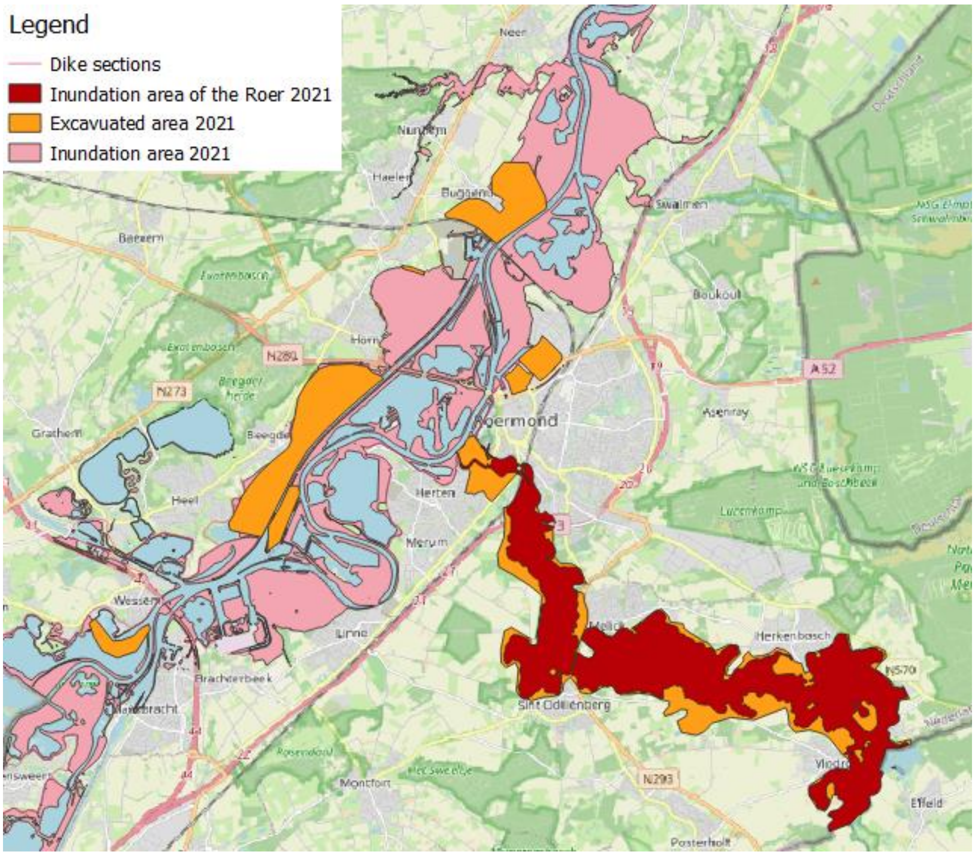

Figure 18: Inundation area of the Meuse and the Roer at Roermond in July 2021

The safety priority level of the dike sections is displayed in bolt lines in different colours in Figure 19. The green line gives a safety level of 1/300 years. Buildings are displayed as green or red. The building is red when unprotected, while they are green behind a dike.

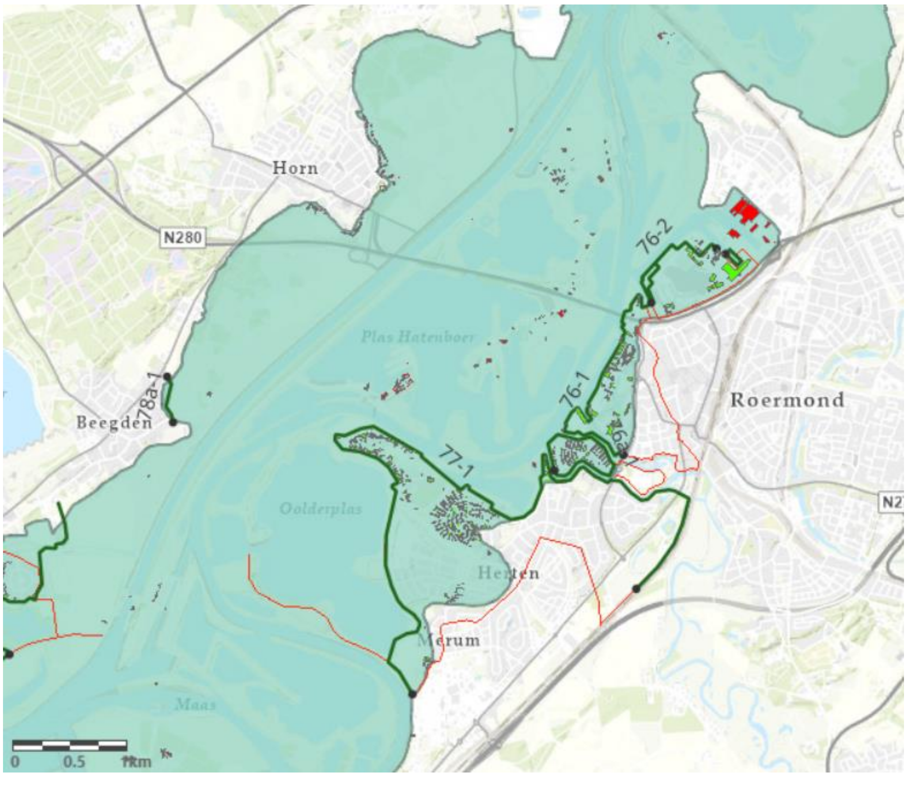

Figure 19: City centre of Roermond (Rozier, 2021)

2.4.5 Venlo

The city of Venlo was originally two cities separated on each side of the river (see Figure 20 right side), Blerick on the left side and Venlo on the right side. Nowadays, Blerick has become part of the municipality Venlo.

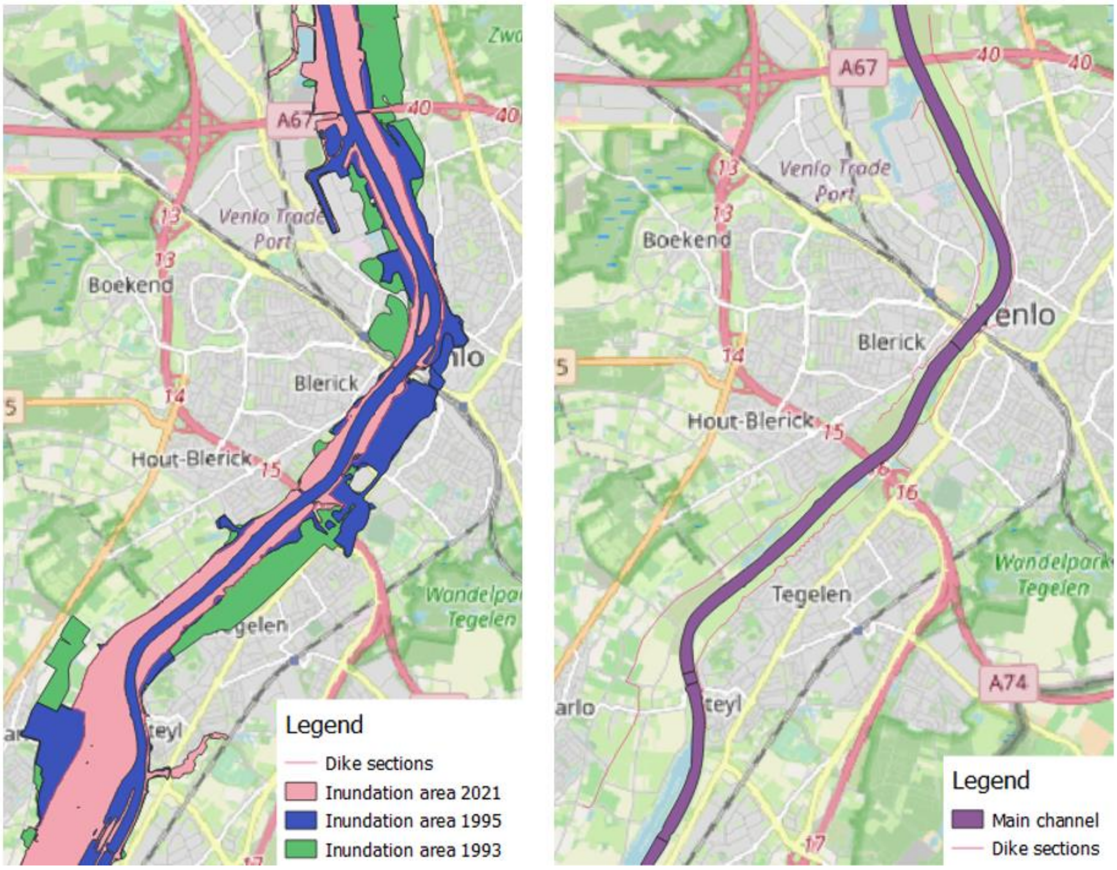

Figure 20: A map of Venlo with the inundation areas of the different floods (left side) and with the dike sections and the main channel (right side)

Similarly to Maastricht, the city of Venlo was built surrounding the river, meaning there is not a lot of room for the river to flow. However, there is still a little room between the main channel and the dike sections, which can be used as a retention area. This means that the cross-section at the city centre of Venlo is the width of the main channel (measured in GIS) times the depth of the main channel. The hydraulic radius is calculated to get a clearer view of the bottleneck. The formula for the hydraulic radius is:

$$R = \frac{A}{P} = \frac{B_{venlo} * h_z}{B_z + 2 * h_z} = \frac{300 * 7{,}5}{300 + 2 * 7.5} = \frac{2250}{315} = 7.14\,m$$

Where R is the hydraulic radius [m], A is the cross-sectional area [m^2] and P is the wetted perimeter in [m].

The hydraulic radius is 8.64 for Maastricht, 3.84 for Roermond and 7.14 for Venlo. Therefore, the city of Maastricht discharges the flow through the channel the most efficient and Roermond the least efficient.

The right shore of Venlo and the city Tegelen, which is located upstream of Venlo, were inundated in 1993 and 1995 (see Figure 20 left side). Following these events, dike sections were built on both sides of the river (see Figure 20 right side) and the following dike sections have protected the inhabitants from high water: Baarlo is protected by dike section 70, Blerick is protected by dike section 71 and Steyl, Tegelen and Venlo are protected by dike section 68.

The safety priority level of the dike sections is displayed in bolt lines in different colours in Figure 21. The green line gives a safety level of 1/300 years, and the yellow line presents a safety level of 1/1000 years. The green/blue bandwidth is the total area that will be inundated by a discharge of 4000 m^3/s. Buildings are displayed as green or red. The red buildings are unprotected from the water, while the green buildings are behind a dike.

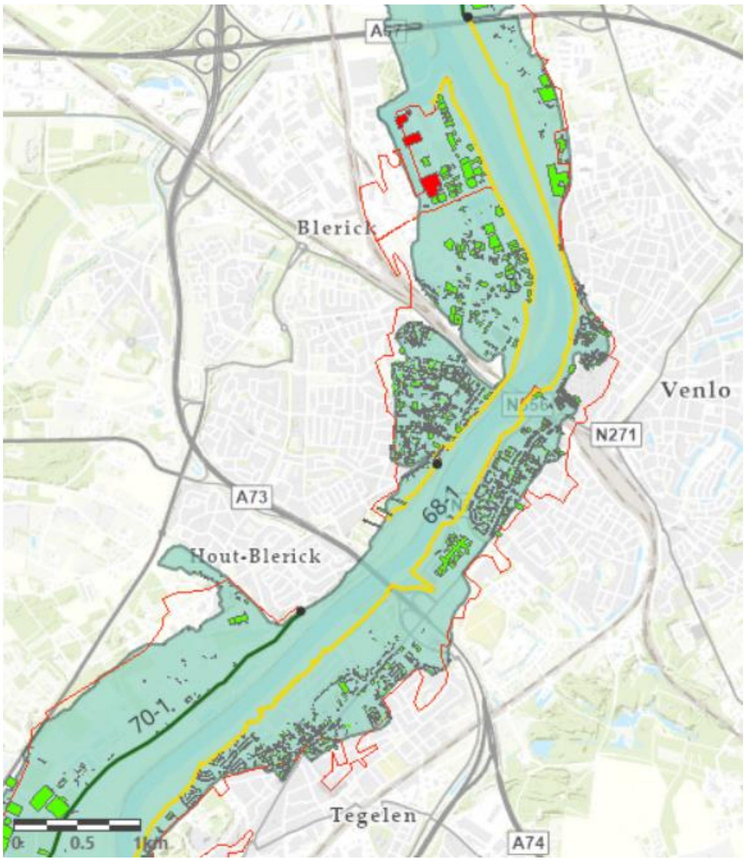

Figure 21: City centre of Venlo (Rozier, 2021)

2.4.6 Maximum discharge scenario

The maximum possible discharge is 6000 m^3/s of the Meuse River, which includes climate change. A scenario with the maximum possible discharge has been simulated, which resulted in the inundation area, as shown in . The backflow of the tributaries is not included in this scenario, just the water upstream of the Belgium-Netherlands border. When simulating the valley of the Grensmaas, the border is not used as a boundary condition. The "Room for the River" projects in Belgium are also used to store water. However, a policy assumption is made where neighbouring countries cannot be intentionally inundated. This means that there is a "glass wall" at the boundary. Therefore, the hinterland in Belgium at the Grensmaas for example Maaseik and Germany at the Niersvalley will not be flooded in this scenario.

Figure 22 shows that all the inundated areas in 1993 and 1995 will be flooded again in the scenario of maximum discharge. However, in this maximum discharge scenario all the previous flood areas will be again flooded. Furthermore, the city centre of Maastricht, parts of the Roermond, Baarlo, Tegelen, Venlo, Wanssum and the Lop of Gennep will also be flooded. This is a scenario that should be avoided since many people currently populate these areas. This map show the vulnerable areas along the River and can be used to identifying locations where extra protections might be needed.

Figure 22: Inundation area with maximum discharge scenario of the Meuse river

3

Methodology

The methodology describes the approach how to answer research question and sub-questions. Finding correct information over the high-water of 1993, 1995 and 2021 was difficult. Most of the information used for the literature review is grey literature. Grey literature information created and/or collected by government agencies, academic institutions or companies that is not typically made available for public use (Janis McKenzie, 2022). The methods used to gather the information are asking experts, apply for information from RWS using the Contactformulier Servicedesk Data and using the database PUC (Publicatieplatform UitvoeringsContent) from the Dutch government. Matthijs Kok, Robert Slomp and Jurgen de Jong were a few of the experts used to collect the information regarding the Meuse from 1993 to 2021. The literature is divided into eight sections with each type of literature categorized as model data, measurement data and background information as shown in Table 2.

Table 2: Types of literature used

	Literature	Model data	Measure data	Background information
1	Papers			X
2	News articles			X
3	Reports of RWS		X	X
4	Water levels		X	
5	Inundation maps and dike sections		X	
6	PhD Berger GRADE			X
7	Factfinding mission	X	X	
8	Report Peak attenuation	X		
9	Report Evaluation Grensmaas	X		
10	Box of building blocks	X		

A more detailed description is given chronologically on all the different types of literature. The academic papers (1), news articles (2) and reports of RWS (3) where used to get a clear view of the events that occurred during the flood events and the magnitude of the event. The papers (1) mostly focus on the damages that occurred during the floods of 1993 and 1995. While, the news articles (2) described the day by day event and water levels for all three flood events. The reports of RWS (3) were collected by using the public government database PUC and asking colleagues for information. The reports were used to understand the system with the different measures taken and collect data to identify the differences between the different flood events.

The water levels (4) are used to measure the differences between the different flood events. There were different measurement stations along the river. The measurement data is available in Appendix A.

The inundation maps (5) are used to analyse the difference in the flooded areas of the three flood events through illustrations. The differences in the occurrence of inundation of specific areas will be researched. Different measurement projects have been implemented into the river landscape. The combination of the flood routing measures and protective measures, which have been implemented since 1995, will show a significant difference between the previous situation and the situation in 2021. However, before an explanation can be made of the differences between the two types of flood protection first, an assessment has to be made of all the river projections projects implemented since 1995.

The doctoral thesis of H.E.J. Berger (6) (Berger, 1992) was used to get a better understanding of the system of the Meuse River not only on the Limburg part of the Meuse River, but also the system upstream.

The first research was carried out by a broad consortium (TU Delft, Deltares, HKV Lijn in Water, VU Amsterdam, Universiteit Utrecht, KNMI, WUR, Erasmus MC, and Universiteit Twente), named Factfindingsmission (7) commissioned by ENW (Expertise Netwerk Waterveiligheid) (ENW, 2021). The government bodies RWS and the water board of Limburg were during the flood event and immediately after busy with monitoring the safety and restoring the damages to their assets. Therefore, experts from the previous named companies and institutions gathered information to give a first estimation of the effect of the flood on affected area. The water board Limburg and RWS have cooperated providing information, supervising field visits and interviews.

The report of peak attenuation (8) commissioned by RWS has researched the effect of peak attenuation on the Dutch part of River Meuse in 2019 (de Jong & Asselman, 2019). The scenarios with different shapes of the peak discharges have been simulated in the peak attenuation. More information about the data used in the scenarios can be found in Appendix E.1. The conclusions that were drawn in the report on the effect of the peak discharge of the report will be explained. For the peak attenuation, the discharges measured along the river are compared with the predicted measures with the closest scenario to the 2021 flood. This will give a better view of the shape of the peak discharge on the flood of 2021 along the river.

The VNBM has commissioned an evaluation of the Grensmaas (9), which has been carried out by D.G. Meijer and R.C. Agtersloot in 2021 (Meijer & Agtersloot, 2021). The evaluation of the Grensmaas occurred just before the flood event of 2021. Therefore, the evaluation showed the situation of the Grensmaas just before the flood event. This report evaluates specifically on the Grensmaas projects. The current situation of the progress of the projects is tested on the objectives that were established by the design of the project and the new general safety standards. More information about the data used in the evaluation can be found in Appendix E.2. The conclusions that were drawn in the report of the recommendations will be explained. For the evaluation of the Grensmaas, the water levels of the flood of 2021 on the section of the Grensmaas is illustrated similar to that in the evaluation. This will show the combined effect of the measures of the Grensmaas on the flood compared to the flood events of 1995.

Box of building blocks (10) ('Blokkendoos') is a software program developed by Deltares (Kroekenstoel, 2014). More information about the data used in the Box of building blocks can be found in Appendix E.3. The program is created to support policymakers in making informed decisions since the effects of each of the different "Room for the River" projects are illustrated on the water height. Moreover, the cost of implementation of each of the measures is predicted. As the name of the program explains, all the projects that have been suggested and can positively affect flood safety have been calculated. The projects have all been simplified and implemented on their location along the river. The tool contains the pre-calculated water level-reducing (or raising) effect of a measure and, after selecting the measure, subtracts this from the climate task (water level rise as a result of higher river discharges and sea-level rise). The basic assumption is that individual water level effects may be added up. This tool can determine which measures are essential in reducing water levels. This way, the association between the different projects and the impact of each project can easily be displayed and compared. The box of building blocks was used to decide which projects have to be implemented while considering both the costs and impact in the reduction of flood risk for the whole river.

The box of building blocks is not intended to make decisions on specific implementation projects since the results of the box of building blocks are too global and uncertain. The reality is simplified in a calculation model such as the box of building blocks, where assumptions are made and rules of thumb are used. The box of building blocks is primarily intended to compare various measures on effects such as casualty risks, avoiding damage and being cost-effective. These uncertainties differ per effect and measure, and general key figures are used to determine the costs (Stronkhorst & Hendriks, 2010).

Due to the simplicity of the box of building blocks, it was decided to design the flood wave as a kinematic wave in the box of building blocks model. All the measures were simulated with two probabilities of exceedance, namely 1/250 years with a corresponding discharge of 3800 m^3/s and 1/1250 years with a discharge of 4600 m^3/s. Only the projects upstream of Roermond will be correctly represented by a kinematic wave, while downstream of Roermond the character of the flood wave will dissipate. However, the project of Ooijen – Wanssum is an essential project. Therefore, this one will also be discussed.

The first step to complete this research was to gather the needed information. The second step is to identify the differences between the different flood events and assessing the impact of the different flood protection measures. The differences are identified and operationalised. This is done by using the data (1-4) collected on the flood events of 1993, 1995 and 2021. By collecting the basic data, the differences between the hydrodynamics and meteorological data will be visible. This will create a feedback loop as shown in Figure 23. This step will answer the first research sub-question. By identifying these differences, it will become measurable to compare the different flood events even between decades.

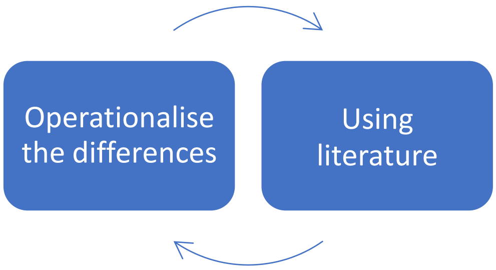

Figure 23: Feedback loop for operationalizing the term differences

The third step is to assess the impact of the different flood protection measures. When the flood protection projects are designed it is intended to protect the hinterland for a certain level of flood risk. This is usually designed with an average shape of the flood wave and a winter discharge. However, the flood of 2021 did not have the average shape of the flood wave and the flood event occurred in the summer. Therefore, it is interesting to compare the theoretical data with the measurement data from the flood events as shown in Figure 24.

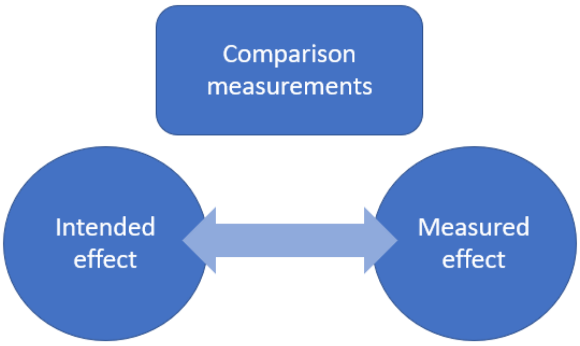

Figure 24: Comparison between the intended effect and the measured effect

The measurement data that is used is the information from the reports of the Factfindingmission (7), Peak attenuation (8), the evaluation of the Grensmaas (9) and the Box of building blocks (10). The measured data is the water levels (4) and the inundation maps and dike section (5).

In chapter 5 the measured effects (4,5) will be compared with the intended effects (7-10). The intended effects are usually expressed as the expected maximum water level reduction of a certain measure or a section. The differences between the intended effect and the measured effect can then be explained with the identified differences in step 2.

4

The flood events

The flood events of 1993, 1995 and 2021 are described below.

4.1 Meteorological

4.1.1 Flood in 1993

The persistent precipitation and heavy rainfall in France and Belgium caused a high discharge. Additional water was supplied from the tributaries when the snow in the Ardennes started melting. In the week before 19th December 1993, a minimum of 6 mm precipitation fell per day in the French and Belgium river basins. Sunday 19th, the precipitation levels increased up to an average of 18 mm and on the following day even to 32 mm. The discharge of the Meuse in Chooz rose to 800 m^3/s; the flows of the Sambre and the Ourthe increased quickly, creating higher water levels at Namur and Liege respectively, where they join the Meuse. For the discharge in Borgharen, this means above the limit of 2000 m^3/s (Bleichrodt & Ensinck, 1994).

4.1.2 Flood in 1995

In January of 1995, it started with winter weather conditions. For a large part of the Meuse catchment area, the temperature was below zero, and it was snowing and/or raining. From 18^{th} of January, the precipitation increased, and it rained for an extended period. In particular, there were several active depressions between 22 and 30 January, causing an abundance of rainfall. The southwest wind pushed the moist air against the Ardennes and gave around 200 mm of precipitation between the 19th till 30th of December, as shown in Figure 25 (IJpelaar, 2020). This heavy rainfall in the Ardennes led to high water levels in the Meuse.

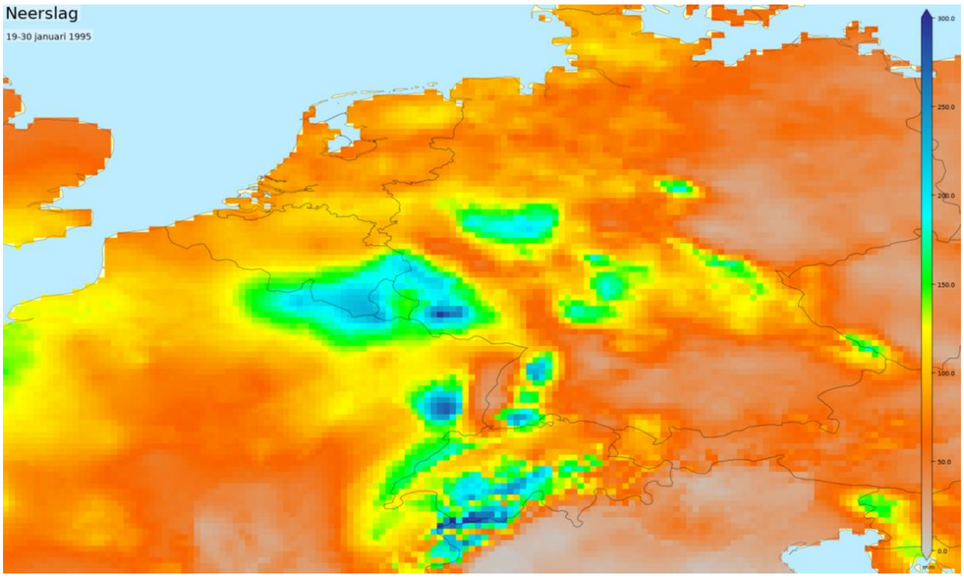

Figure 25: The total precipitation between 19 and 30 January 1995 (IJpelaar, 2020)

4.1.3 Flood in 2021

Since the beginning of July 2021, warm gale-force winds have come from France and Piedmont. cool current flows from the North to Central Europe with a low elevation. These two wind flows collide, creating a large and relatively fixed low-pressure area in the Ardennes (KMI, 2021), which leads to large sums of precipitation in the catchment area of the Meuse River (see Figure 26). On these two days, more than 150 millimetres fell in some parts of South Limburg (KNMI, 2021). The flood of the summer of 2021 was extraordinary and was created by the low-pressure area that remained stationary for a long time.

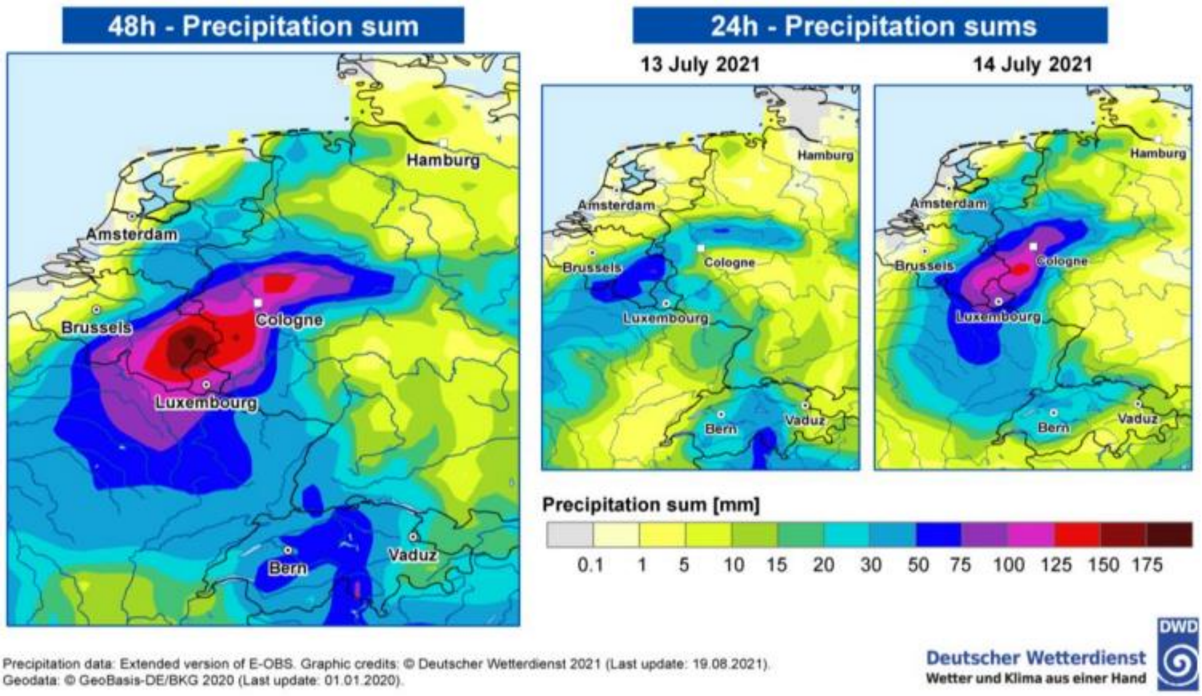

Figure 26: Precipitation in the catchment area of the Meuse River (KreienKamp, et al., 2021)

4.2 Hydrological/hydrodynamic differences

First the hydrological and hydrodynamic differences for each of the flood events are described.

4.2.1 Flood of 1993

Due to the heavy rainfall in December, the water of the Meuse was already 4 metres above the average water level on 15 December 1993 at Borgharen. On 18/19th of December the water level had dropped slightly to 42.90 m. The water level rose very fast for the next three days, measuring 45.90 meters on 22 December at 9:00 AM. At the highest level, the discharge was 3120 m^3/s, more than 13 times as much as the average discharge. Since 1911, these water measurements, like this high discharge, has never been measured on the Meuse. After 22 December, the water level and discharge decreased slowly. On New Year's Day 1994 there was another slight increase and again a week later. These last two increases remained more than 1 meter below the 22 December peak. After that, the decline continued (TAW, 1994).

4.2.2 Flood of 1995

The maximum water level that occurred in 1995 was in Borgharen + 45.71 metres NAP. This level was reached on January 31, 1995. The Meuse at Borgharen reached a peak discharge of 2746 m^3/s with a corresponding water level of 45.71 metres above NAP with a recurrence time of 50 years. However, the KMNI has estimated that the same discharge in 2050 will have a recurrence time of 30 years due to climate change (IJpelaar, 2020).

4.2.3 Flood of 2021

On 15 July, the flow of the Meuse at Eijsden (3260 m^3/s) exceeded the (winter) record of 1993. A significant difference between the 2021 and the previous floods is that not all of the flooding was caused by the main river, but most of the flooding occurred in the tributaries. For the Dutch province of Limburg flooding, occurred in the Geul (100 m^3/s) and the Roer (270 - 305 m^3/s) (along the Hambeek) (ENW, 2021). The tributaries Jeker 35 m^3/s and Geleenbeek 35 m^3/s had a higher discharge, without the occurrence of flooding (Stroming, 2021). The measurement data of the Roer and the Geul is not exact, because measurement stations were failing during the flood event. For the tributary the Roer there was only one measurement station that failed Hambeek. While at the Geul the measurement station at Hommerich, Eyserbeek and Seizerbeek failed due to high discharges (Waterschap Limburg, 2021).

4.2.4 Duration of the floods

The threshold of the threat of high water in the river Meuse starts at 1750 m^3/s in the Netherlands (D. Klopstra, 2000). This means that the duration of the flood in 1993 was six days, in 1995 11 days and in 2021 2 days as shown in Figure 27. This is at least half the duration of the flood in 1993 and a quarter of 1995. The duration of the flood is important, because the saturation of dikes can lead to dike failures. And the shape of the flood wave plays a vital role in the effect of peak attenuation as described in 3.4 Peak attenuation.

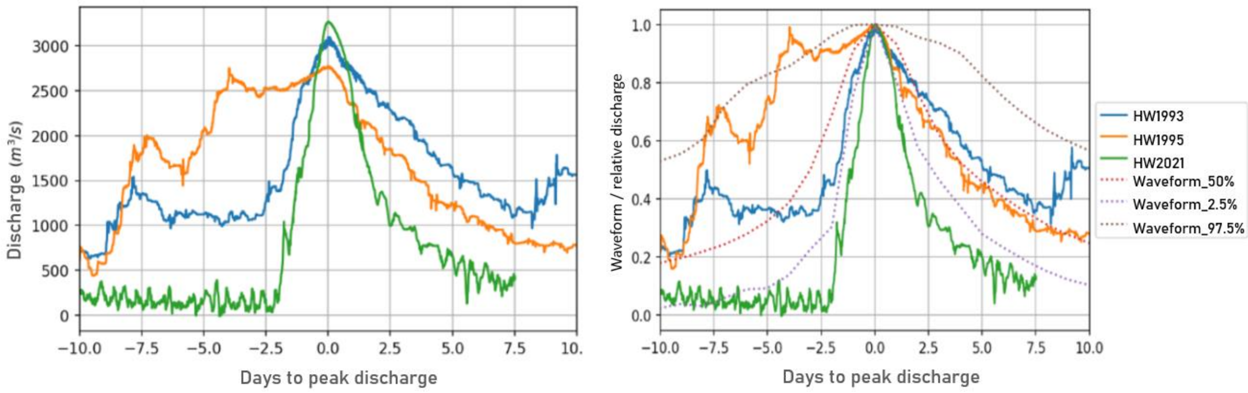

Figure 27: Flood waves of the high-water of 1993, 1995 and 2021 (ENW, 2021)

4.3 Damage

The floods have resulted in physical damage to objects and crops and other types of damage such as business failures. Some consequences are less easily measurable and cannot be expressed in monetary terms, such as stress and loss of personal possessions with emotional value (ENW, 2021). An overview of the different types of damages is shown in Table 3.

Table 3: Types of damages caused by flooding (ENW, 2021)

	Monetary value	Non-monetary value
Physical damage	Capital costs and cleaning costs	Victims, stress, ecosystems, pollution, monuments and cultural loss
Business failure	Loss of production downtime, income and interruption of infrastructure	Social disruption, emotional damage and inconvenience due to infrastructure interruption

In December 1993 and January 1995, Limburg only dealt with flooding in the Meuse valley. A significant difference with the event in the summer of 2021 was that most of the flooding occurred in the tributaries, much less damages occurred in the main channel. During the summer of 2021, the top discharge of the Meuse at Borgharen was comparable to the peak discharge in December 1993 and January 1995. The damages covered only the river Meuse for each flood, because the tributaries are outside the scope of this research. The damage along the Meuse in 1993 was estimated at 250 million guilders and in 1995 at 165 million guilders. To make an easier comparison, the amount of damage in 1993 and 1995 are converted to euros as shown in Table 3. These amounts do not include loss of business interruptions.

Table 4: Damages of the floods 1993, 1995 and 2021 (ENW, 2021)

	1993 (milj. Euro)	1995 (milj. Euro)	2021 (number)
Private damage	76.4	31	300 – 400
Agri- and horticulture	15.4	16	9500 – 10.000 (ha)
Companies	58.6	47.5	190 – 200
Institutions	2.1	1.6	72
Government	48.5	29.9	70
Total financial damage	201	126	100-150 Milj. euro

4.4 Conclusion

All three flood events had heavy rainfalls in the Ardennes. In 1993 and 1995, the winter snow will slowly accumulate and when the snow melts, more water will easily flow to the main channel. The snowmelt with heavy rain leads to the two winter flood events in the Netherlands. While in the summer of 2021, only extreme heavy rainfall led to even a higher discharge than the two winter floods.

The shape of the flood wave differs between 1993, 1995, and 2021. The most significant difference is the width of the flood wave and the duration. The short period of heavy rainfall in Euregio Meuse-Rhine in July 2021 created a steep flood wave with a short duration. The duration of the flood wave in 2021 was only 2 days compared to the six days in 1993 and 11 days in 1995. This is at least double the duration. In 1993, the heavy rainfall over nine days combined with the melting snow in the Ardennes created the obtuse flood wave. In 1995, heavy rain occurred in the Ardennes for eighteen days with combined average precipitation of 200 mm.

The shape of the flood wave has a significant impact on the behaviour of the flood. The flood wave of 2021 had a short duration. Therefore, as explained in section 3.4 the peak attenuation was significant and deduced the discharge downstream significantly.

A significant difference is that the 1993 and 1995 flood happened in the winter, while the flood of 2021 occurred in the summer. This indicates that the initial discharge in 1993 and 1995 was already more significant than in 2021 as shown in Figure 27.

5

Results

In this chapter the intended effects of the measures taken since 1995 will be compared with the measured effects in the flood of 2021.

5.1 Peak attenuation of the Meuse

Deltares was commissioned to investigate the peak attenuation by RWS-ZN. RWS-ZN would like to know the extent of the peak attenuation and how the areas along the Meuse contribute to this. Furthermore, they want to understand the influence on the widening bottlenecks on the river (de Jong & Asselman, 2019). The degree of peak attenuation depends on the height of the peak discharge wave, but even more on the waveform. The same discharge is chosen for each peak discharge, only the shape of the discharge wave differs. The shape of the wave is the same as used in WBI2017 and the sharp discharge wave (blue line) is 2.5% confidence interval at Borgharen, the average discharge wave (orange line) is 50% confidence interval and the blunt discharge wave (green line) is 97.5% of the confidence interval at Borgharen as shown in Figure 27. The result of the research will be described in the following section.

5.1.1 Summary of Peak attenuation Meuse

The most important findings from the report of Peak attenuation will be explained. As shown in Figure 28, peak attenuation at a very blunt discharge wave is many times smaller than with a very sharp discharge wave. At a peak discharge of approximately 4400 m^3/s, the peak discharge decrease can vary from 200 m^3/s for a blunt wave to 1200 m^3/s for a pointed wave. There was chosen for a peak discharge of 4400 m^3/s, because the effect of peak attenuation is clearly visible.

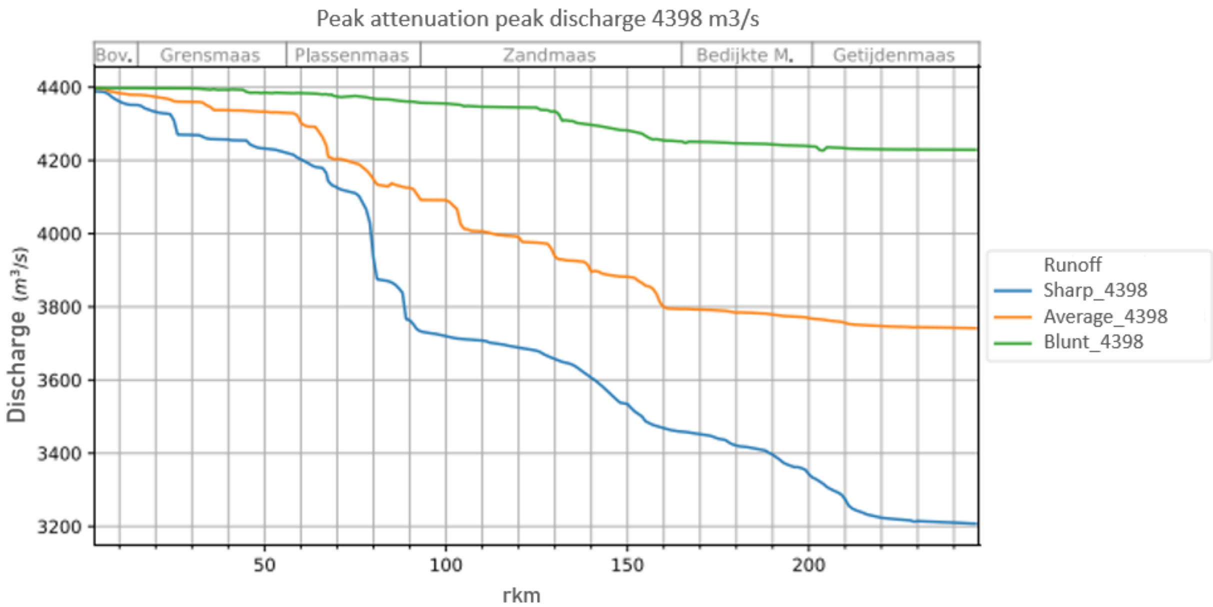

Figure 28: Peak attenuation of the peak discharge in the Meuse River (de Jong & Asselman, 2019)

The study, as shown in Figure 28 concluded that (de Jong & Asselman, 2019):

- The peak attenuation is limited on the Bovenmaas and the Grensmaas (rkm 3 to 60). This is mainly because the gradient here is relatively large and has a smaller conveyance width (1500 m) than the conveyance width of 3000 m at Roermond.
- The Maasplassen area (rkm 60 to 80, mentioned as "Plassenmaas" in Figure 27) contributes strongly to the peak attenuation. The peak attenuation is large in the upstream part of the Maasplassen area (between rkm 60 and 70) due to Thorn's flood defence system and the storage in the lakes at Heel. The Maasplassen were quarries created by excavating sand and gravel, later turned into recreation/nature areas. At slightly lower discharges, the peak attenuation flattening is significant in the downstream part of the Maasplassen area, due to inflow into the LKW (Lateraal Kanaal West) retention area. This significant increase changes the kinematic wave approximation upstream to dissipative wave approximation downstream. This trend only happens for the sharp flood wave.
- On the Zandmaas (rkm 80 to 160), a lot of the peak attenuation occurs, especially when the discharge is above 3500 m^3/s. This is because the former dike-rings, now called dike stretches, are flooded during this discharge. The substantial decrease in peak discharge at rkm 160 results from storage at the Lob van Gennep.
- Earlier studies have calculated the effect of the reactivation of the Old Meuse arm near Ooijen-Wanssum (around 130 rkm). The project could lead to a delay of the discharge wave of 1.5 to 2 hours. The largest effect is for a sharp discharge wave. At relatively low high-water levels (3200 m^3/s and 3600 m^3/s) there is hardly any decrease in peak discharge on the stretch to Ooijen-Wanssum. Peak attenuation is in the current situation at lower high-water, therefore very minimal. In the past (1995) peak attenuation has decreased due to deepening of the summer bed and the construction of a high-water channel.
- Little peak attenuation occurs on the diked Meuse (from rkm 160, mentioned as "Bedijkte Maas." in Figure 28). The river is rather straight and resembles a canal. A small decrease in the discharge peak can still be observed at Alem (rkm 210) where ox-bows are filled up for some peak discharges.

5.1.2 Comparison of peak attenuation and the flood of 2021

To make a comparison between the modulation data in the report of peak attenuation and the flood of 2021, the most similar scenario is chosen to compare. The sharp discharge wave scenario has a very similar shape of the discharge wave as shown in Figure 28. Therefore, the hypothesis is that the peak attenuation should look similar to the blue line in Figure 28. This means that a lot of water will fill the floodplains and reduce the peak of the flood wave.

Table 5: Peak discharges at measurement locations (van der Veen & Agtersloot, 2021)

Location	Rkm	Peak discharge [m^3/s]	Time [CEST]
Eijsden-grens	2.56	3260	15-7-2021 21:50
St. Pieter	10.80	3310	15-7-2021 23:10
Borgharen – Dorp	16.00	3284	16-7-2021 01:20
Venlo	107.47	2850	17-7-2021 11:50
Megen	190.75	2328	19-7-2021 07:30

In Table 5, the maximum discharge of 3310 m^3/s at St. Pieter (rkm 10.80), reduces to 2328 m^3/s at Megen (rkm 190.75). This is a difference of 982 m^3/s. The difference between the peak attenuation is circa 1000 m^3/s between St. Pieter and Megen. Therefore, the peak attenuation is similar even though maximum discharge of the sharp discharge scenario is circa 1000 m^3/s higher than the flood of 2021.

Due to the decrease in discharge of the peak discharge downstream. It will change the return period of the flood wave. The flood wave at Borgharen (rkm 16) has a return period of 100 years, while Venlo (rkm 108) has a return period of 25 years, and Gennep (rkm 155) of 10 years (Slomp, 2021). The change in width of the river bed after Roermond from circa 1500 m to 3000 m, significantly flattens the flood wave as shown in Figure 28 and is an important measure in reducing the height of the flood wave.

Simulations with the waveforms from the GRADE database showed that peak attenuation at a discharge peak occurred in July 2021, and a pointed waveform can lead to up to 1 m lower water levels at the beginning of the diked Meuse. In comparison, for an average waveform, this is 0.4 m, and a blunt waveform can reduce this to less than 0.1 m. The relatively low water levels measured downstream of the Meuse lakes will largely result from peak attenuation.

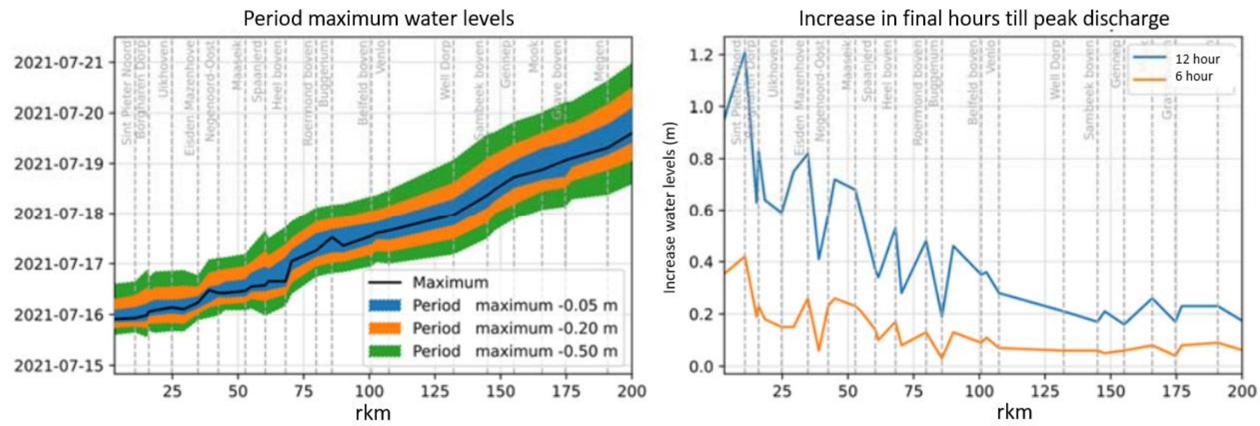

Figure 29: Moment of the maximum water level and the period when the water level almost reached this height (left) and the increase in water level in the last hours up to the water level peak (right) (ENW, 2021)

The effect of peak attenuation as the wave moves downstream can be concluded from the measurements. Figure 29 on the left showed when the water level was only 20 cm below the maximum. This increases along the Meuse due to the peak attenuation of the waveform (4 hours at Maastricht; 13 hours at Grave). The change in wave shape is also visible from the rise of the water level in the last hours up to the peak (on the right side). In Maastricht the water level rose by more than 1.0 m in the last 12 hours, from the Meuse lakes this has already decreased to 0.5 m, and at Venlo this is less than 0.3 m (ENW, 2021).

5.2 Effects of Grensmaas Meuse and the Box of Building blocks

The peak attenuation report shows the behaviour of the flood wave on the topography. While this section will show the intended impact of measures on the water level. The Box of Building blocks is only useful from Eijsden till Roermond, because it changes from a kinematic wave approximation to a dissipative wave approximation due to peak attenuation. The Box of building blocks is calculated with a kinematic wave, while the shape of the flood wave in 2021 has changed significantly along the river. An exemption was made for the project Ooijen-Wanssum, because it is a big and important project. Furthermore, the shape of the kinematic flood wave is an average discharge wave not a sharp flood wave as in 2021.

Only the Belgium Grensmaas projects were implemented in the Box of building blocks, while the Dutch Grensmaas projects were already concrete and signed in 2005 (Consortium Grensmaas BV, 2021). Therefore these projects are not separate building blocks, but are part of the existing topography of the river.

The bottlenecks in the Limburg section of the river Meuse at circa 1996 are shown in Figure 30. The first bottleneck is visible near Maastricht with a backflow of circa 0.5 m. The second bottleneck is at Linne/Herten, where the dikes extend far into the floodplain and thus reducing the width greatly. Between Roermond and Venlo the width of the river narrows again, which leads to various bottlenecks.

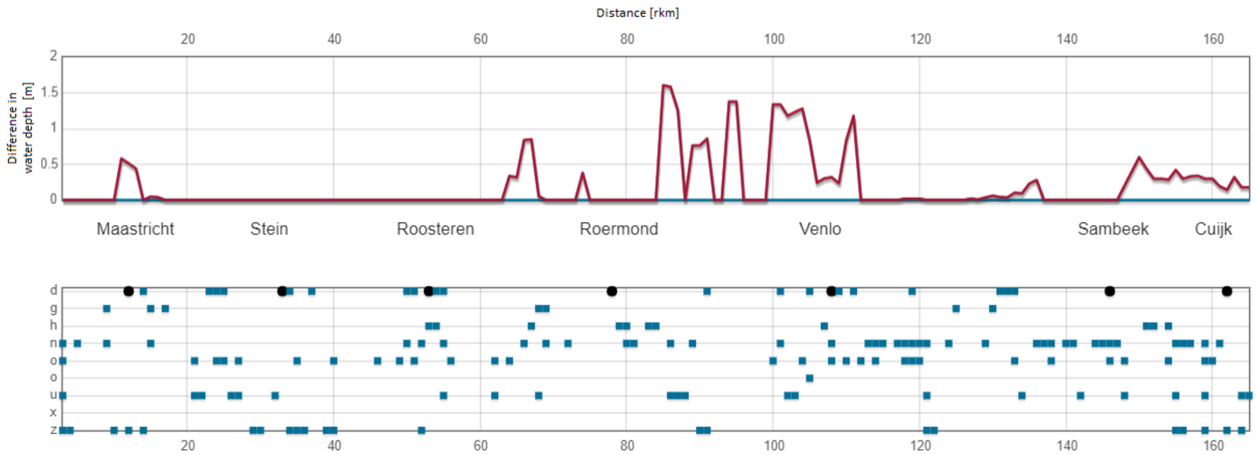

Figure 30: Bottlenecks in the Limburg section of the Meuse (Wilson, 2022).

The bottom part of the graph shows all the different measures that were explored. Each measure has been placed on the x-axis on their location. On the y-axis is defined the type of flood protection measure. The description for the different types of measures are explained in Table 6.

Table 6: Explanation for the different types of measures (Kroekenstoel, 2014)

Symbol	Meaning in Dutch	Meaning in English
d	Dijkverlegging	Dike relocation
g	Groene rivier/retentie/rivierkering	Green river/retention
h	Hydraulisch obstakel	Hydraulic obstacle
n	Nevengeul/hoogwatergeul	Secondary channel/High-water channel
o	Overig	Other
u	Uiterwaardproject	Floodplain project
x	Onbekend	Unknown
z	Zomerbedmaatregel	Main channel measure

5.2.1 Summary of the Grensmaas evaluation

The results of the evaluation are shown in Figure 31. The water level line of 1995 at a discharge level of 3275 m^3/s at Borgharen has been chosen as the reference line. The choice for this reference is related to one of the first agreements in the VNBM. The blue line shows the water level line relative to the reference line. The red line is the new design standard WBI2017, which must be met in 2050. The red line is a few decimetres above the blue line. The Flemish (red dots) and Dutch (green dots) crest heights of the flood defences are also indicated. In some places, the water level is above the reference line.

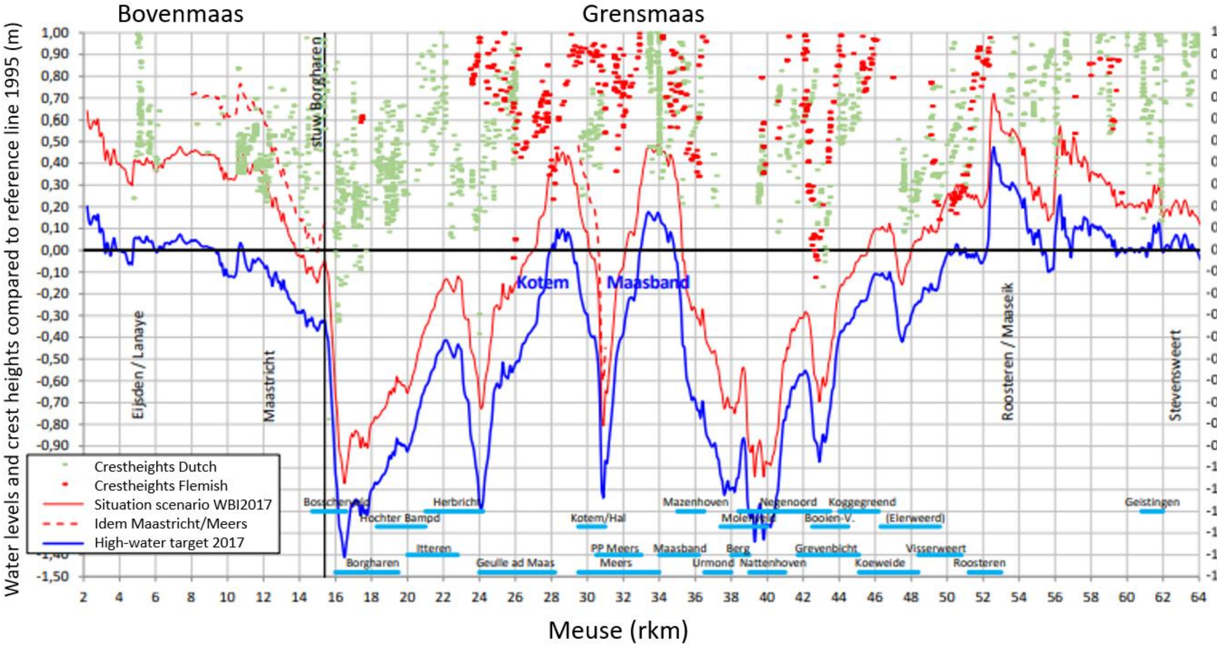

Figure 31: Grensmaas with it projects and dike heights (Meijer & Agtersloot, 2021)

From Figure 31 can be concluded that:

- At rkm 2 to 15.4, the exceedances are relatively small and may be related to minor morphological developments, especially at Maastricht. Almost no river-widening measures have occurred.
- Upstream of Kotem (rkm 28-29) is the downstream effect of Geulle aan de Maas, which the river widening by Meers cannot compensate because it cannot pass the bottleneck at Kotem. The Kotem river widening, as foreseen in the plan of Boertien II, has not yet been carried out. Instead, a ground defence has been constructed in the bed of Meers (rkm 29-31).
- At Maasband (rkm 33-35) the objective is not met because, at the time of the evaluation, the high water channel has not been realized yet (Meijer & Agtersloot, 2021). It is expected that the construction will take up to 2025 before completion (Consortium Grensmaas BV, 2021).
- In the northern sector, some exceedances may be related to morphological developments and the fact that no river-widening measures have taken place. At Roosteren there is a very large exceedance, where there is a lot of sedimentation in one of the river bends resulting in the narrowing of the river. On the Flemish side, the dike is sufficient at Heppeneert (rkm 49.5 – 51.0), where it does not meet the required 0.5 m guard height.

5.2.2 Comparing the Grensmaas measure with the flood of 2021

To make a comparison between the modulation data in the evaluation report of the Grensmaas and the flood of 2021, a similar graph to Figure 31 is created. The hypothesis is that the water levels will flow similar to the red line in Figure 31.

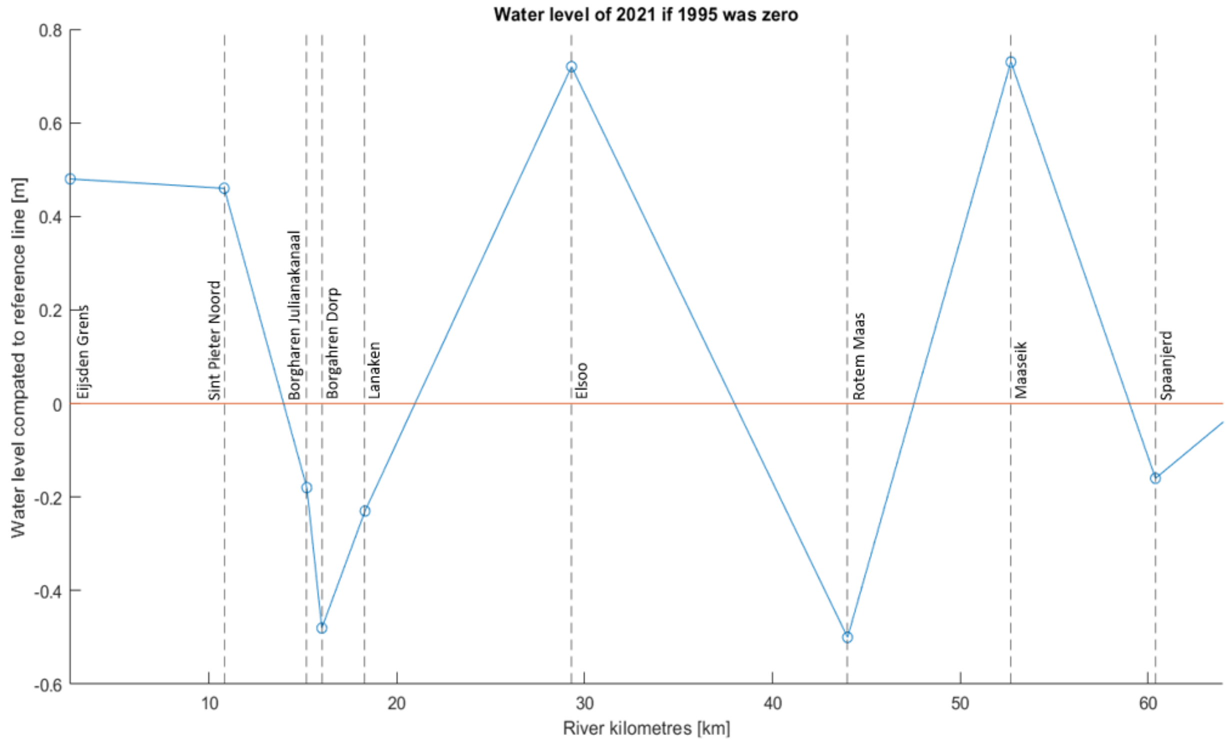

Figure 32: Water levels in 2021 to reference line 1995

Figure 32 was created with the maximum water level at each measuring location along the Meuse till 64 rkm displayed as a dot. The line created between the dots is just a linear line. The graph has only eight measurement locations in the Grensmaas (Appendix F), so compared to Figure 31, it is a simplistic graph. There are three peaks above the zero line. At Borgharen (15.25 to 16 rkm), at 44 rkm measurement station Rotem Maas and the measurement station Spaanjerd at 60.4 rkm. The first peak is 0.18 higher at Borgharen Juliana Canal, 0.48 m higher at Borgharen Dorp and 0.23 higher at Lanaken than in 1995. The discharge at Borgharen Dorp was 2746 m^3/s in 1995, while 3284 m^3/s in 2021 (van der Veen & Agtersloot, 2021). This is a 538 m^3/s difference in discharge. As explained in section 2.3.2.2.1 Grensmaas project Koeweide and Grevenbicht are projects in the Grensmaas region that still have to be completed. This can explain why the water level at rkm 45 is 0.36 m higher than in 1995.

5.2.3 Summary of the important measures of Box of building blocks

The four most important measure in Box of building blocks are described in this section. For each measure at least one scenario, namely 1/250 years event with a corresponding discharge of 3800 m^3/s. Some have also the more extreme scenario of 1/1250 years events with a discharge of 4600 m^3/s each with an average flood wave shape. Therefore, the first scenario has approximately a 500 m^3/s higher peak discharge than the flood of 2021.

Deepening the main channel by another two meters from 2.6 to 15.3 rkm till the weir at Borgharen (Wijbenga, 2021) is a very effective measure, as shown in Figure 33. Mostly, because it reduces the bottleneck. This will reduce the backwater flow created by the narrow channel through the city centre of Maastricht. The maximum drop in water level is 110 cm for a discharge of 3950 m^3/s, which mean that 8743 m^2 water can be stored extra in the main channel (Wilson, 2022).

The contract to carry out dredging works around various locations in the Meuse was signed in 2020. The tender for the work that was planned to be carried out was suspended last year due to the PFAS situation (RWS, 2020). Therefore the deepening of the main channel was still in the planning phase during the flood event of 2021.

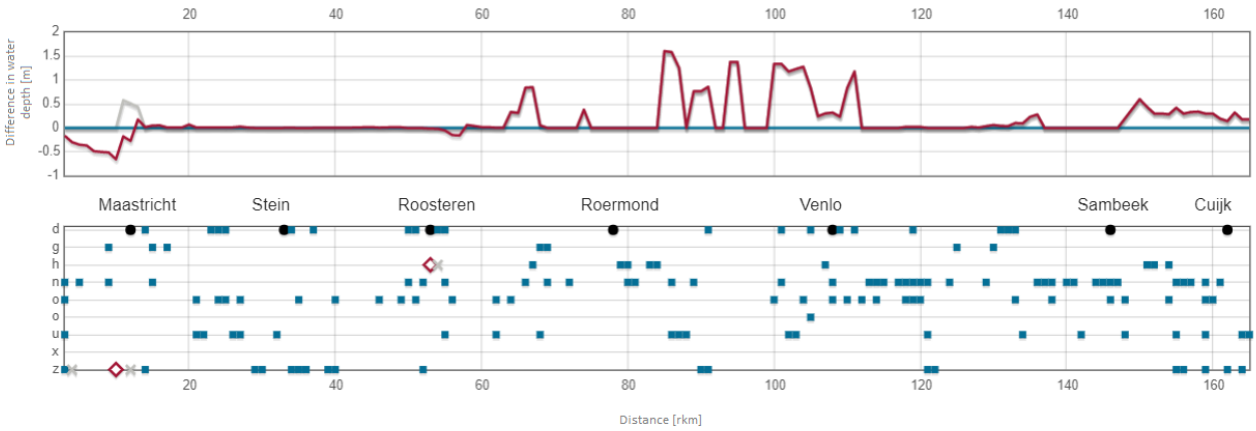

Figure 33: Deepening of the main channel at Maastricht (Wilson, 2022)

There is a plan for a high-water channel east of Borgharen and Itteren from 15.5 to 22.5 rkm with a length of 3100 m, an average width of 200 m, and a depth of 2 m (MVW, 2002). Was an optional plan that wasn´t implemented. However, it would have reduced the water level in Maastricht by circa 0.1 m, but the largest reduction will happen just before Borgharen with a reduction of 0.5 m as shown in Figure 34.

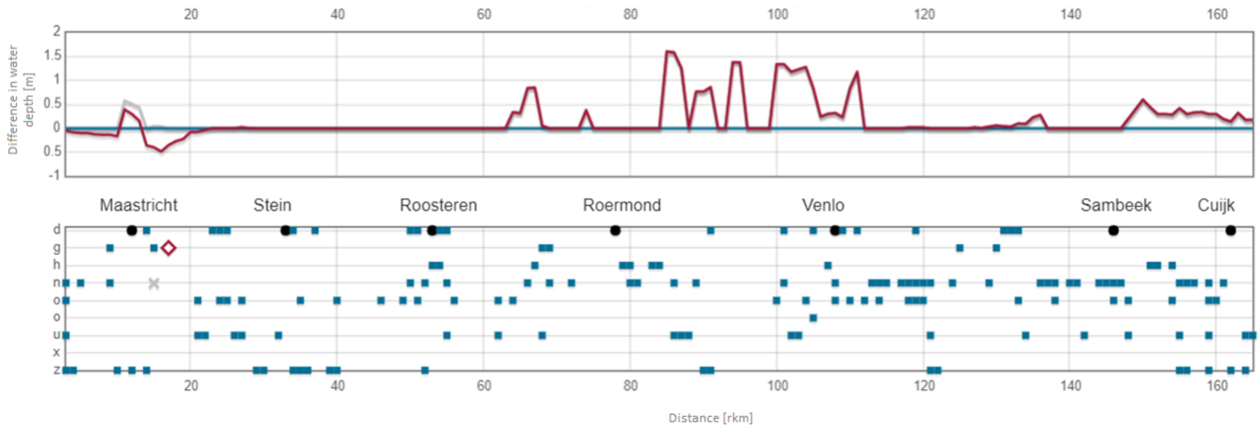

Figure 34: High-water channel Borgharen and Itteren (Wilson, 2022)

Another high water channel has been built on the Flemish side of the border from Kotem till Meers. The flood plain has been lowered and the dike is relocated further from the main channel, creating a wider and lower flood plain. The high water channel at rkm 28 till 31 has a length of 1400 m, a width of 500 m, and a surface area of 67.3 ha. This will have a large impact since it reduces the bottleneck at the bend (MVW, 2002). One of the downsides of this measure was that three houses had to be demolished to create enough room (Gielen, 2008). The maximum water level drop is -2.55 m and a conveyance capacity of 14091.7 m^2, as shown in Figure 35. The measured effect is substantial because it even affects the water level at Borgharen, which is upstream from Kotem.

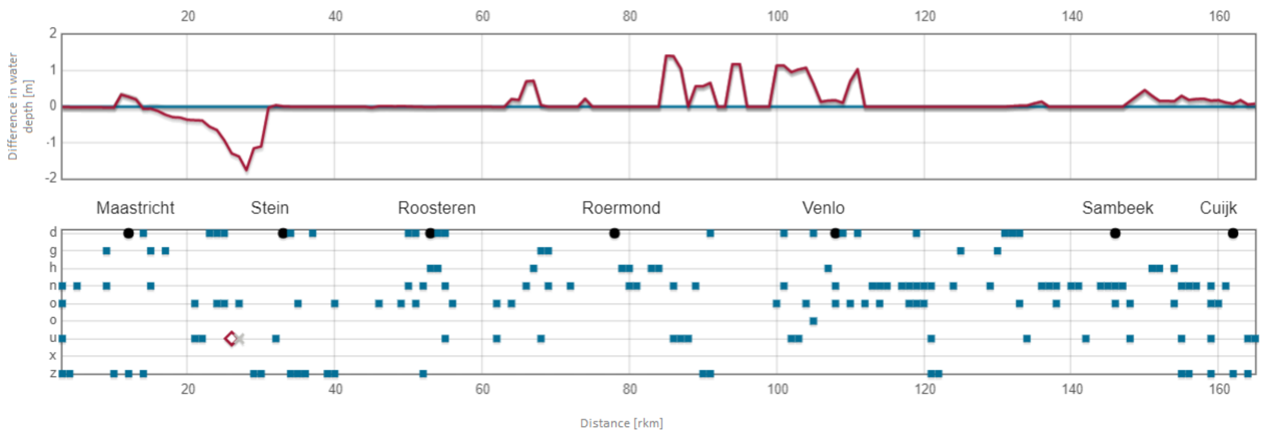

Figure 35: High-water channel at Kotem (Flemish) (Wilson, 2022)

Wanssum and Ooijen were inundated in 1993 and 1995, as shown in Appendix C.5.1. Ooijen Wanssum. To prevent this from happening again, the following measures have been implemented at Ooijen and Wanssum (rkm 124.3 – 133.3). The three high-water channels create a maximum water level drop of 58 cm and the effect is visible upstream till Roermond, which is circa 30 km upstream (Wilson, 2022) as shown in Figure 36.

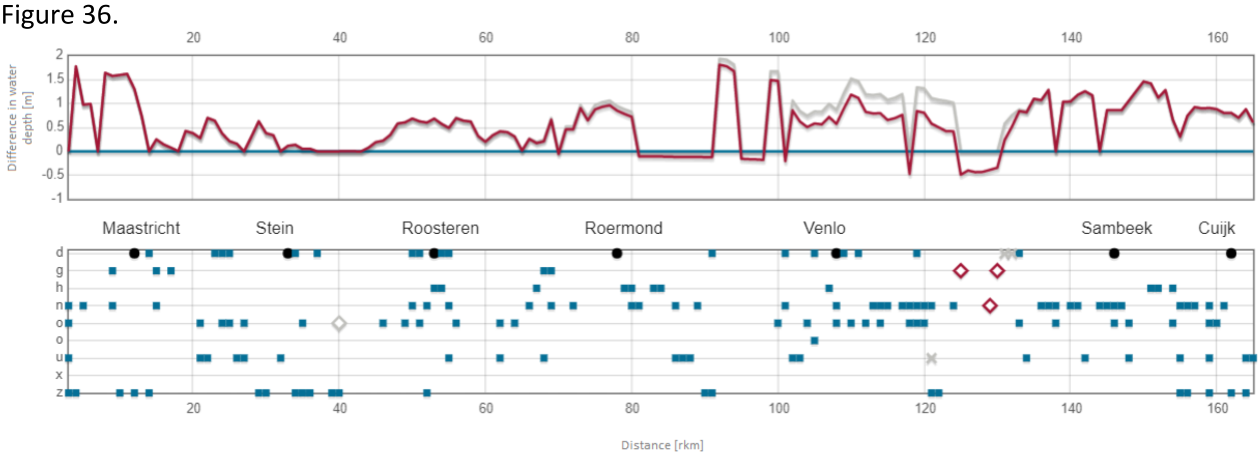

Figure 36: Effect of the project Ooijen-Wanssum on the Limburg Meuse river

Because of the sharpness of the flood wave when it arrives at the Dutch border the effectiveness of the high-water channels will be large, because it will increase the effect of peak attenuation and reduces the peak of the flood wave. The maximum reduction of the water level due to the main channel deepening in Maastricht and the high-water channel at Kotem will be closer to the calculated effect of the Box of building blocks than by Ooijen-Wanssum.

The measured effect of project Ooijen-Wanssum on the water levels was a reduction 37 centimetres at Broekhuizen, 20 cm at Venlo and 5 cm at Roermond during the flood of 2021 (Kusters, 2021).

5.3 Effect of all measures on peak attenuation

Previously the intended effect calculated in each report or tool is discussed separately on the flood of 2021. In this section links between the obtained knowledge from previous sections in chapter 5 will be combined to explain the total impact that the measures had on the flood event of 2021 compared to 1993 and 1995. Therefore, along the entire stretch of the Limburg's Meuse the water levels have been plotted for the three flood events as shown in Figure 37.

Over the years, some measurement stations have changed or moved and new measurement stations have been included, as shown in Appendix A. The absolute water levels for each flood event are unreadable as shown in Figure 37; on marked sections within the graph will be zoomed in.

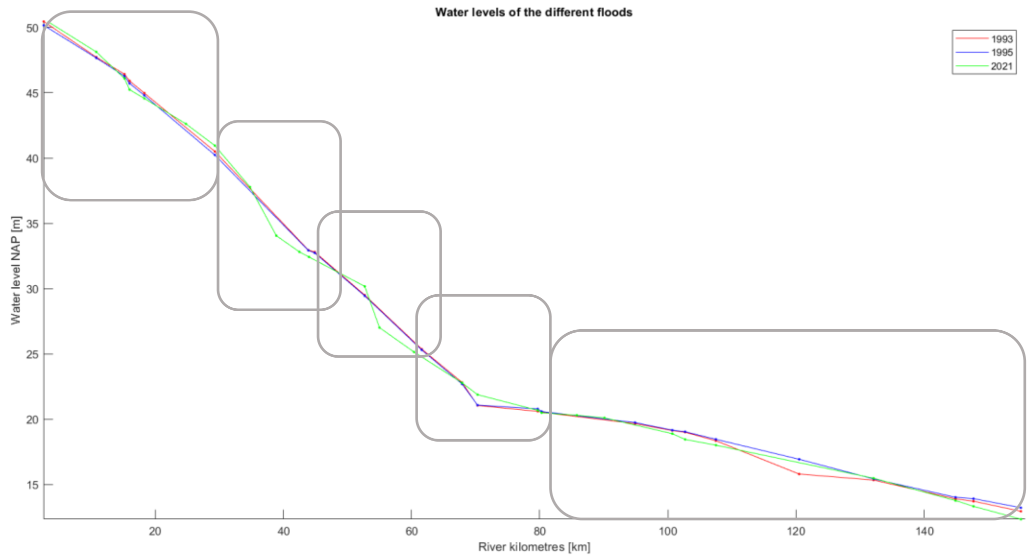

Figure 37: Measured maximum water levels of the high-waters of 1993, 1995 and 2021

The global trend is that the difference between the water levels in 1993 (red) and 1995 (blue) are very similar and follow the same trend since the topography is almost identical during both events. In 1993, the discharge was higher than in 1995 hence higher water levels upstream. However, in 1993 also the inundated area upstream is higher than in 1995. This means that more water is temporary stored in flooded area than in 1995. The discharge downstream decreases faster in 1993 because of the effect of peak attenuation than in 1995, as a result around 70 rkm the water levels of 1995 are higher than 1993.

At St. Pieter Noord the water level is higher in 2021 than in the previous years as shown in Figure 38. The discharge is also higher in 2021, which can partly explain the increase in the water level. However, it was expected to become lower, because of the main channel deepening.

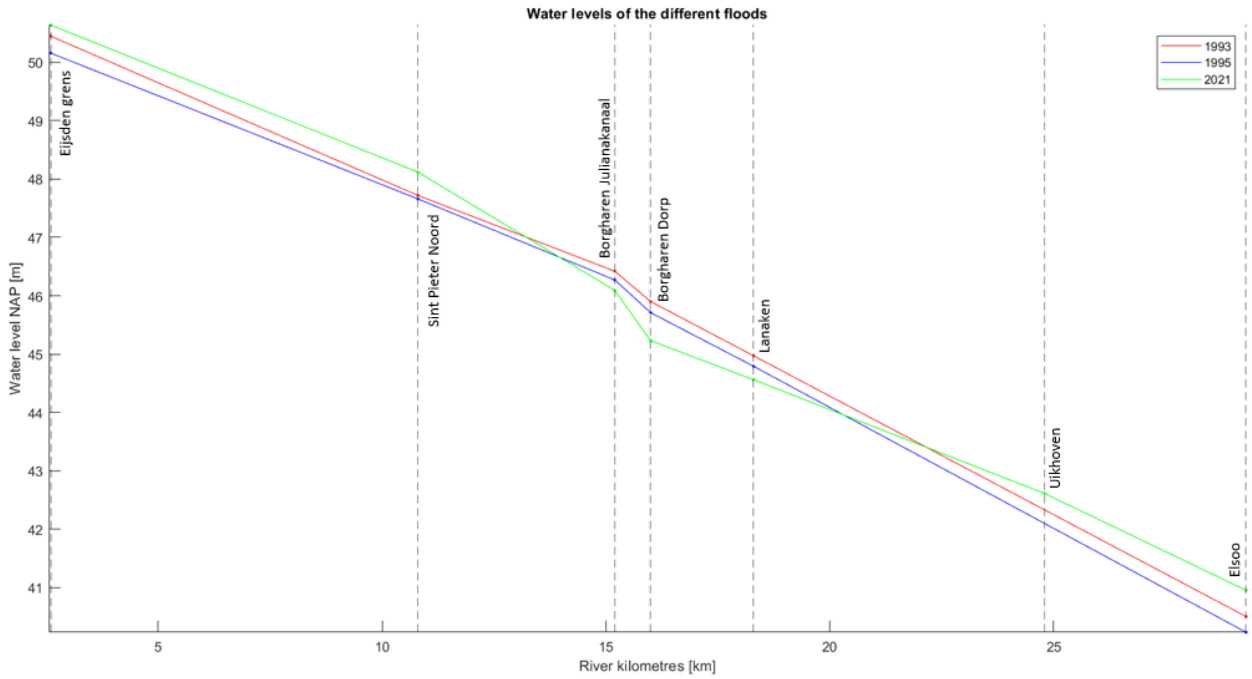

Figure 38: The water levels between the measurement stations Eijsden (2.6 rkm) and Elsoo (29.3 rkm)

The measurement at Elsloo is significantly higher in 2021, with a steep decrease in almost three water levels. This is due to the high-water channel at Kotem, which is located just south of Elsloo. As explained in section 5.2.4, the maximum calculated water level drop was 2.55 m. The observed water level difference is even more significant than the calculated because in Box of building blocks the shape of the flood was average. In Figure 39 the green line is higher upstream and downstream of Kotem similar to Figure 35.

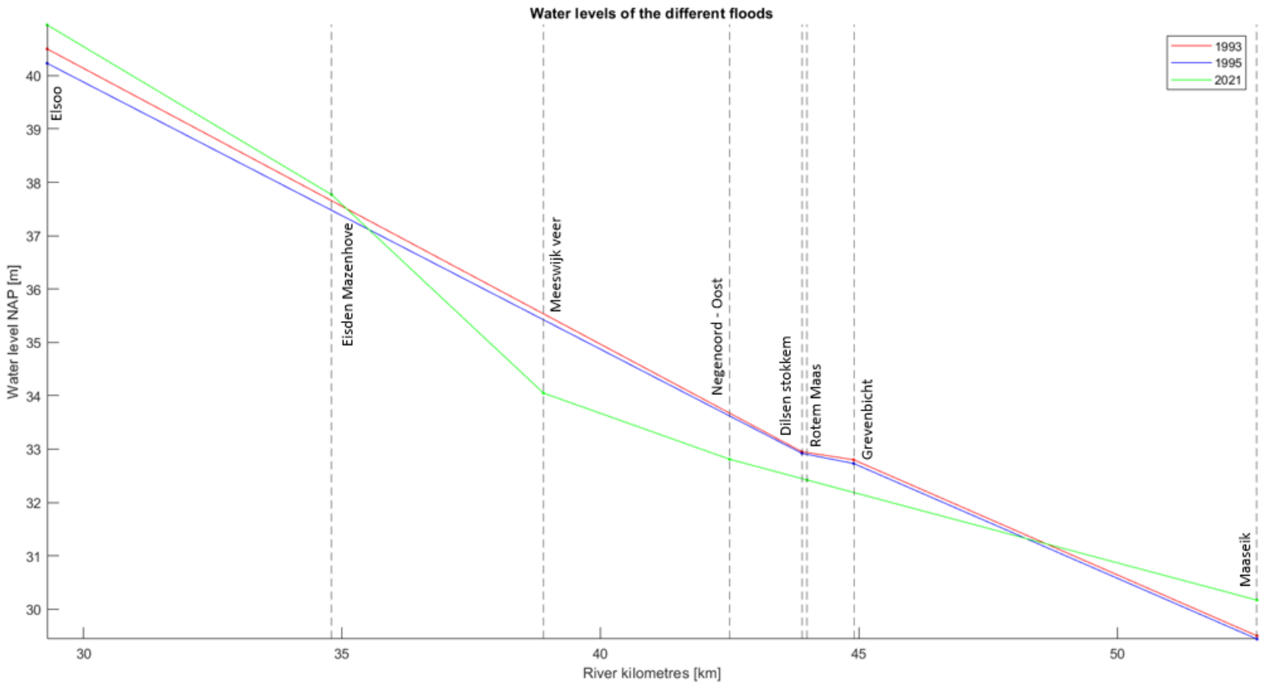

Figure 39: Water levels between the measurement stations Elsoo (29.3 rkm) and Maaseik (52.7 rkm)

The bottleneck at Maaseik is even more significant because of the lower water levels upstream and downstream. Furthermore, the water level was circa 0.7 higher than 1993 and 1995. So by (partly) solving the bottleneck at Maaseik flood safety will also increase significantly. The green dot above the blue and red line is the measurement station at Maaseik see Figure 40.

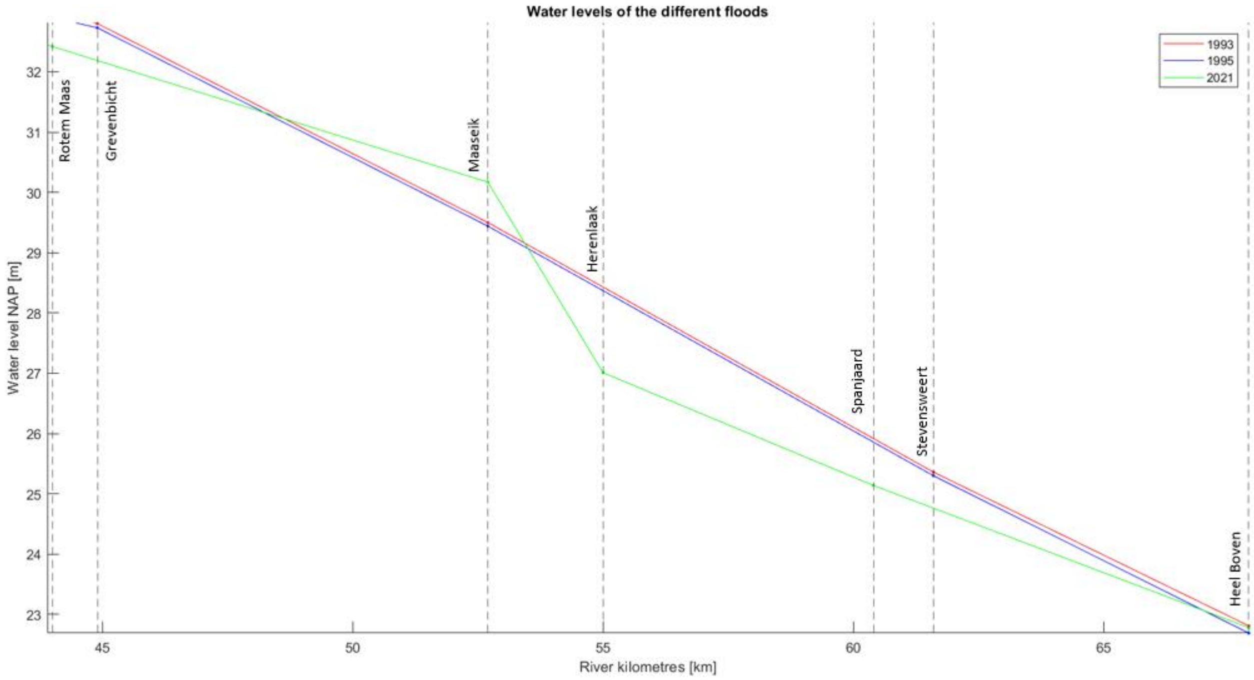

Figure 40: Water levels between the measurement stations Rotem Maas (44 rkm) and Heel boven (67.9 rkm)

In Figure 41, there is no measurement station for Stevensweert (61.6 rkm) in 2021. However, there is a measurement station Spaanjerd at 60.5 rkm with a water levels of 25.14, which is already lower than the water levels that were recorded at the measurement station Stevensweert in 1993 and 1995. Therefore, it can be concluded that water levels will also be lower at Stevensweert. The most significant difference in water level is at Linne beneden. Heel boven and Heel beneden at the measurement station upstream and downstream of the weir and lock at Linne. These will be relatively fixed water levels on the Lateraal Canal Linne-Buggenum, while Linne beneden and Roermond boven are measurement points on the main river. At Linne beneden the water level was approximately 80 cm higher in 2021 than in previous flood events. An explanation for the increase in water levels is the built of the dikes particularly surrounding Herten.

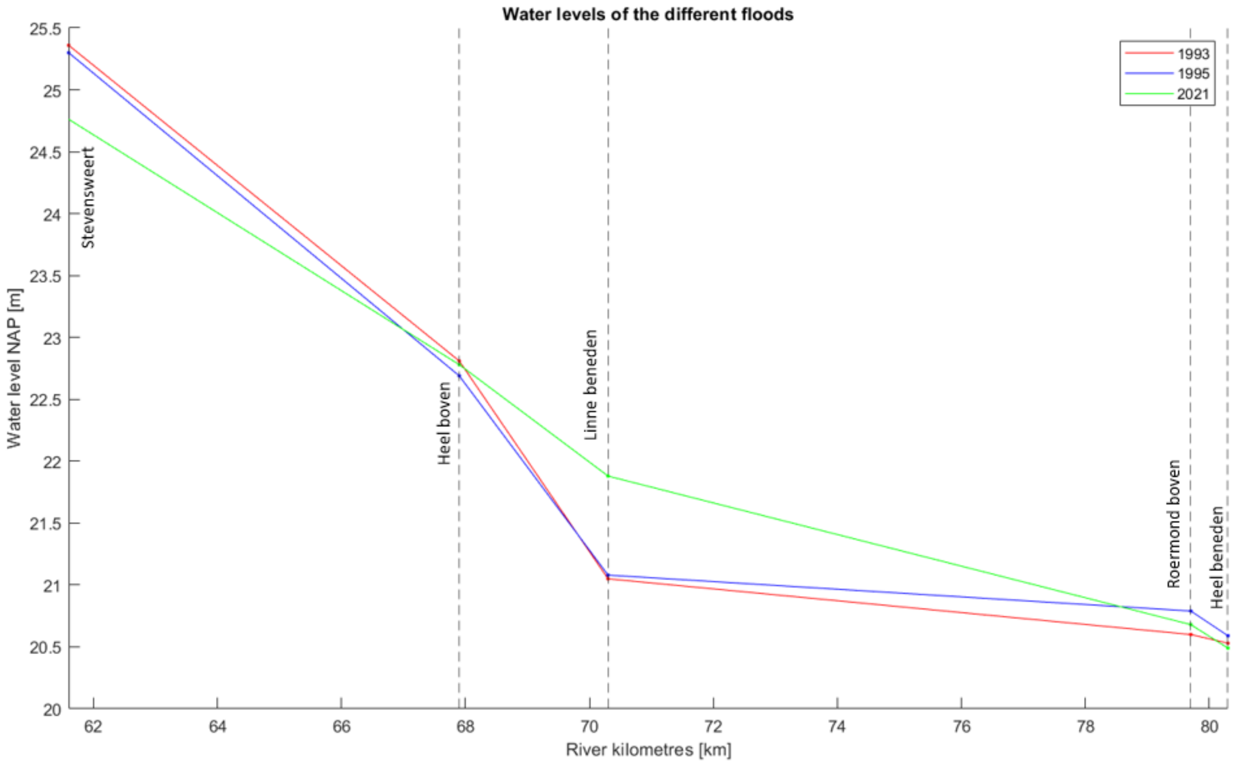

Figure 41: Water levels between the measurement station Stevensweert (61.6 rkm) and Heel beneden (80.3 rkm)

In 1993 at Arcen (120 rkm) the water levels were significantly lower than in the later years as shown in Figure 42. One of the reasons can be that only in 1993 Arcen was inundated. Furthermore, there were no measurements taken in 2021, and the measurement of 1993 and 1995 were only recorded every eight hours (ENW, 2021). This means that the maximum water levels in 1993 and 1995 could be higher than measured. For this reason, the drop in water level will not be as significant. However, there is no measurement station anymore for 2021. The measurement station Arcen would be an important station, because Arcen is located just upstream of Ooijen-Wanssum. The station would have given a good indication of the measured effect upstream of Ooijen-Wanssum if it was similar to the intended effect as predicted in the Box of building blocks.

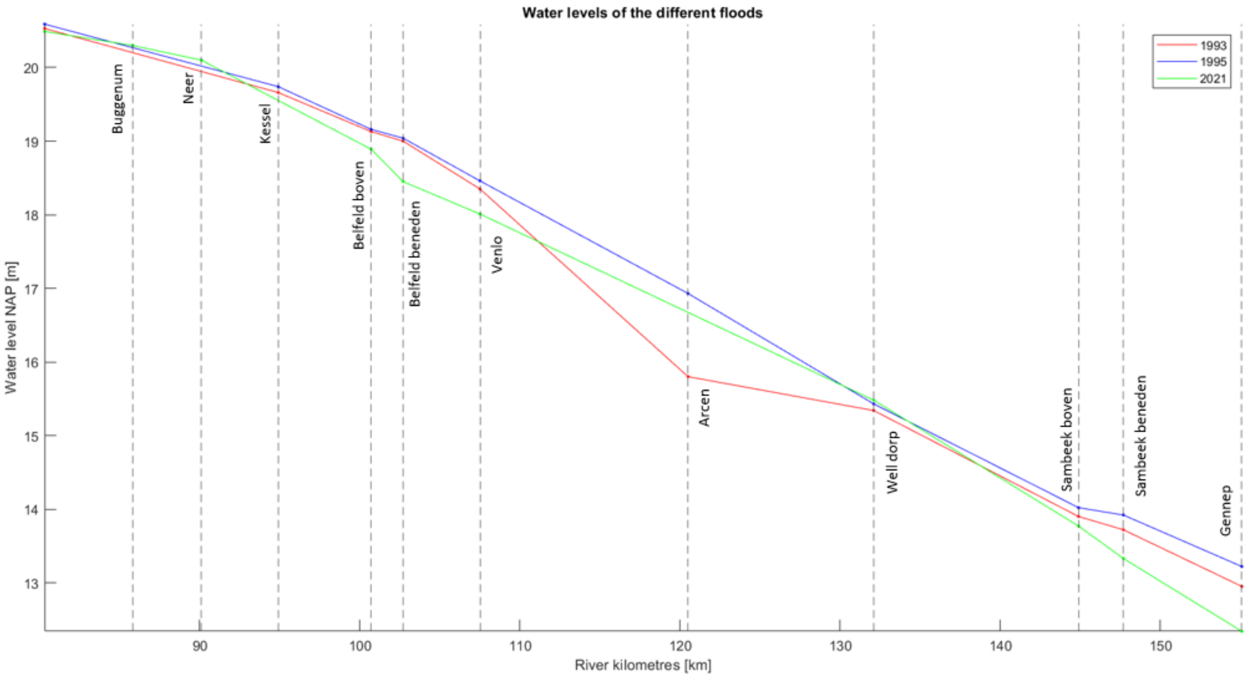

Figure 42: Water levels between the measurement stations Heel beneden (80.3 rkm) and Gennep (155.1 rkm)

Downstream of Well – Dorp, the water level of 2021 decreased significantly compared to 1993 and 1995. This illustrates the effect of peak attenuation that significantly reduced the discharge and corresponding water levels.

A rating-curve can be used to compare a water level (and the discharge) at Sint Pieter Noord and an expected value of the maximum water level on the river axis of the entire Meuse (RWS, 2020). To verify whether the measured water levels correspond to the expected, reference lines were used. Water level differences arise due to different starting points in the model calculations that form the basis of a relationship line. For example, in model calculations, assumptions are made about the duration of the high-water, i.e. the shape of the discharge wave (point or blunt), the size and timing of the discharge waves from tributaries and the brooks along with the Flemish and Dutch Meuse, the hydraulic roughness (summer or winter situation) and about the measures implemented (for example the process in the activities of the Meuse Works) (ENW, 2021).

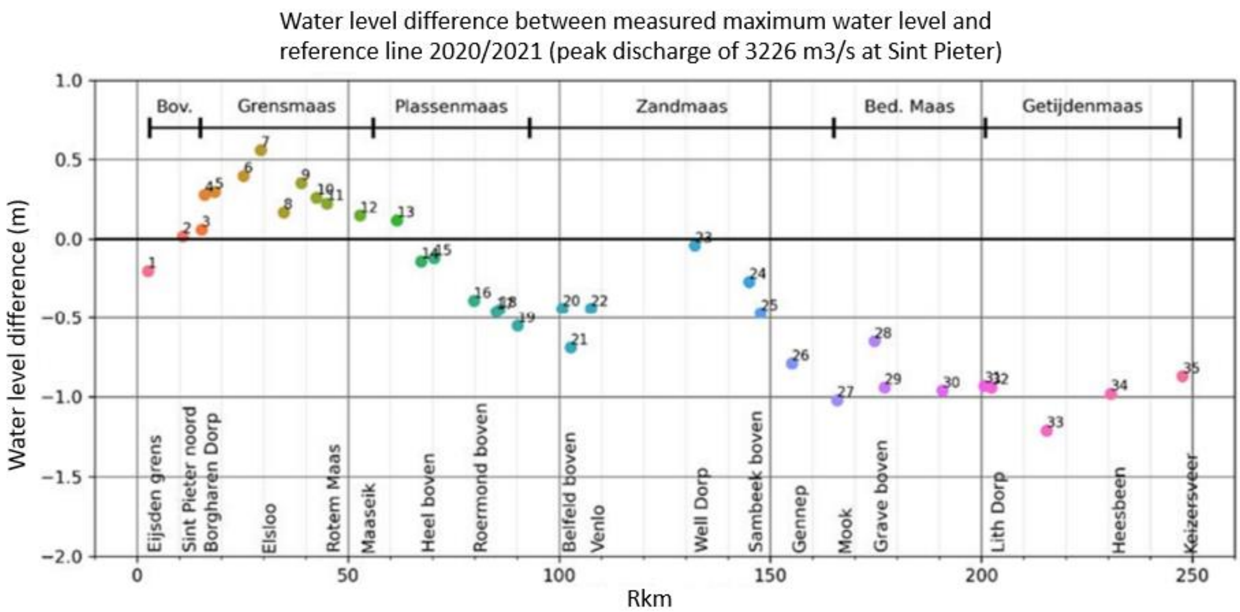

Figure 43: Water level differences between the measured maximum water level of the high-water 2021 and the reference line 2020/2021 with a peak discharge of 3326 m^3/s at St. Pieter (ENW, 2021)

Figure 43 shows the difference between the water level and the calculated relation curve of 2020/2021. Therefore the following can be concluded:

- Between rkm 10 and 60, the water levels that have occurred are higher than expected. Limitations of the models probably cause this. Possible explanations are deviating from the model's hydraulic roughness or bottom position in reality. The hydraulic roughness's are now determined on the basis of historical high-water of 1993 and 1995 in which the geometry of the river deviates locally from the current situation (for example the implementation of the Maaswerken program). Therefore, the assumption that (the calibration of) the model remains usable with changing geometry is at stake. This is also referred to as 'stationarity'.
- Downstream of rkm 60, the maximum water levels that have occurred are significantly lower than the reference line, probably due to the peak attenuation. The effect of peak attenuation of the high-water of 2021 was more significant than the relation curve predicted due to the sharp shape of the discharge wave.
- The measurement station Well Dorp is significantly higher than the surrounding measurements. However, the largest distance between the measurement station is between Venlo and Well Dorp. An explanation for the difference can also be the limitation of the modelling (difference in soil or vegetation roughness or the bed position).
- A few kilometres upstream of Sambeek, the water level difference is smaller than the surrounding measuring locations. Possible explanations are the inability to level the weir at Sambeek or a possible greater roughness due to the many vegetation in the floodplains.

From 10 till 60 rkm the reference line differs the most from the flood event of 2021 in a negative way. If the calculated curve is lower measured water levels it is only positive.

Figure 44 compares the height of the dike sections with the water levels along the Limburg part of the Meuse. The most critical point of each dike section is displayed as a thicker dot. This graph is created with data received from the measurements of AHN3 for the dike height of permeant dikes and the height of demountable barriers was provided by the water board. The location and height of sandbags placed on top of certain dike sections are not taken into account. Furthermore the simulated water levels were corrected with correction factors. The will lead to small local differences between measurement in the graph and reality (ENW, 2021).

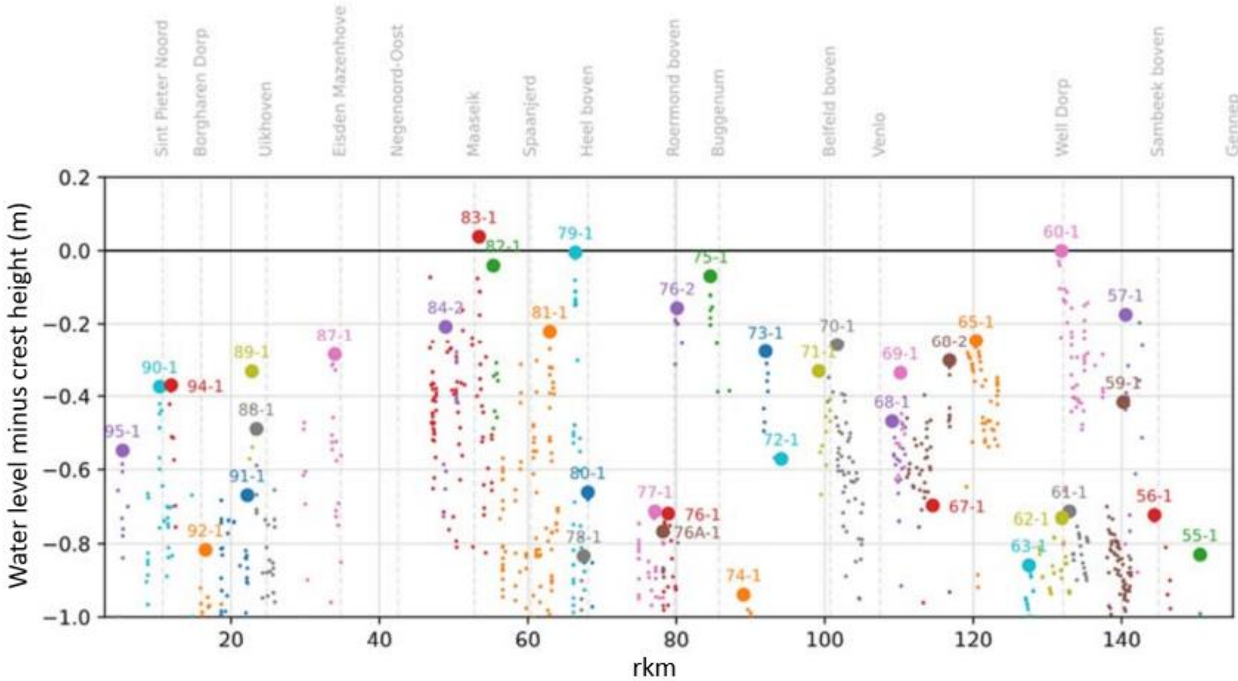

Figure 44: Differences between crest height derived from AHN3 and modeled water levels for all dike sections along the Meuse between the Dutch border and Gennep (ENW, 2021)

The dike sections 83-1, 82-1, 79-1, 75-1 and 60-1 are the highest points in respect to the crest height:

- 83-1: Visserweert became an island during the flood as planned. The dike ring 83-1 protected the village for flooding. The inhabitants were evacuated as a precaution even though the village was still accessible via the high-water bridge (Het Parool, 2021).
- 82-1: the small village of Aasterberg the maximum water levels were higher than displayed in the graph. Sandbags were needed to protect the hinterland against overflow, because the water level was higher than the crest of the dike. Before the flood wave arrived at Aasterberg sandbags were placed on the road behind the dike to prevent flooding of the village. The inhabitants were evacuated as a precaution (Beaumont, 2021).
- 79-1: in the night from Thursday to Friday, the military started reinforcing 1.1 kilometre of the dike ring with sand bags between Thorn and Wessem (Laarman, 2021). This dike section was planned to be reinforced and completed in 2026 (Waterschap Limburg, 2022).
- 75-1: this dike section at Buggenum was planned to be reinforced and completed in 2025 (Waterschap Limburg, 2022).
- 60-1: Well Dorp was reinforced with demountable barriers and with two rows of big bag of sand. Parts of the village Buggenum were evacuated on Friday (Laarman, 2021). The water was a few centimetres below the top of the demountable quay wall. The inhabitants were asked to evacuate (1Limburg, 2021).

Furthermore, it is important to note the water levels at the Claus centrale and the Chemelots water treatment plant, because the expected consequences of flooding for the surrounding area are large. That the dike section 80-1, which protects the Claus centrale, a supercritical power station was at least 0.6 m below the crest height as shown in Figure 44. Chemelots water treatment plant protected with dike section 87 was the minimum water level difference 0.24 m below the crest height. These dike sections have the same level of exceedance as the surrounding urban areas as shown in Appendix B.2, while the consequences of flooding is higher than for a normal urban setting.

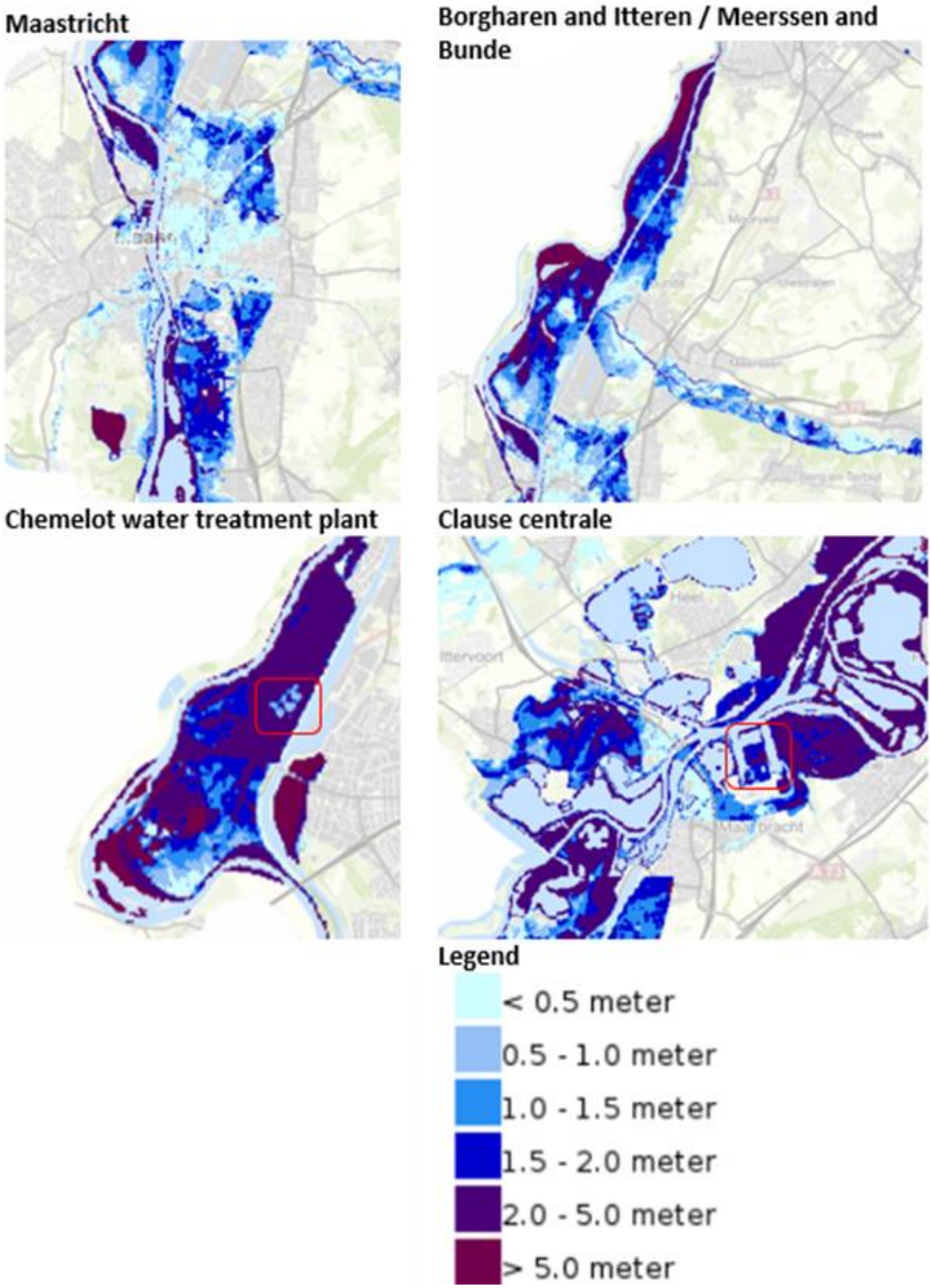

Figure 45: Maps of probability of flooding with their corresponding water depths.

In Figure 45 maps for the probability of flooding is created for the city of Maastricht, the villages of Borgharen, Itteren, Meerssen and Bunde, the important industrial areas of Chemelot's water treatment plant and the Clause Centrale. The top right shows that larger parts of the city of Maastricht are vulnerable to flooding. The top left map shows that the Juliana Canal is a barrier between the main channel and the villages of Meerssen and Bunde. The villages of Borgharen and Itteren at the least prone areas of flooding between the Juliana Canal and the main channel bordering the Belgium side as shown with their lighter coloring. The maps of the Chemelot's water treatment plant and the Clause centrale are better identified by the red box surrounding the location. The map shows that if a flooding occurred the water treatment plant would be inundated between 2.0-5.0 meter. However the basins where the wastewater is treated will only be inundated between 0.5 – 1.0 meter, because the basins are built on a platform. The clause centrale is located next to the Meuse at Maasbracht and it would be inundated between 1.5 – 5.0 meter.

6

Discussion and conclusions

6.1 Discussion

The inundation maps of 1993 and 1995 include the flooded areas in Belgium, while the inundation maps of 2021 only show the flooded areas in the Netherlands. Some of the Belgium measures are important for the total flood safety of the regions. Especially, the newly created high-water channel at Kotem is one of the most important measures taken. However, the inundation maps only show the inundation areas in the Netherlands. For example it could be possible that certain inlet of high-water channels or retention areas were too high in Belgium, it would not be possible to verify this with this inundation map. It is difficult to determine how effective the measurement was in reality. Therefore, the flood inundation map of 2021 gives an incomplete picture.

The discharge measurements of the tributaries, the Geul and the Roer, are estimates. The measurement stations Hommerich and Eyserbeek in the catchment areas of the Geul and Hambeek in the Roer tributaries have failed in the catchment area, because of the extreme discharge. The difference in the discharge of the Roer within the range of 270 or 305 is significant for a small tributary. Because the Hambeek measurement station is at the confluence point it makes it difficult to reconstruct the confluence point with corresponding problem areas accurately. Therefore the range of uncertainty for the discharge at the Roer is larger than the Geul. It is important to assess the location and the type of measurement equipment for each of the measurement stations, because several failed, which made accurate prediction of the water levels difficult.

The number of measurement stations and the locations to measure the water level in 1993, 1995 and 2021 changed. In 1993 and 1995, there were 23 measurement stations to register the water level. The water levels at the measurement station differ between the different flood events. Six of the stations (Linne beneden, Roermond boven, Kessel, Belfeld beneden, Arcen and Gennep) only measured every eight hours in 1993 and 1995. In July 2021 the measurements were taken every 10 minutes for all the measurement stations. Five stations (Elsloo, Roermond boven, Belfeld beneden, Venlo and Sambeek beneden) have been relocated to a maximum of 700 m. Three measurement stations were relocated more than 700 m. The measurement station at Dilsen Stokkem was dismantled, and a new measurement location was established at Rotem Maas 900 m further downstream. The measurement station the Spaanjerd was created after 1995, and the location at Stevensweert 1.2 km downstream was dismantled. The measurement station at Neer was created after 1995, and the location at Kessel 3.8 km downstream was dismantled. Further seven measurement locations (Uikhoven, Eisden Mazengove, Meeswijk veer, Negenoord-Oost, Herenlaak and Buggenum) were added along the river after 1995. The measurement station Arcen was also dismantled, but no measurement station is built to replaced it. These differences in measurement locations and the measurement frequency make a skewed image of the water level difference between the different flood events.

The assumption was made that the average water depth is 7.5 m in the main channel as in the calculation model Zwendl. In this thesis the assumption is made that no sedimentation occurred, except at the river bend next to Maaseik. However, the sedimentation can occur after completing the room for the river projects, as explained by Meijer and Agtersloot in the report Evaluation of the Grensmaas. Furthermore, sedimentation can occur to restore the equilibrium after dredging works. For example, the deepening of the main channel with two meters at Maastricht is an important measure. If sedimentation has occurred at

Maastricht before the flood of 2021, the estimated maximum drop of 80 cm in the water level will be reduced.

In the siphon by Bunde, a lot of debris was found after the flood event. It was not clear if the siphon was clear before the flood or when debris started blocking the siphon, resulting in a reduction of the discharge capacity. This was not the only place where water transported debris. Debris has been transported in the whole river system due to the flooding upstream. Calculating with the debris itself was outside of the scope of this research.

Box of Building Blocks is a simplistic program to illustrate the measures along the river section. The reality is simplified in a calculation model such as the box of building blocks, where assumptions are made and rules of thumb are used. The tool is designed to simulate the flood wave as a kinematic wave in the box of building blocks model. A kinematic wave correctly represents only the upstream measures. After Roermond, the character of the flood will dissipate and resembles to a dissipative wave. All the measures were simulated with at least one probability of exceedance, namely 1/250 with a corresponding discharge of 3800 m^3/s and several times also with the probability of exceedance of 1/1250 with a discharge of 4600 m^3/s. It was also simulated with one shape of the flood wave. The simulated flood waves were designed with an average width, the most common occurring shape. This however differs with the flood wave of 2021. A few set of combined measures have been simulated as one measure in the model. However, combining measures manually in the model will simply be added to the programmed results of each measure. It will not consider the effect the measure have on each other.

6.2 Conclusions

The main objective is to understand the effects of the shape of the flood wave during a high-discharge event and to understand the impact of the different types of flood protection along the river. The main research question of this study will be answered in this section:

What are the hydrodynamic differences between the high-waters on the Meuse in Limburg in 1993, 1995, and 2021, and how can these differences be explained?

The flood event of 2021 happened in July, therefore the amount of water already in the river system, before the heavy rainfall in the southern part of the Netherlands, Ahr-Eifel region in Germany, Luxemburg and Eastern part of Belgium, was only approximately 200 m^3/s instead of the 600-700 m^3/s in 1993 and 1995. This means that there was a large buffer, before the water level increased to dangerous levels.

The short duration of the flood event in 2021 compared to 1993 and 1995 the role of peak attenuation was bigger. The flood routing-measures have clearly helped to increase this effectivity due to the fact that more water could be stored in floodplains, high-water channels and retention areas.

The Maasplassen remained largely unchanged since 1995, while the largest effect of peak attenuation occurs at the Maasplassen if the duration of the flood event is relatively small as in 2021. Therefore the duration of the flood events play a significant part in the flood safety further downstream.

For this event it can be concluded that the duration of the flood event in combination with the already executed flood-routing measures have prevented further flooding.

This research question will be answered further by providing answers to the following sub-questions.

What are the similarities and differences between the hydrodynamics on the floods in 1993, 1995, and 2021?

The shape of the flood wave differs between 1993, 1995, and 2021. The most significant difference is the duration of the flood wave. The short period of heavy rainfall in Euregio Meuse-Rhine in July 2021 created the steep flood wave with a short duration. The duration of the flood wave in 2021 was only 2.5 days compared to the six days in 1993, and 11 days in 1995 which is at least double the duration. In 1993, the heavy rainfall over nine days combined with the melting snow in the Ardennes created the obtuse flood wave. In 1995, heavy rain occurred in the Ardennes for eighteen days with combined average precipitation of 200 mm.

Another difference is that the floods in 1993 and 1995 occurred in the winter, meaning there was already a higher discharge from precipitation before the additional heavy rainfall resulted in a flood event. While the flood of 2021 happened in the summer when the discharge previous to the flood event was only approximately 200 m^3/s.

Furthermore, the tributaries of the river Meuse in the Netherlands were only flooded in 2021. For the Dutch province of Limburg, flooding occurred with the estimated value in the Geul of 100 m^3/s and the Roer of 270 - 305 m^3/s (along the Hambeek) in 2021.

What impact did the protective and flood routing measures have on the behaviour of the flood?

New dikes were constructed in 1995 and 1996 and have protected the inhabited areas against flooding. The flooded areas in 1993 and/or 1995 along the Meuse remained dry in 2021. However, the dikes also created a reduction of the flood plains of the river by 40% in 1996. This led to a high water level compared to 1995 because of a decrease in conveyance width.

The flood routing measures have restored parts of the old flood plains, which were lost due to the construction of the new dikes. Furthermore, the flood routing measures have helped to increase the effect of peak attenuation to decrease the peak discharge. High-water channels is one of the most important flood routing measures, because it takes up a lot of water in a flood event. However, a problem may occur whenever a channel meets the main river again if the water level is still high. Because suddenly the water discharge becomes higher again. This is one of the most important flood routing measures because it will only be used in a flood event. Climate change will lead to a higher chance of droughts in summer. This type of flood routing measure does not reduce the water level in the drought further. The same reasoning can be applied to a retention basin.

What are the bottlenecks in the Limburg part of the Meuse River?

The first bottleneck from the Belgian border is the city of Maastricht, since there is only one channel without the presence of flood plains, while flood plains were presented upstream of Maastricht. The reduction in the total width of the cross section from approximately 800 m till 150 m and even with the main channel deepened by 2 meters, this will result in high water levels, as can be seen in July of 2021. It is important to continue to maintain the water depth by dredging the main channel every few years.

The second bottleneck is at Roosteren-Maaseik, the river makes a sharp turn at the bend with urban areas on both sides, which reduces the possibilities for Room for the river projects. Here the peak discharge is significantly higher than the upstream measurement stations showed. Furthermore, the dike section at the Dutch side are not built streamlined to the river, but makes a 90° angle. This causes turbulence in the inner curve, due to the circulation zone that is formed just behind the 90° corner. This circulation zone will cause a mixing layer, which leads to more turbulence and a decrease in flow velocity. The reduction in flow velocity will cause a back flow upstream. Streamlining dike section 84 will reduce the turbulence in the river and will increase the discharge capacity in the bend.

The third bottleneck is at Linne/Herten, the village of Herten is located further into the flood plains as the other towns and villages on both sides of the Meuse. Because it is located in the floodplain dikes have been built to protect the inhabitants, resulting in a dike being extended far into the floodplain. This results in a width reduction from approximately 3 km to 1 km of the floodplain compared to the situation in 1993, which reduces the discharge capacity of the cross section and creates a backflow. The Lateral Canal Linne-Buggenum and the village of Herten on the right leaves not a lot of room for extra flood-routing measures.

What protective measures have the largest impact?

The up-to-date dike sections on the Meuse river have protected urban areas against flooding, some dike sections were still planned to reinforced these some inundation occurred. Even though the Room for the river projects are important and reduce the flood risk. The reason that no flooding has occurred on the protected areas is because it is protected with dikes. Therefore dikes will have a large impact on the flood safety.

Deepening the main channel by another two meters from 2.6 to 15.3 rkm till the weir at Borgharen will be an effective measure, because it reduces the bottleneck at Maastricht. This will reduce the backwater flow created by the narrow channel through the city centre of Maastricht. The maximum drop in water level is estimated 110 cm for a discharge of 3950 m^3/s with a conveyance capacity of 8743 m^2.

The maximum water level drop of the high-water channel (from 28 to 31 rkm) with a width of 500 m increases the conveyance width significantly with an increase to 14091.7 m^2. The measured effect at Kotem is a water level drop of 2.55 m for a discharge of 3950 m^3/s and it affects the water level at Borgharen, which is upstream from Kotem. The explanation for this significant effect is that a combination of measures has been taken. The dike has been relocated further from the main channel and a high-water channel is created parallel to the main channel. Furthermore the main channel makes a sharp turn without much room for the floodplains on the Dutch side. The river is located almost parallel to the Juliana canal, which is an excellent protection against high water. The Juliana Canal functions as a dike for the hinterland.

Ooijen and Wanssum is a large project, where an extra conveyance width of 14145.1 m^2 is created in three high-water channels to reduce the peak discharge. The project creates a maximum water level drop of 58 cm for a discharge of 3950 m^3/s and the effect is measurable upstream till Roermond, which is circa 30 km upstream. The measured effect of project Ooijen-Wanssum on the water levels was a reduction of 37 centimetres at Broekhuizen, 20 cm at Venlo and 5 cm at Roermond during the flood of 2021 (Kusters, 2021).

The high-water channel on the left side of the villages Borgharen and Itteren (from 15.5 to 22.5 rkm) has not been implemented. It was a suggested solution in Box of building blocks. This is an option that can be executed which will further decrease the bottleneck around Maastricht. The high-water channel is designed with a length of 3100 m and an average width of 200 m and a depth of 2 m, it will store circa 3838 m^3 of water for a 1/250 flood event. The dike rings 91 and 92 surrounding the villages already decreased the river's floodplains. By implementing the project, more of the natural floodplains will be restored. This will lead to a maximum water reduction with 0.5 m before Borgharen and a water level reduction of 0.1 m at Maastricht. To achieve the desired result the deepening of the main channel is a better solution to solve the bottleneck.

7

Recommendations

Meerssen and Bunde

The problem of Meerssen and Bunde is complex and needs to be further investigated. Pluvial flooding happens more often in Bunde and Meerssen because the towns are located in basically a polder. Water run-off of the surrounding areas flow to the deepest point. Previous the town has already dealt with water drainage problems. As a result, drainage pumps were installed in the area. However, during the flood, the pumps failed. Furthermore, the desired capacity of the siphon under the Juliana Canal should be investigated.

Maaseik

More research has to be done on the Bottleneck at Maaseik. The Flemish traffic minister has already commissioned an investigation to design and possibly relocate a new bridge between Maaseik and Roosteren. Furthermore, the shape and the number of pillars in river bed can reduce the amount of turbulence.

As previously discussed, sedimentation occurred in the river bend between Roosteren and Maaseik. It would be interesting to simulate the impact of the sedimentation that was deposited before the flood occurred. A 3D model simulation can be made for the specific river bend. For sedimentation two scenarios can be made: first the current scenario, where the sedimentation was still deposited in the river bed and the other scenario is, where the extra sedimentation was dredged before the flood of 2021 as shown in Table 7.

Table 7: Scenarios for the river bend at Roosteren - Maaseik

		Sedimentation	
		Current	Dredged
Relocation dike	Current	Scenario current	Scenario dredged
	New curved dikes section	Scenario dike section	Scenario combination

Furthermore an option to investigate is a possible relocation of a part of the dike section 83-1 to flow more naturally along the main channel. It would mean that farmers field has to be reduced. Here similarly also two scenarios can be simulated, the current situation and a situation with a newly designed dike section. In total four scenarios can be simulated: a scenario of the current situation, a scenario where the extra sedimentation is removed, a scenario where the dike section is relocated and a combination scenario where the sedimentation is removed and the dike section is relocated.

Summer/winter

The difference in bottom friction in the summer and winter is briefly discussed in the report. However, in the scope limitations the research can go in two different directions, namely difference in the damage between the two seasons or to investigate the effect of the increased drag coefficient on the propagation of the flood wave. For both an assessment need to be made for the different land use in the floodplains of the River Meuse. Not only vegetation was present in the floodplain when the flood occurred. For example also campsites are located in the floodplains. The report: 'Extreme hoogwaters in de zomer' written by E.H. van Velzen and P. Jesse in 2005, can be used as the beginning of the literature review. In this report the different vegetation characteristics are described for the winter and summer with their corresponding drag coefficient.

Furthermore the land use of the future can be taken into account. Maybe, the province of Limburg made plans/predictions of the landscape in 2050 (concerning climate change).

The measurement station Arcen

In 2021 there was no measurement station in Arcen, however previously in 1993 and 1995 there was a measurement station. Even though it only measured the water levels every eight hours in both years. Furthermore, without the measurement station at Arcen the distance between Venlo and Well Dorp is 24.6 km which is the largest distance between two measurement stations. The measurement station at Arcen would give a good estimation of the effect of the project Ooijen-Wanssum upstream. But without a measurement station directly upstream of the project the maximum water level reduction is more difficult to measure. My recommendation is to build a new measurement station downstream of Broekhuizen for example Arcen.

Dike reinforcement vs flood routing measures

More research needs to be done on the difference between the dikes built along the river and flood-routing measures. It would be interesting to see the difference between the different levels for example:

- Scenario 1: where there were no flood routing measures done and since 1995 only dikes were built.
- Scenario 2: no dikes where built only flood routing measures.
- Scenario 3: the current scenario
- Scenario 4: dikes were built and only the most important flood routing measures

For this research a 3D model has to be made for the whole river section and separate modules for all the different measures that have been implemented have to be made that can be implemented and removed from the model. Then the effect of each of the measures and combinations of measures can be investigated.

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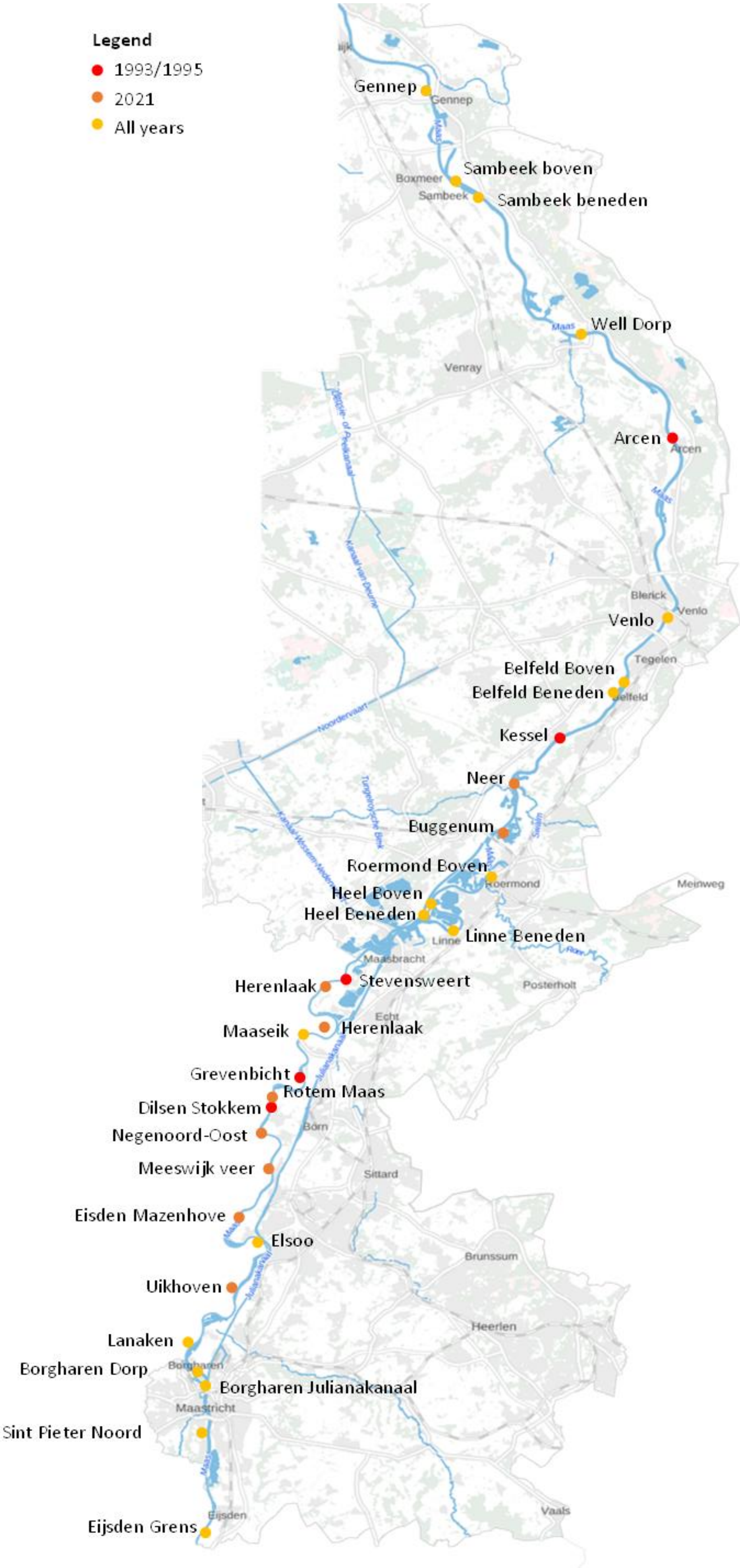
Appendix A - Maximum water heights

The maximum water levels in the Dutch river Meuse (ENW, 2021)

Rkm	Name	HW1993	HW1995	HW2021
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	Borgharen Dorp	45.9	45.71	45.23
18.3	Lanaken	44.97	44.79	44.56
24.8	Uikhoven			42.61
29.3[1]	Elsoo	40.5	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	Rotem Maas			32.42
44.9	Grevenbicht	32.8	32.73	
52.7	Maaseik	29.5	29.44	30.17
55	Herenlaak			27.01
60.4	Spaanjerd			25.14
61.6	Stevensweert	25.36	25.3	
67.9	Heel boven	22.81	22.69	22.78
70.3	Linne beneden[2]	21.05	21.08	21.88
79.7[1]	Roermond boven[2]	20.6	20.79	20.68
80.3	Heel beneden	20.53	20.59	20.49
85.8	Buggenum			20.3
90.1	Neer			20.1
94.9	Kessel	19.66	19.74	
100.7	Belfeld boven	19.13	19.16	18.89
102.7[1]	Belfeld beneden[2]	19	19.04	18.45
107.5[1]	Venlo	18.35	18.46	18.01
120.5	Arcen[2]	15.8	16.93	
132.1	Well dorp	15.34	15.43	15.48
144.9	Sambeek boven	13.9	14.02	13.77
147.7[1]	Sambeek beneden	13.72	13.92	13.33
155.1	Gennep[2]	12.95	13.22	12.34
165.8	Mook			10.78

[1] These measurement stations were relocated a maximum of 700 m between 1993 and 2021

[2] These measurement stations were measured only every eight hours during the high-waters of 1993 and 1995


Legend
1993/1995
2021
All years
Gennep
Sambeek boven
Sambeek beneden
Well Dorp
Arcen
Venlo
Belfeld Boven
Belfeld Beneden
Kessel
Neer
Buggenum
Roermond Boven
Heel Boven
Heel Beneden
Linne Beneden
Herenlaak
Stevensweert
Maaseik
Herenlaak
Grevenbicht
Rotem Maas
Dilsen Stokkem
Negenoord-Oost
Meeswijk veer
Eisden Mazenhove
Elsoo
Uikhoven
Lanaken
Borgharen Dorp
Borgharen Julianakanaal
Sint Pieter Noord
Eijsden Grens

Appendix B- Dike sections

B.1 Dike reinforcement (RWS, 2021)

Location	Length (km)	Year completion
Maastricht	4365	2015
Geulle aan de Maas	3060	2016
Meers - Maasband	3515	2017
Urmond	325	2020
Grevenbicht - Roosteren	4430	2018
Aasterberg	635	2016
Ohé en Laak - Stevensweert	7165	2018
Brachterbeek	1240	2016
Merum	360	2016
Neer	2425	2020
Gelissensingel Venlo	400	2013
Grubbenvorst	850	2019
Lottum	1130	2019
Bergen - Aijen	6620	2019
Afferden	3130	2020
Milsbeek	900	2020
Ven-Zelderheide	150	2020
Mook	1825	2019
Total	42525	

B.2 All dike sections

Dike section no.	Name	Probability of exceedance/year (MVW, 2018)
54	Mook Ottersum	1/300
55	Gennep - Heijen	1/300
56	Afferden	1/300
57	Nieuwe Bergen	1/300
58	Groeningen	1/300
59	Aijen – Bergen	1/300
60	Well	1/300
61	Wanssum-West	1/300
62	Wanssum-east	1/300
63	Ooijen	1/300
64	Broekhuizenvorst	1/300
65	Arcen	1/300
66	Lottum	1/300
67	Grubbenvorst	1/300
68-1	Venlo-Velden	1/1000
86-2		1/300
69	Blerick	1/1000
70	Baarlo	1/300
71	Belfeld	1/300
72	Kessel	1/300
73	Beesel	1/300
74	Neer	1/300
75	Buggenum	1/300
76	Roermond	1/300
76a	Roermond Het Ham	1/300
77	Merum Roermond- Hambeek	1/300
78	Heel	1/300
79	Thorn – Wessem	1/300
80	Clauscentrale	1/300
81	Ohé and Laak – Stevensweert	1/300
82	Aasterberg	1/300
83	Visserweert	1/300
84	Nattenhoven-Roosteren	1/300
85	Urmond	1/300
86	Maasband	1/300
87	Meers	1/1000
88	Geulle aan de Maas	1/300
89	Voulames	1/300
90	Maastricht Oost	1/3000
91	Itteren	1/300
92	Borgharen	1/300
93	Maastricht NW	1/1000
94	St. Pieter	1/300
95	Eijsden	1/300

Appendix C- Global overview of all the measures

The analyses of the flood extent between the flood events of 1993, 1995 and 2021 will be described in this chapter. Inundation maps of each flood event is mapped, they are used to illustrate the differences in the inundated areas. In Figure 46 the left graph with the green marking is the flooded area in 1993, the middle graph is the flooded area in 1995 and the right graph of 2021. The analyses is described from upstream till downstream.

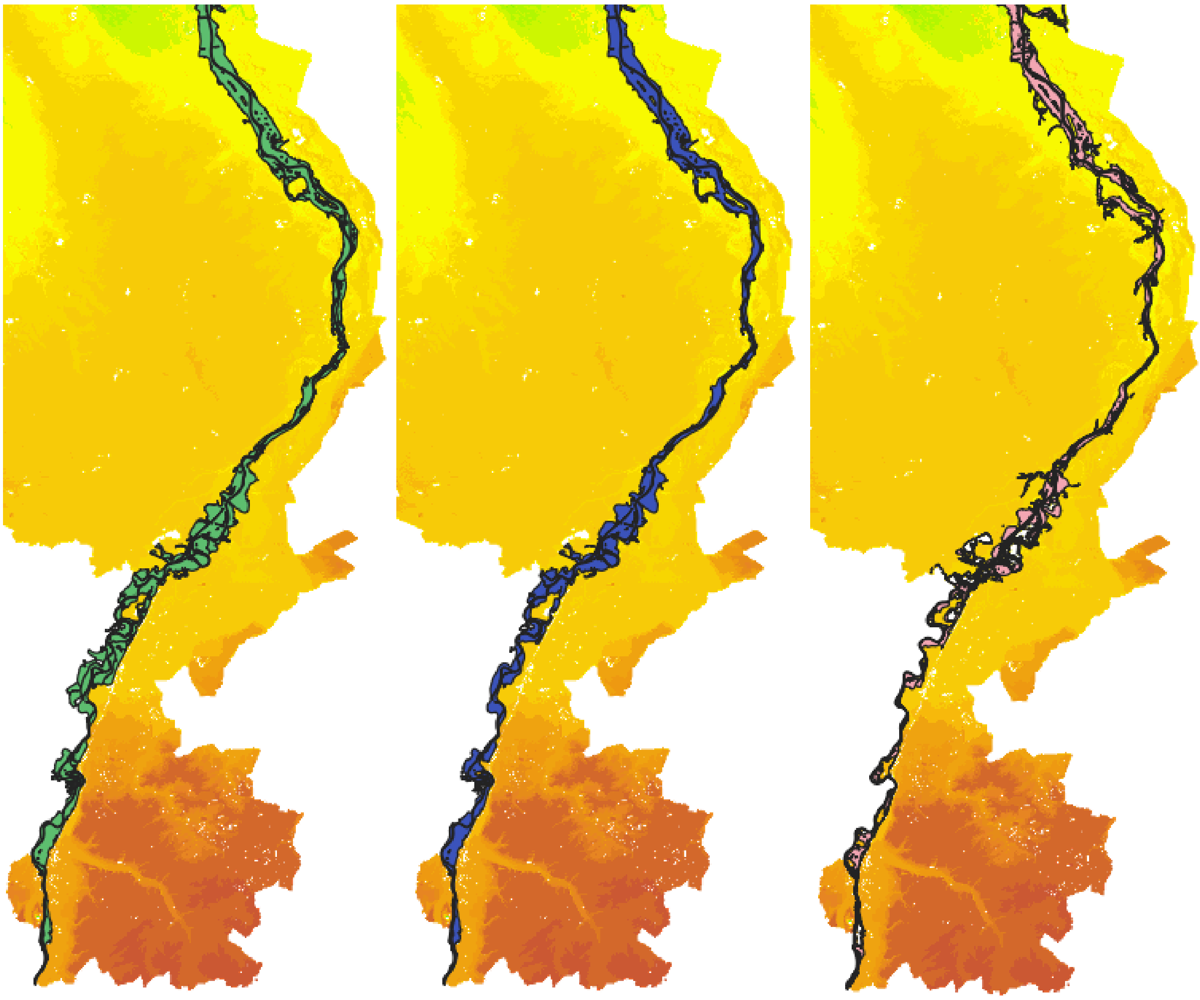


Figure 46: The inundation areas of the River Meuse in the Limburg section

The research is divided into the following sections (Asselman, Barneveld, Klijn, & van Winden, 2019):

- Bovenmaas, from Eijsden till Borgharen (0.0 – 15.3 rkm): in the hilly southern part of Limburg the Maas cuts itself deeply in the landscape and left terraces which are up to 150 meters higher than the current river. The river flows here over hard marl soil, which is highly resistant to erosion. Around the urban cores dikes are built after the flood of 1995.
- Grensmaas/Gemeenschappelijke Maas, from Borgharen till Thorn (15.3 – 55.5 rkm), is the most natural part of the Meuse River in the Netherlands. The water flows freely, there are rapids, shallows and gravel banks and wide floodplains. The river bed consists of gravel and sand, often covered by plaster layers of coarse gravel. Water depths and flow rates can fluctuate greatly. Shipping follows the adjacent Juliana Canal. On the Dutch side there are only dikes around the cores. While, on the Flemish side, the route is completely embanked.
- Plassenmaas, from Thorn till Roermond (55.5 - 87 rkm), flows into the Roer Valley. From this point on, the slope of the river becomes noticeably smoother. In the past, the Meuse deposited thick

packages of coarse sand and gravel here. The river flows through large meanders in a wide valley. Large puddles have been created by gravel extraction. The puddles have a damping effect on high water peaks. Commercial shipping follows the Lateral Canal. There are two weirs in the Plassenmaas, near Linne and Roermond. Several streams flow into the Meuse in this section. There are dikes around the urban cores.

- Peelhorstmaas from Roermond till Aastbroek (87 – 121 rkm) is a narrow valley without a separate shipping canal. The shipping will go through this narrow section. There is a weir at Belfeld to control the water level.
- Venloslenk Aastbroek till Mook (121 – 164 rkm) allows the river width to widen again. Up to tens of meters above the river are old river terraces. Where the Meuse runs through the Venloslenk, thick parcels of gravel lie in the subsoil. In some places in this section very fine sand from the Miocene lies close to the river bed. There is one weir at Sambeek. There are dikes around the urban cores.

C.1 Bovenmaas

The first part also known as the ‘Bovenmaas’, is situated between the border with Belgium at Eijsden till Borgharen (rkm 0.0 – 15.3). The following measures have been taken (Wijbenga, 2021):

- Deepening of the main channel with 2 m till the weir at Borgharen
- Widening of the main channel with 12.5 m on each side from 1.8 rkm till 4.2 and from 5.5 rkm till 7.0.
- Lowering of the floodplain with an average lowering of 1 m over a width of 300 meters at the floodplain on the right side (1.5 – 3.5 rkm).
- High water channel Eijsden with an average width of 100 m and a depth of 2 m (2.2 – 4.6 rkm)

There is not a lot of difference between the different inundation areas. The main difference is where the Oost of Oost-Maarland is still visible in the right figure in the left figure the area is inundated. The newly inundated area is green space and is as described above a room widening project meant to overflow.

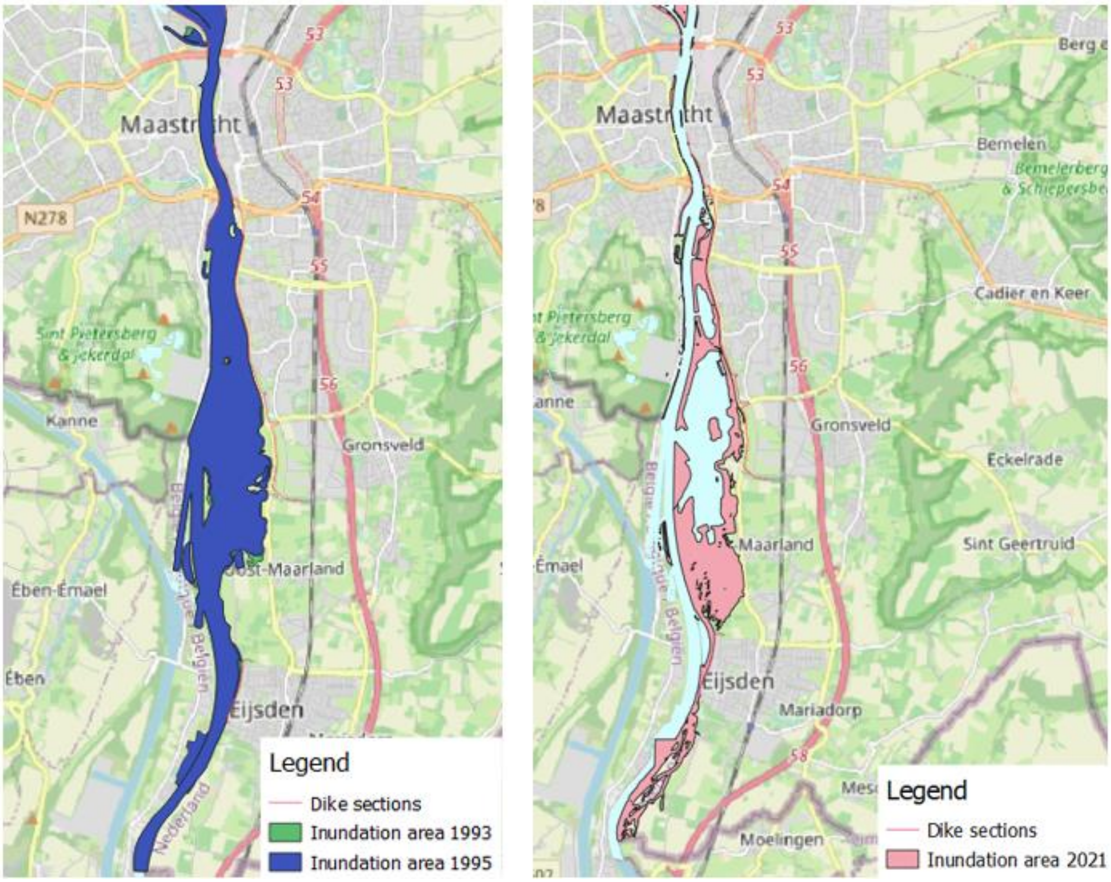


Figure 47: Inundation area of the Bovenmaas in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

C.2 Grensmaas

The Grensmaas is second part of the river from 15.3 till 55.5 rkm. The difficult part of the Grensmaas is shares a border with Belgium. Work has been done on both sites of the river and a certain amount of water is stored in secondary channels and inundation basins. Inundation maps of 1993 and 1995 the Belgium inundation areas are also included. However, this is not the case for the inundation maps for the 2021 as shown in Figure 48. This result is making a good comparison difficult. For example the high-water channel at Kotem, which was used in the flood event of 2021 is not shown in the left side Figure 48. Because of the many differences in the inundation maps of the different flood, the section Grensmaas is further divided as Borgharen and Itteren, Geulle aan de Maas, Meers and Maasband, Visserweert and Roosteren.

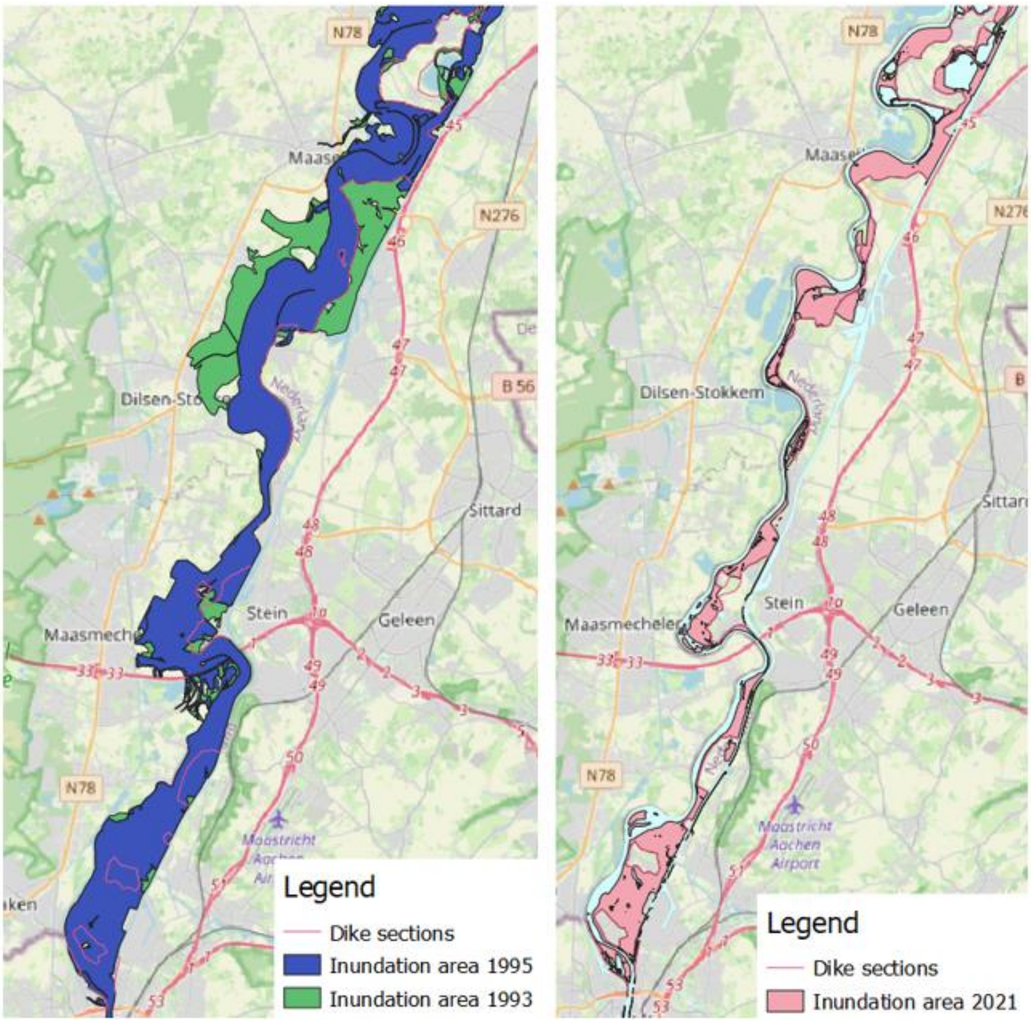


Figure 48: Inundation area of the Grensmaas in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

C.2.1 Maastricht

The city of Maastricht is a big city located around the Meuse and is a bottleneck when implementing preventive measures for flooding. Even though Maastricht has not been flooded in each of the three floods (see Figure 11 left side), all the water is pushed through the city centre, creating a risk. Currently, there is only one main channel without any flood plains (see Figure 49 right side).

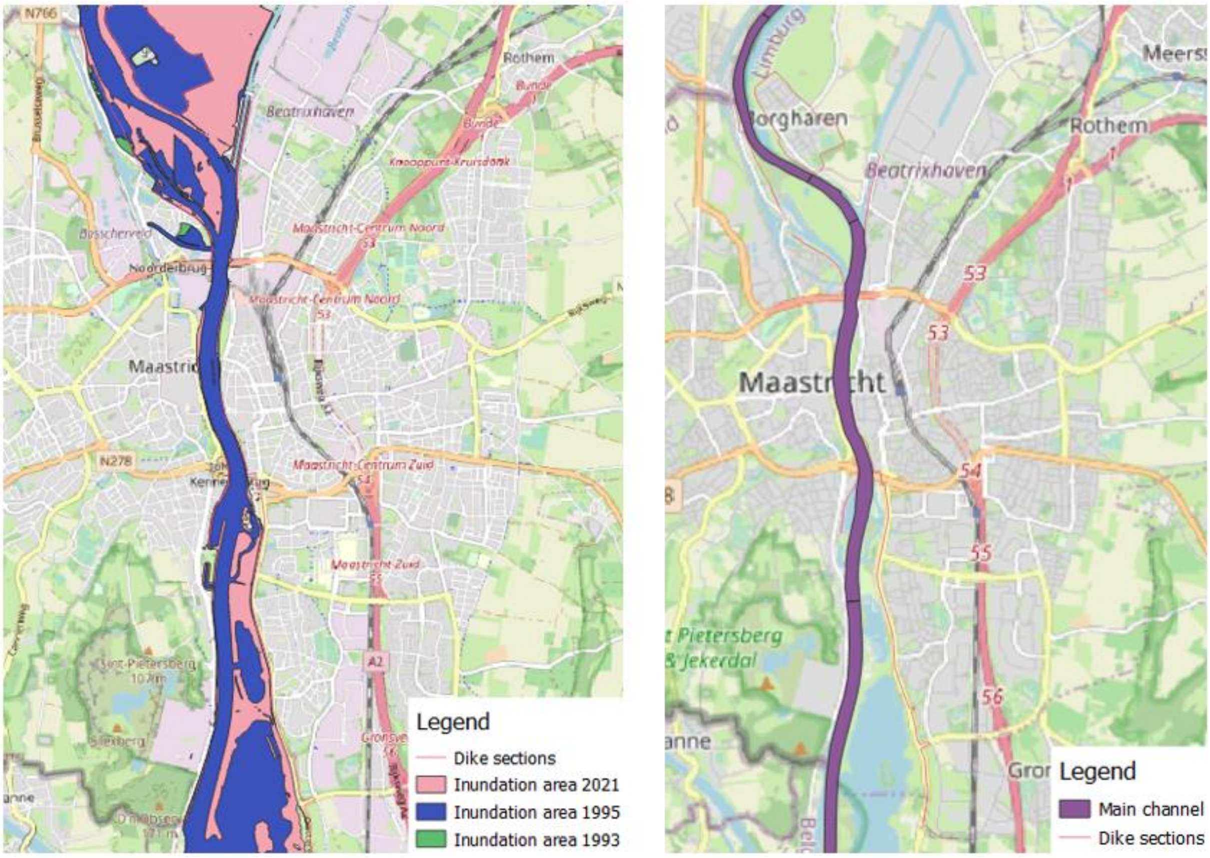


Figure 49: A map of Maastricht with the inundation areas of the different floods (left side) and with the dike sections and the main channel (right side)

Bosscherveld is one of three locations – next to Itteren and Borgharen – within the municipal boundaries of Maastricht where the Grensmaas project is being carried out. The island Bosscherveld in the Meuse is located North of Maastricht and will change into gravel after excavation. In times of high-water the area will be inundated.

C.2.2 Borgharen and Itteren

The villages of Borgharen and Itteren were inundated in 1993 and 1995 as shown on right side of Figure 50. Therefore, the following measures have taken place since the floods in area of Borgharen and Itteren (15.3 – 22.5 rkm) (Wijbenga, 2021):

- Dike rings have been built surrounding the villages Borgharen (dike ring 92) and Itteren (dike ring 91), which will lead to an increase in the water level in the River Meuse (see on the left side of Figure 50).
- Lowering of the floodplains, with a certain parts extraction of gravel.
- Widening of the main channel with 12.5 m on each side (22.5 – 55 rkm).
- At the village of Smeermaas at the Flemish side the floodplain was lowered with 2.5 m (Gielen, 2008).
- The nature area of Hochter Bampd has the floodplain lowered and the winter dike widened before the secondary channel. The secondary channel is widened (Gielen, 2008).

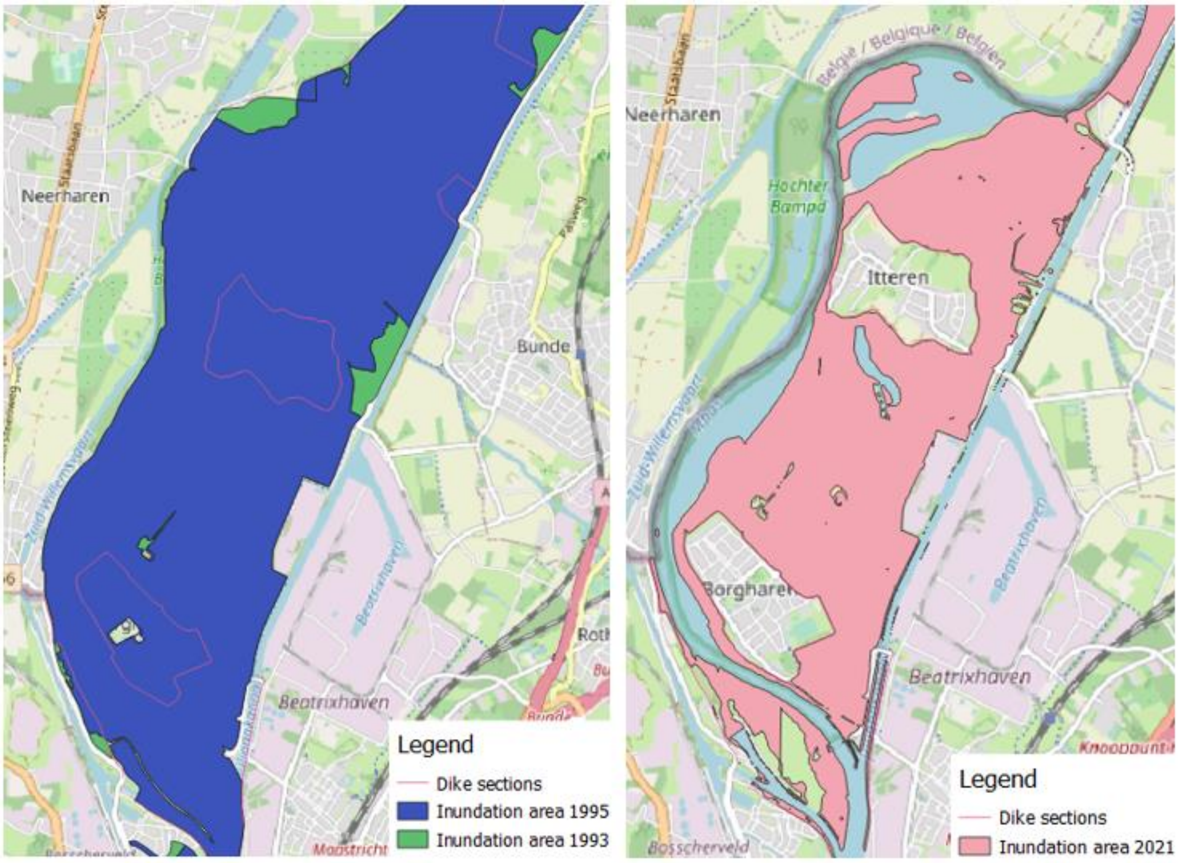


Figure 50: Inundation areas of Borgharen and Itteren in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

C.2.3 Bunde and Meerssen

The Geul is a right-bank tributary to the River Meuse, and the location of the confluence is at Bunde. It flows from the siphon at Bunde into the main channel. For modelling the discharge for the tributary the Geul at Meerssen the value 61 l/s/km^2 is used (Acima, Rura-Arnhem, 2018), while the observed discharge was 100 m^3/s. This means that the discharge capacity of the siphon was less than was needed. However, the local people were convinced that the maintenance of the siphon was less than desirable. There were no pictures taken before the flood event, so it is unclear if the siphon was working fully at the beginning of the flood event. In the end, there was a lot amount of debris (ENW, 2021).

The area of Bunde is the lowest point on the right side of the Juliana Canal. The Juliana Canal acts as a dike to protect Bunde and Meerssen from the Meuse River. This has created a (semi) natural polder. The water run-off of the surrounding area will flow into the polder and cause fluvial flooding to Bunde and Meerssen.

Furthermore, the peak of the Geul and the peak of the Meuse River arrived at Itteren almost simultaneously in 2021. This created a backflow in the Geul since it could not even discharge the maximum capacity of the siphon into the main river. Therefore, the water in the Geul overflowed its banks. However, due to the Juliana Canal, the water could not flow back into the Meuse, creating an issue for the inhabitants of Bunde and Meerssen, while it was supposed to be a protection. Therefore, the water couldn't be drained naturally. The area remained flooded for approximately a week.

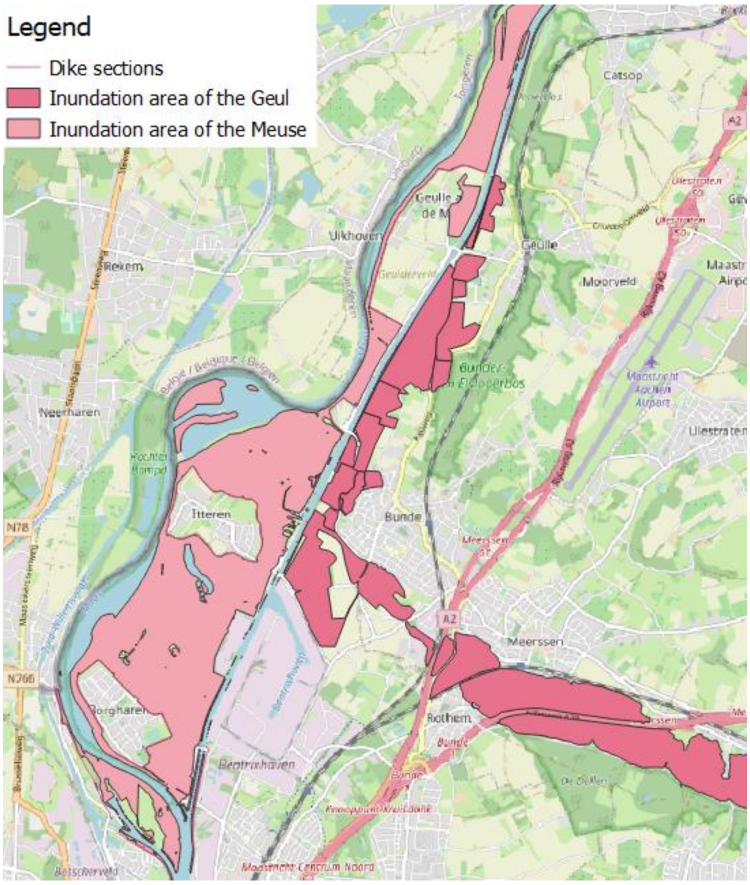


Figure 51: Inundation area of the Geul and the Meuse in July 2021

C.2.4 Geulle aan de Maas

The villages of Voulames and Geulle aan de Maas were inundated in 1993 and 1995 as shown on right side of Figure 52. Therefore, the following measures have taken place since the floods in area of Voulames and Geulle aan de Maas (22.5 – 26.8 rkm) (Wijbenga, 2021):

- Dike rings surrounding the municipality of Geulle aan de Maas (dike ring 88) and the village Voulames (dike ring 89), which will lead to an increase of the water level in the River Meuse (see on the left side of Figure 52).
- High-water channel is created in the Flemish side at Herbricht from 21 till 23 rkm (Gielen, 2008).
- Widening of the main channel on the right side with 80 m from the dike ring surrounding Geulle aan de Maas till Kotem.
- Improvement of the winter dike before the village of Uikhoven at the Flemish side (Gielen, 2008).

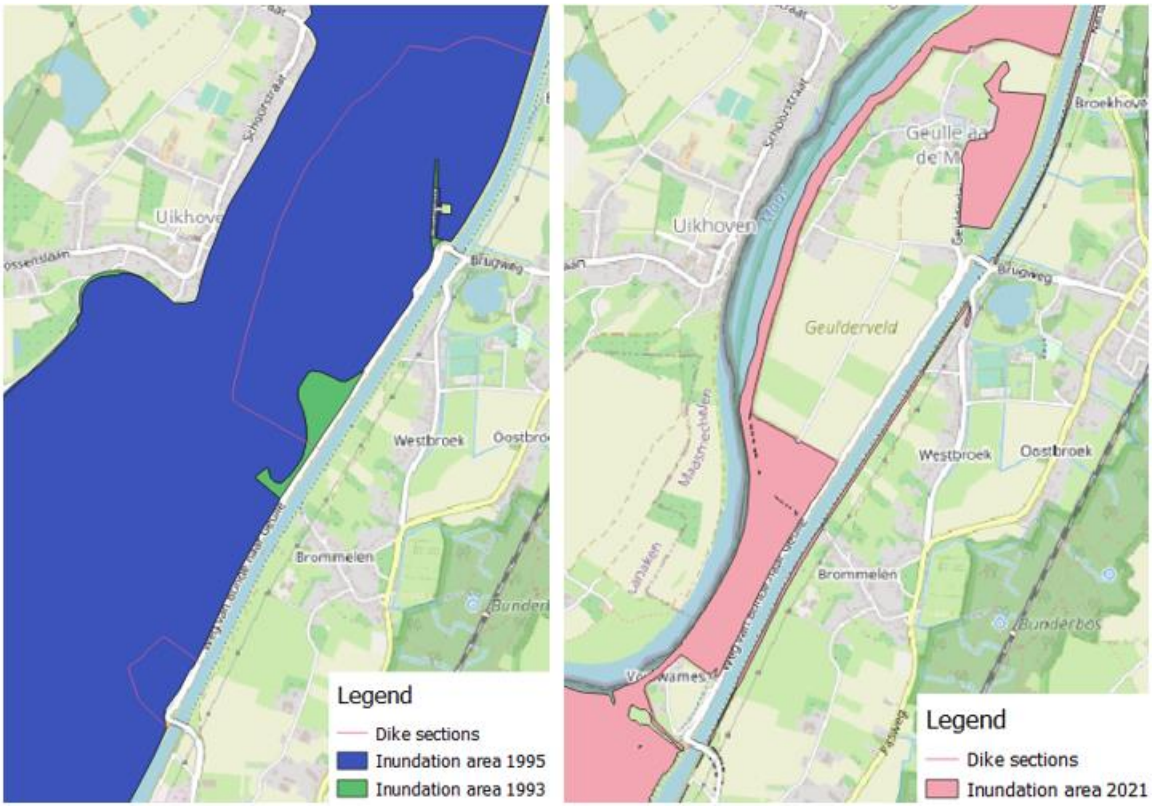


Figure 52: Inundation areas of Voulames and Geulle in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

C.2.5 Meers and Maasband

The municipalities of Meers and Maasband and of Chemelot were inundated in 1993 and 1995 as shown on right side of Figure 53. Therefore, the following measures have taken place since the floods in area of Meers and Maasband (30.3 – 36.3 rkm) (Wijbenga, 2021):

- Widening of the main channel on the right side.
- There is also a high water channel on the Flemish side of the order from Kotem till Meers (at the word Scharbergburg of the right graph). The high water channel at 28 till 31 rkm has a length of 1400 m and a width of 500 m with a surface area of 67.3 ha. This will have a large impact, because it reduces the bottleneck at the bend (MVW, 2002). Because of the high water channel three houses had to be demolished (Gielen, 2008).
- Dike ring 87 surrounding the village Meers, which will lead to an increase in the water level in the River Meuse (see on the left side of Figure 53).
- Between the dike ring 86 of Maasband and the WWTP (wastewater treatment plant) of Chemelot a secondary channel is created.

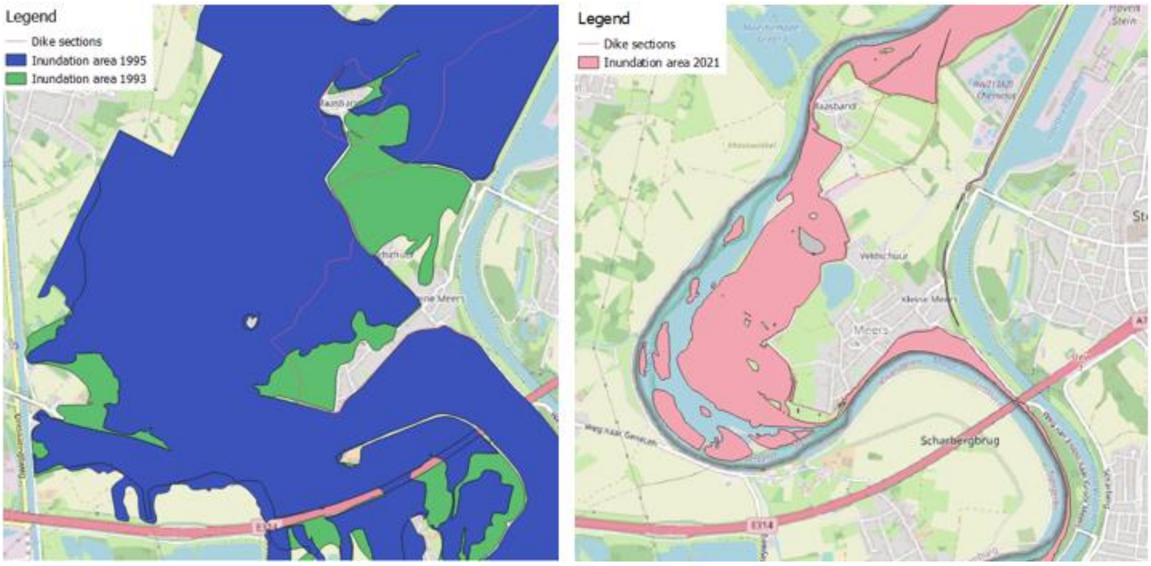


Figure 53: Inundation areas of Meers, Maasband and WWTP in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

C.2.6 Visserweert and Roosteren

The village of Visserweert was inundated in 1993 and 1995, while the villages of Ilkhoven and Roosteren were only inundated in 1993 as shown on right side of Figure 54. Therefore, the following measures have taken place since the floods in area of Ilkhoven, Visserweert and Roosteren (47.35 – 55.3 rkm) (Wijbenga, 2021):

- Creating a secondary channel on the right side of the village Visserweert with a lowering of the floodplains on each side (see on the left side of Figure 54).
- Lowering of the floodplain downstream of the village on the right side.
- Dike ring 83 surrounding the village Visserweert which will lead to an increase in the water level in the River Meuse.
- Dike section 84 from Ilkhoven till Roosteren, with a length of 3370 m (RWS, 2016), will lead to an increase in the water level in the River Meuse.

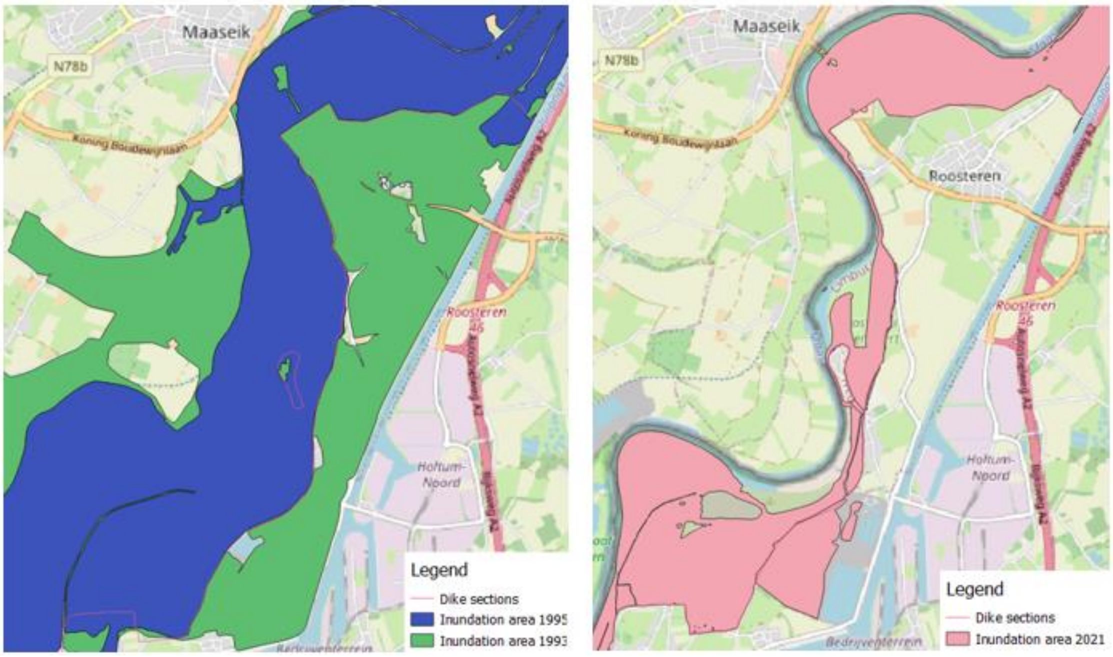


Figure 54: Inundation areas of Ilkhoven, Visserweert and Roosteren in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

C.2.7 Maaseik

The Flemish city of Maaseik is a big city located on the right side of the Meuse and is a bottleneck for implementing preventive measures for flooding. Even though the city of Maaseik has not been flooded in every floods event (see Figure 55 left side), all the water is pushed through the bend to the city, creating a risk. The bend near the town of Maaseik is very sharp. The dike section 83 was built to protect surrounding the town of Roosteren on the Dutch side. The village of Roosteren was inundated in 1993. The dike section has protected Roosteren from the flood of 2021. However, this dike section has significantly limited the flood plain on the river.

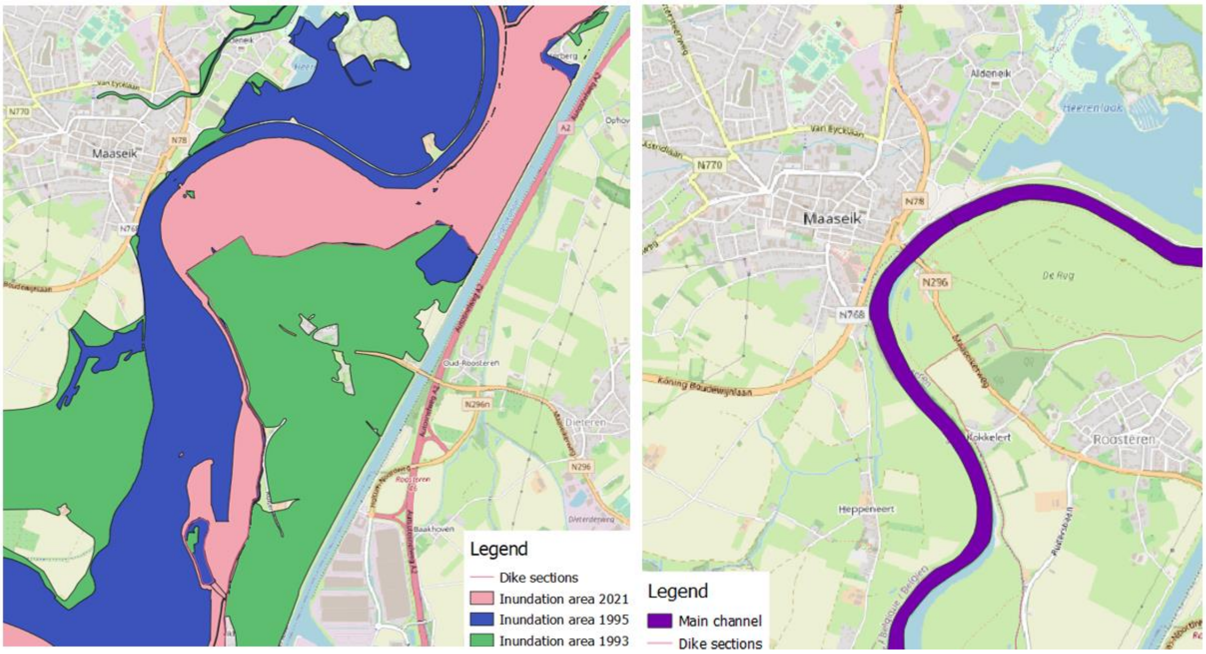


Figure 55: A map of Maaseik and Roosteren with the inundation areas of the different floods (left side) and with the dike sections and the main channel (right side)

C.3 Plassenmaas

The inundation areas of the Plassenmaas are very similar as shown in Figure 56. The dike section created since 1995 have created the biggest difference in the inundation areas.

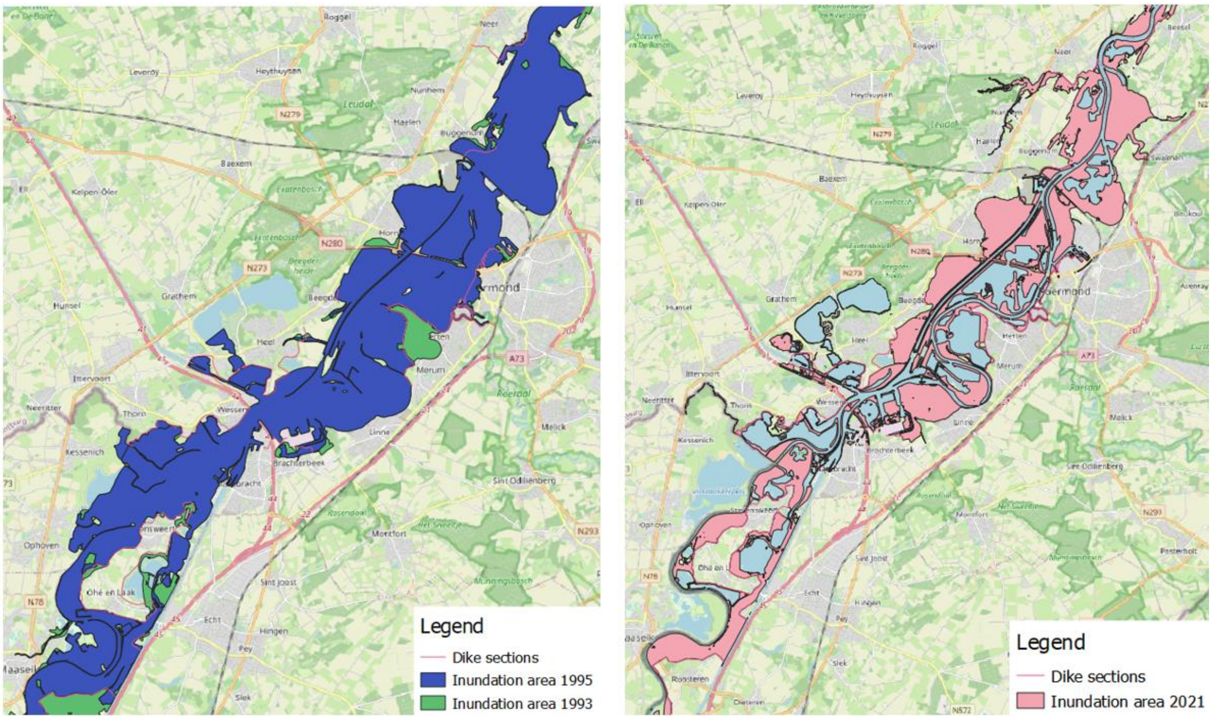


Figure 56: Inundation areas of the Plassenmaas in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

C.3.1 Stevensweert and Ohé en Laak

Stevensweert together with Ohé en Laak, are located on an island formed by two (former) arms of the river Meuse. This island is called the "Eiland in the Maas". The dike ring 81 with a length of 6385 m with a chance of exceedance of 1/250 years (RWS, 2016). Ohé en Laak and Stevensweert have not been inundated in 1993, 1995 and 2021 see Figure 57. A High-water channel Oude Maas (55.5 – 65.5 rkm) is created between Ohé-Laak and Maasbracht with an average width of 100 m and a depth of 2 m. The high-water channel flows out into the Stevolplas (Wijbenga, 2021).

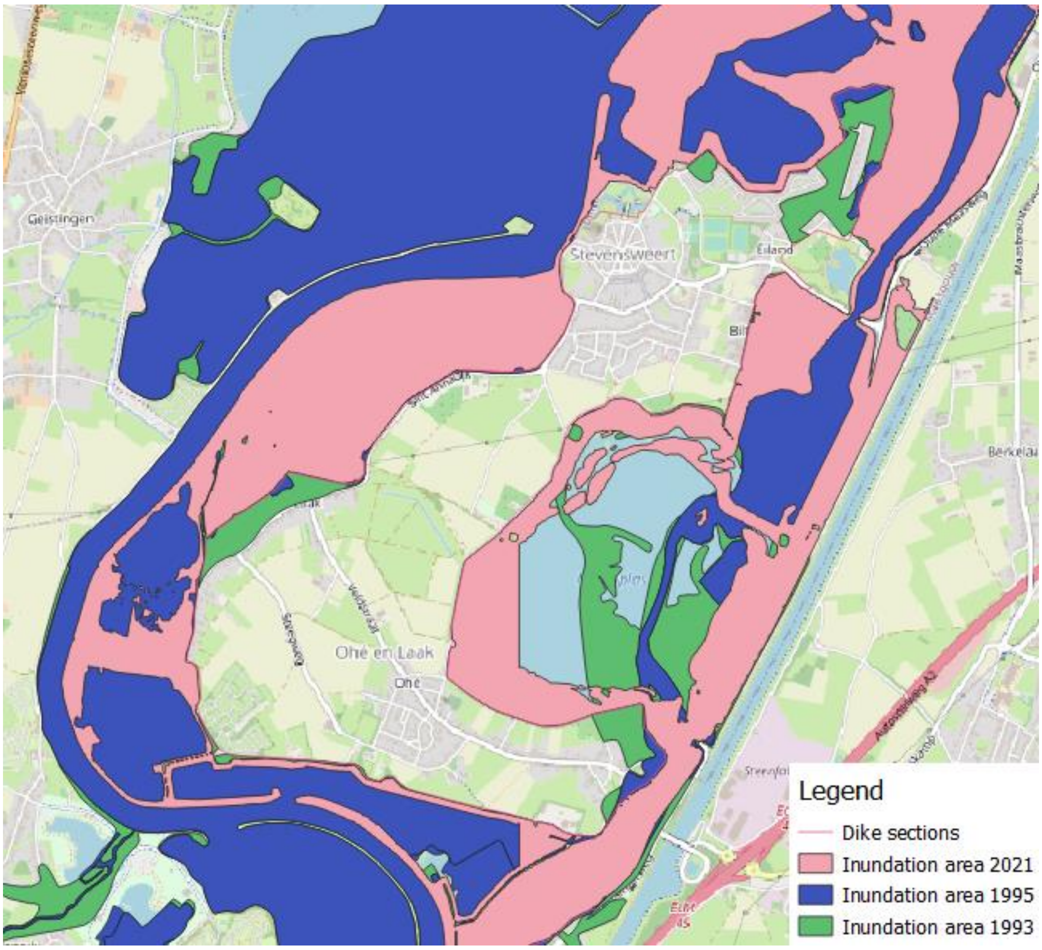


Figure 57: Inundation's areas of the floods in 1993, 1995 and 2021 with their dike ring 81

C.3.2 Roermond

Roermond lays only on the right side of the river (see Figure 17 right side). While the village Horn lies on the left side. The part of the Meuse near Roermond differs from Maastricht and Venlo due to the Maasplassen (see Figure 17 right side). The Maasplassen are artificial lakes created by mining gravel that was naturally deposited over the past centuries by the Meuse. The gravel extraction was phased out after 1990, although gravel is still being mined in a few places on a much smaller scale. A new purpose for the gravel holes was found in water recreation and with a bonus of retention areas. The Maasplassen are located in both Belgian and Dutch Limburg from Maaseik till Roermond, and their combined surface is approximately 30 km^2.

Since the Maasplassen can store part of the excess water, the height of the peak will be less in Roermond than Maastricht. Furthermore, the lakes for example Hatenboer lie between the Lateraalkanaal and the Meuse River. The discharge is split between the Lateraalkanaal and the river Meuse, connected to the Maasplassen. Therefore, it can be concluded that the city of Roermond is less of a bottleneck than Maastricht. However, small parts of a sub municipality of Roermond, Herten, was flooded in 1993 and 1995 (see Figure 17 left side) and a large part of Herten was flooded in 1993. After these floods, the dike sections were constructed to protect Herten. The dike sections have protected the inhabitants from the flood of July 2021, so this can be marked as a success (see Figure 17 right side).

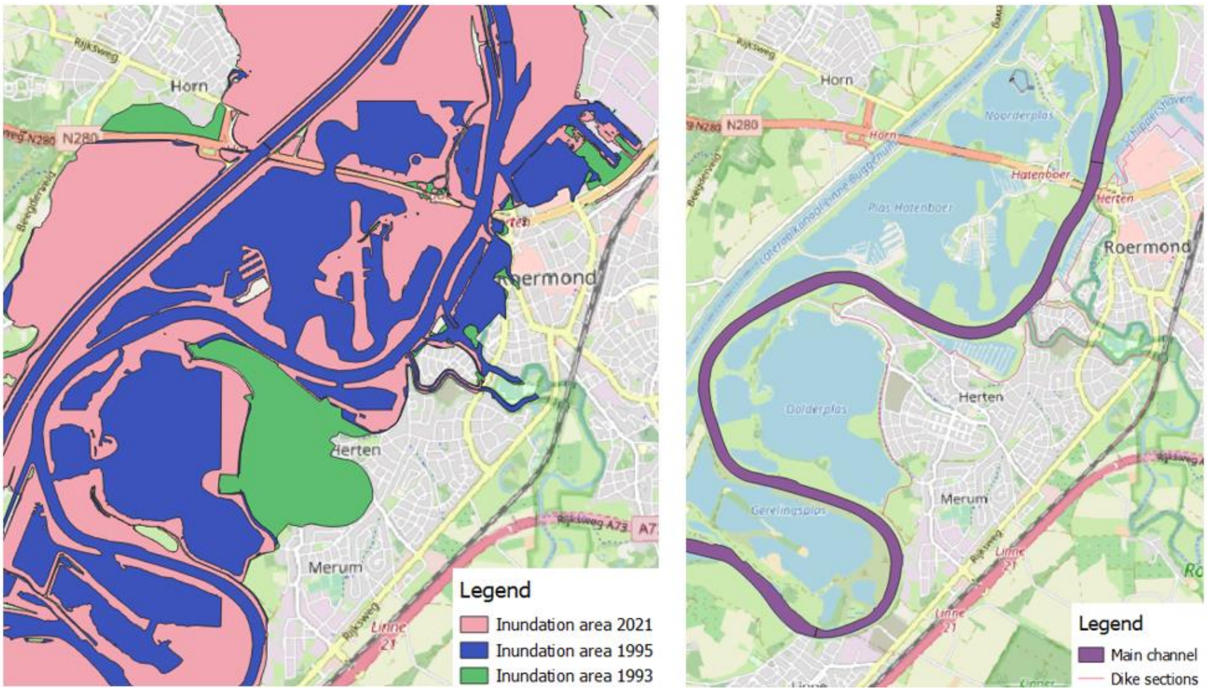


Figure 58: a map of Roermond with the inundation areas of the different floods (left side) and with the dike sections and the main channel (right side)

C.4 Peelhorstmaas

The river bed of Peelhorstmaas is very narrow, there is very little room for the water to flow as shown in Figure 59. The dike sections protected the urban areas in 2021.

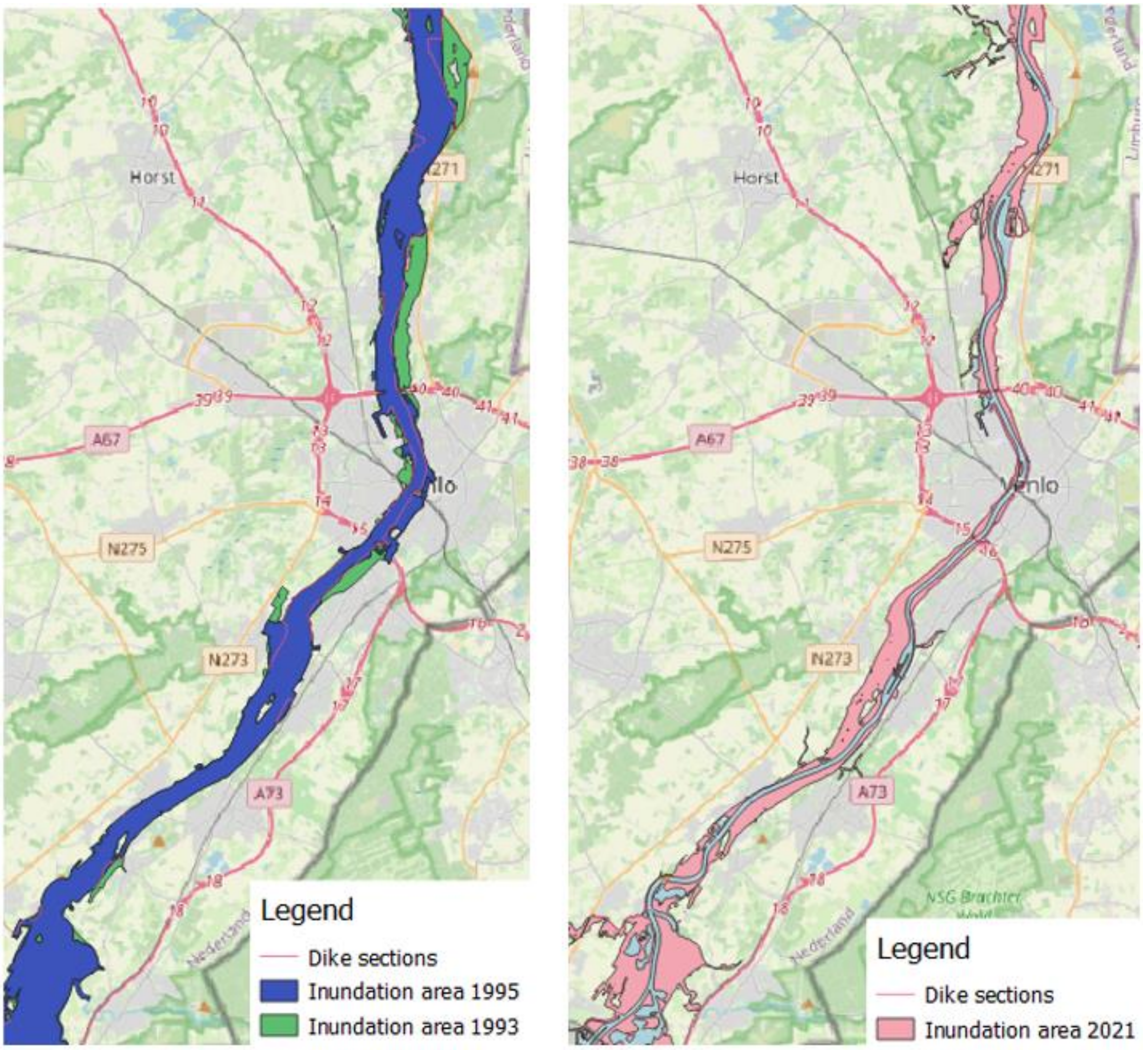


Figure 59: Inundation areas of the Peelhorstmaas in 1993 and 1995 with the future dike sections (right side) and inundation area of 2021 with their current dike sections (left side)

The city of Venlo was originally two cities on each side of the river (see Figure 20 right side), Blerick on the left side and Venlo on the right side. Nowadays, Blerick has become part of the municipality of Venlo.

Similarly to Maastricht, the city of Venlo was built surrounding the river, meaning there is not a lot of room for the river to flow. However, there is still a little room between the main channel and the dike sections, which can be used as a retention area.

The right shore of Venlo and the city Tegelen, which is located upstream of Venlo, were inundated in 1993 and 1995 (see Figure 60 left side). Following these events, dike sections were built on both sides of the river (see Figure 60 right side), and the following dike sections have protected the inhabitants from high water:

- Baarlo is protected by dike section 70.
- Blerick is protected by dike section 71.
- Steyl, Tegelen and Venlo are protected by dike section 68.

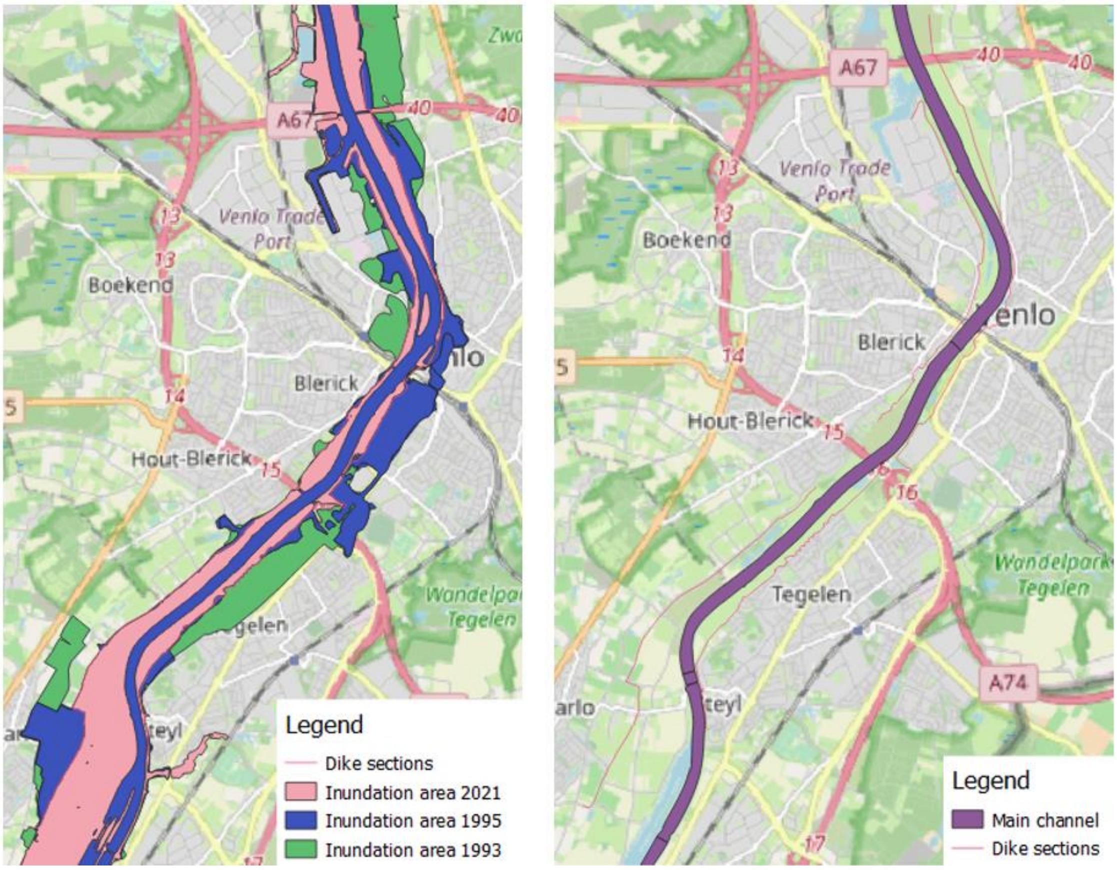


Figure 60: A map of Venlo with the inundation areas of the different floods (left side) and with the dike sections and the main channel (right side)

C.5 Venloslenkmaas

The inundation areas of the Venloslenkmaas are very similar as shown in Figure 61. The dike section created since 1995 have created a big difference in the inundation areas. The sections Ooijen Wanssum, Well – Aijen and Gennep are described in detail in the following sections.

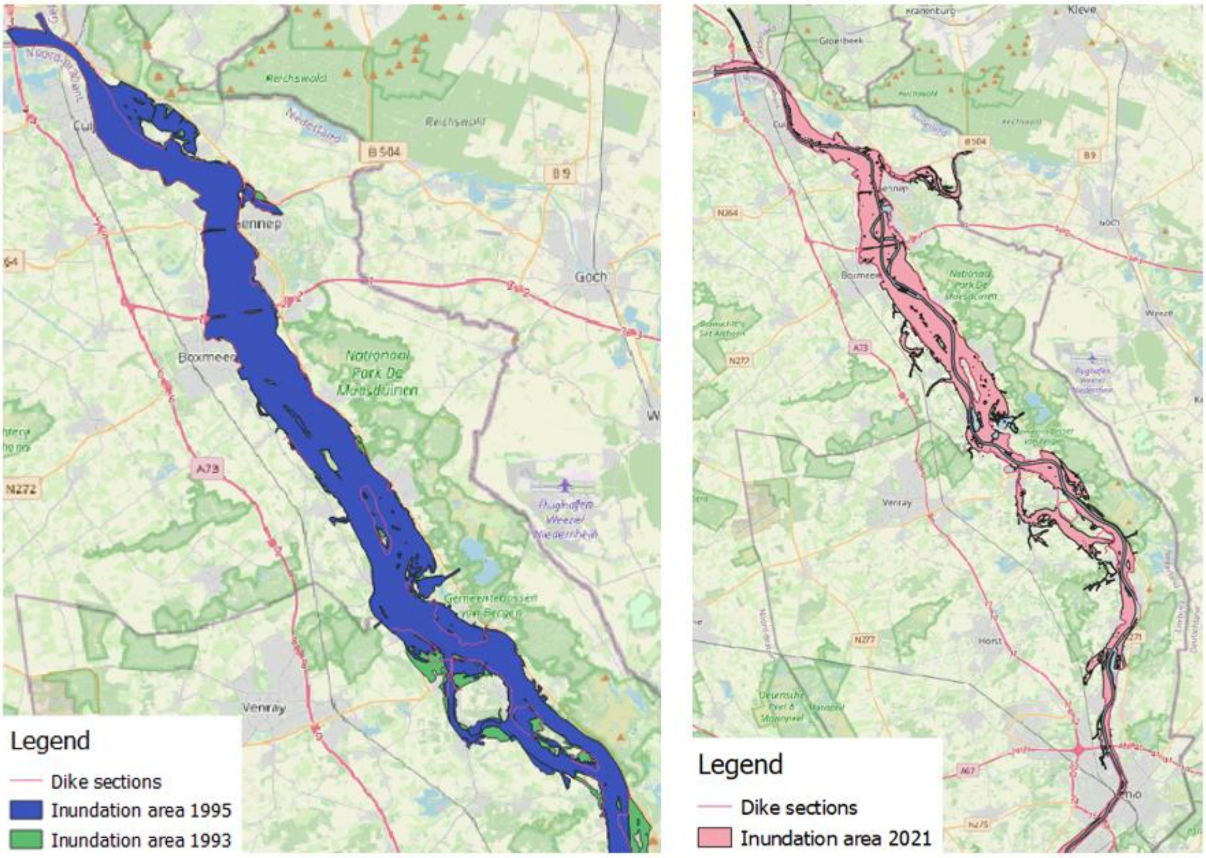


Figure 61: Inundation areas of the Venloslenkmaas in 1993 and 1995 with the future dike sections (right side) and inundation area of 2021 with their current dike sections (left side)

C.5.1. Ooijen Wanssum

The village of Wanssum and Ooijen were inundated in 1993 and 1995 as shown on right side of Figure 62. Therefore, the following measures have taken place since the floods in area of Ooijen and Wanssum (124.3 – 133.3 rkm):

- Creating a high-water channel on the left side of the village Ooijen (see on the left side of Figure 62) was constructed in 2021. This will lead to a described drop in the water level of 35 cm maximum.
- Dike ring 63 surrounding the village Ooijen, which will lead to an increase in the water level in the River Meuse was constructed in 1995.
- Dike section 64 protecting the village Broekhuizenvorst, which will lead to an increase in the water level in the River Meuse was constructed in 1996.
- Dike sections 61 and 62 to protect Wanssum, which will lead to an increase in the water level in the River Meuse.

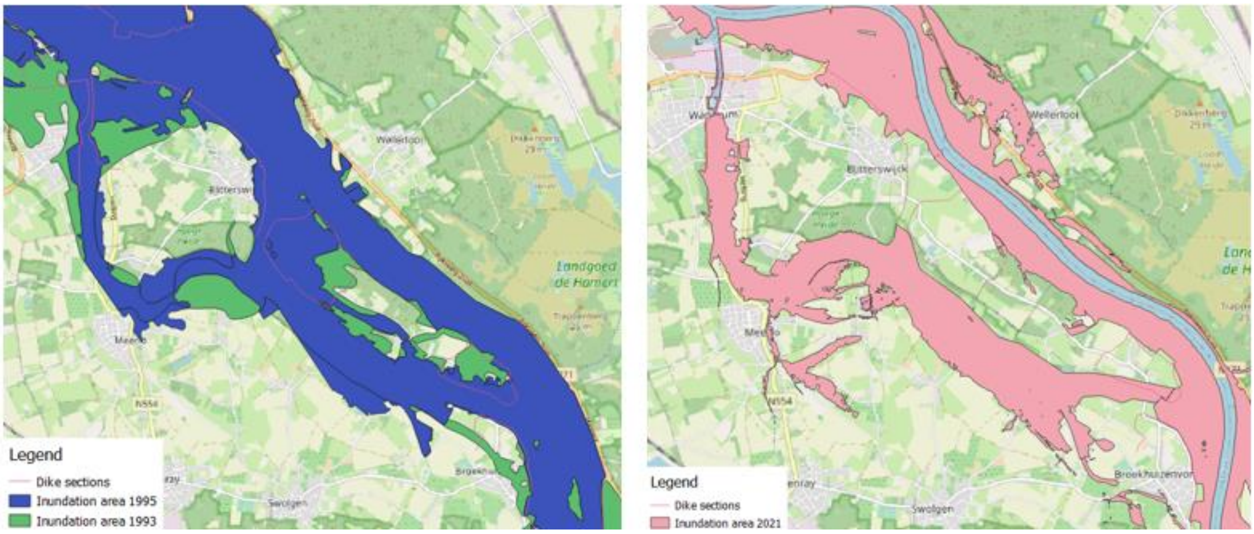


Figure 62: Inundation areas of Ooijen and Wanssum in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

C.5.2. Well - Aijen

The villages of Well, Kampen, Aijen and Oud Bergen were inundated in 1993 and 1995 as shown on right side of Figure 63. Therefore, the following measures have taken place since the floods in area of Well and Aijen (130.8 – 142.5 rkm):

- High-water channel was created from Well till Oud Bergen with an average width of 100 m and a depth of 2 m (139.9 – 142.5 rkm) (Wijbenga, 2021).
- Dike ring 60 surrounding the village Well, which will lead to an increase in the water level in the River Meuse (see on the left side of Figure 63).
- Dike ring 59 surrounding the villages of Aijen and Bergen, which will lead to an increase in the water level in the River Meuse.

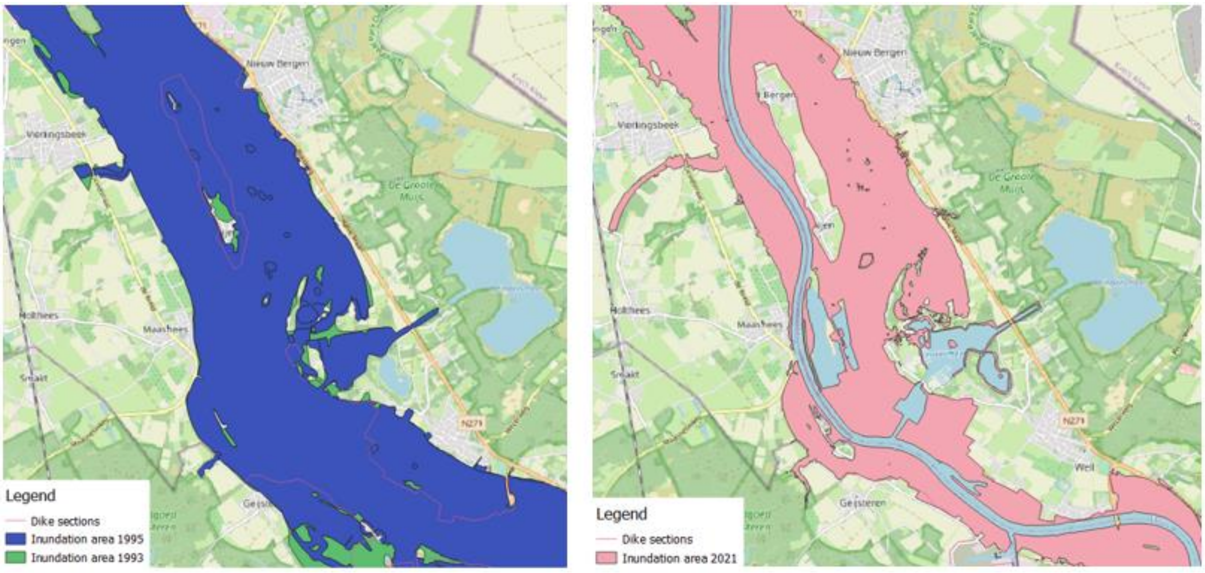


Figure 63: Inundation areas of Elsteren and Aijen in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

C.5.3 Gennep

The village Plasmolen was inundated in 1993 and 1995 as shown on right side of Figure 64. The tributary the Niers has flooded more in 2021 than the previous floods. Further there are not a lot of differences between the floods of 1993, 1995 and 2021. Therefore, the following measures have taken place since the floods in area of Gennep and Boxmeer (130.8 – 142.5 rkm):

- From Boxmeer further downstream the river is completely diked till it flows into the sea, which will lead to an increase in the water level in the River Meuse.
- Dike section 55 protects the villages Heijen and Gennep, which will lead to an increase in the water level in the River Meuse (see on the left side of Figure 64).
- The lob of Gennep is now a special case, because the dike does not meet the safety standard (Lob van Gennep, 2021). A new project is started to increase the safety standard, to improve the water storage in extreme high-water events and reinforce the spatial quality of the area. At the end of 2021 the project solution will be chosen (Waterschap Limburg, 2021).

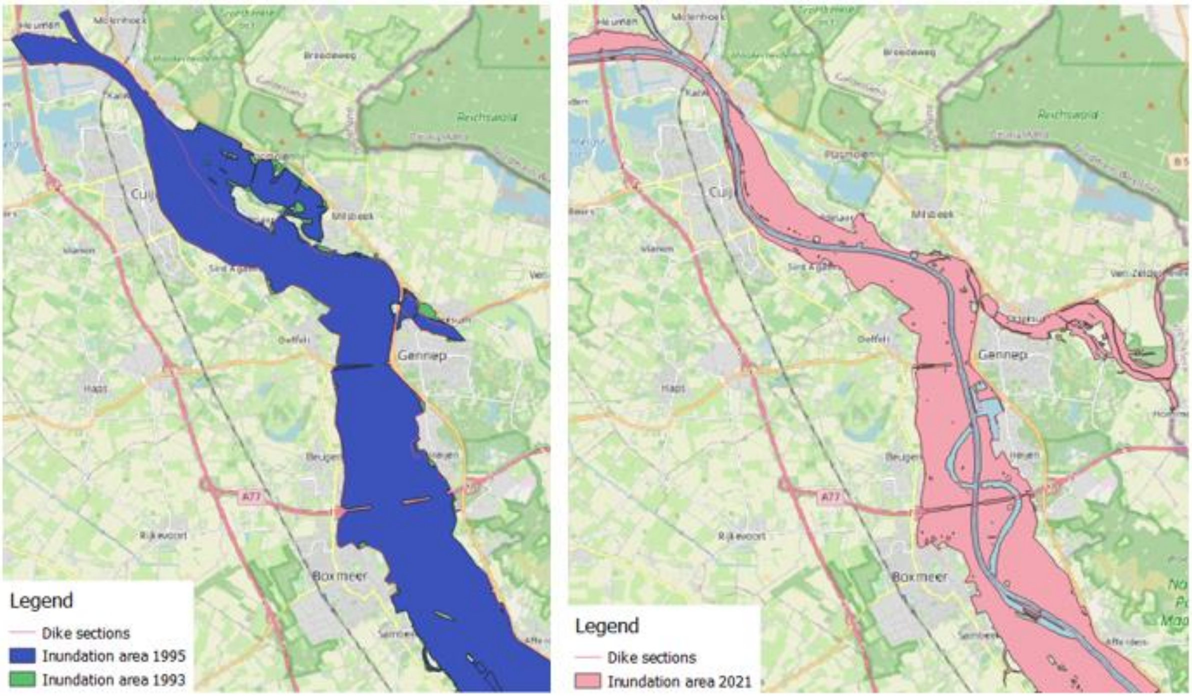


Figure 64: Inundation areas of Gennep and Boxmeer in 1993 and 1995 with the future dike sections (right side) and Inundation area of 2021 with their current dike sections (left side)

Appendix D- Average river dimensions

Legal standard of the Meuse for the calculating Model Zwendl (RWS, LB, 1993):

Grensmaas (rkm 0 – 65)	
$B_{w,1}$	800 m
$h_{w,1}$	1.6 m (equilibrium depth)
$h_{w,1}$	1.4 m (Zwendl)
$C_{w,1}$	31 $m^{1/2}/s$
$i_{w,1}$	4×10^{-4}
$k_{w,1}$	0.35
Maasplassen (rkm 65 – 90)	
$B_{w,2}$	1100 m
$h_{w,2}$	2.9 m (equilibrium depth)
$h_{w,2}$	2.5 m (Zwendl)
$C_{w,2}$	34.5 $m^{1/2}/s$
$i_{w,2}$	0.8×10^{-4}
$k_{w,2}$	0.35 – 0.4 (Zwendl – equilibrium depth)
Northern Meuse (rkm 90 – 160)	
$B_{w,3}$	800 m
$h_{w,3}$	2.7 m (equilibrium depth)
$h_{w,3}$	2.7 m (Zwendl)
$C_{w,3}$	36.5 $m^{1/2}/s$
$i_{w,3}$	1.4×10^{-4}
$k_{w,3}$	0.3
Main channel	
B_z	150 m
h_z	7.5 m
C_z	40 $m^{1/2}/s$

Appendix E- Data

In the sections below the data that is used for each evaluation is described.

E.1 Peak attenuation

Deltares was commissioned to investigate the peak attenuation by RWS-ZN (de Jong & Asselman, 2019). Deltares is an independent knowledge institute for applied research in the field of water and subsurface. RWS-ZN would like to know the extent of the peak attenuation and how the areas along the Meuse contribute to this. This insight is important with a view to future changes in the river. Peak attenuation is the phenomenon that a runoff wave, as it propagates in a downstream direction, sinks and flattens more and more, As a result, the peak discharge decreases and water levels in the lower reaches of the river are lower than in the situation without peak attenuation. This has a favourable effect on the required dike height. To investigate the importance of peak attenuation, a large number of model analyses were carried out by Deltares model on behalf of RWS. The study shows that the Meuse Lakes (including the Lateral Canal West retention area), the Lob of Gennep and the dike ring areas in the Meuse valley contribute the most to the peak attenuation. Peak attenuation is expected to decrease in the future when the dikes in the Meuse valley are raised to meet the new flood risk management standards. The study also shows that the degree of peak attenuation increases with the height of the river discharge and that the wave shape (pointed or obtuse) also has a major influence on the degree of peak attenuation.

The 2D hydraulic model instrument WAQUA is used to calculate flow and storage in the winter bed of the Meuse. In WAQUA, originally developed by RWS, models of the Dutch rivers have been set up. These models are regularly (usually annually) updated to the current situation (the current models) and the expected future situation, which also includes all licensed measures (B&O models). This study uses the most recent B&O model of the Meuse (waqua-maas-beno17-5-v1). In this model, the flood ability requirement of the Meuse defences applies, with a height according to the current situation (the dike heights are based on the 1/250 design water levels after the Maaswerken). The threshold heights of retention areas, such as Lateral Canal West, have not been optimized again. This means that a high water retention area with a deviating peak discharge or wave shape may be less effective. It should be noted that the model will have to deal with 'glass wall' at several locations in the Meuse valley in the event of very extreme discharges. When the water level in the model rises further, the flooded surface cannot increase further, because the adjacent area is not included in the model schematics. This can result in peak attenuation at extreme discharges. This can result in peak attenuation at extremely high drain and this is sometimes underestimated.

Different waveforms and peak discharges from GRADE are used for the boundary conditions of the models (Hegnauer, Beersma, Van den Boogaard, Buishand, & Passchier, 2014). In GRADE, a time series of the discharge at Eijsden is calculated with precipitation-runoff modelling based on a generated precipitation series of 50.000 years. The return time of various peak discharges has been determined for the discharge wave in this time series. In addition, the waveform of all discharge waves in this time series was also analysed. The averaged waveform was determined by superimposing the peak of all effluents and then taking the average value of all effluents for each of the 15 days before and after the draining peak. By not taking the average but higher or lower cut-off limit, a more obtuse or more pointed waveform is obtained.

At peak attenuation, WBI looks at more discharge levels, but these discharges were selected for this study, because they are also used in the Flood Risk Directive (ROR) and analyses for the safety regions. The discharges of 3224 m^3/s and 4118 m^3/s correspond to the high water reference for the diked Meuse and the Meuse Valley respectively, which are used, among other things, to assess Water Acter permit applications.

These five peak discharges are each calculated for three waveforms: the average waveform (50% underrun, also used for WBI), a very pointed wave (2.5% underrun) and a very obtuse wave (97.5% underrun). In the simulations, the waveforms have been shortened to a period of 12 days per the official discharge (De Jong, 2018).

Stationary simulations were also performed to properly quantify the effect of peak attenuation on the discharge and water levels. With a stationary discharge, no peak attenuation occurs at all. By comparing the calculated water levels per river kilometre for each variant with the calculated water levels in the stationary calculation, it can be determined how great the effect of peak attenuation is for each section.

E.2 Evaluation of the Grensmaas

The VNBM has commissioned an evaluation of the Grensmaas (Meijer & Agtersloot, 2021), which has been carried out by D.G. Meijer and R.C. Agtersloot. This evaluation was completed before the flood in July.

The research is largely based on existing model results. There is for this research no new model built. However, some additional model simulations have been performed to obtain the highest discharge range required results. This study does not assess flood risk management, but provides an exploratory analysis of flood risk management in various target years. The fourth–generation hydraulic model set of instruments (Baseline and Waqua modelling) were used on which the evaluation of the Grensmaas is based.

Facts about the data:

- They are no true 2D analyses, but are 1D analyses based on correlations of dike sections with river hectometres. The correlation is based on (approximately) similar water levels and was determined in a previous study (Agtersloot and Meijer, 2018).
- The crown heights are determined based on the heights in the mode beno17_5-v1. The Flemish heights are an exception, which are taken from heights supplied based on measurements in 2014 after completion of the Maasdijkenplan).
- The Flemish dike heights at Kessenich (peripheral zones) are an exception to this, because these are adjusted thereafter. These heights are also based on the beno17_5-v1 model.
- For the first two analyses, ws03 – ws14 for the design years 2017, 2030, 2050 and 2100, the new standard and a robustness allowance of 0,3 m has been applied.
- The new standard is based on a standard probability distribution between the failure mechanisms. Although it is allowed to deviate from this for each dike section, is failure mechanism “ overtopping” (height) uses the standard failure probability of 24%. This means that the standard has been translated in a recurrence time, with the lower limit as the starting point. In this way, the signalling standard of 300 years has been translated into a return period of 417 years via a lower limit of 100 years. A standard of 1000 years results in a return period of 1250 years via a lower limit of 300 years.
- Only crown heights were considered. The technical condition of the flood defences was not included in the data. These results are, therefore inconclusive about the total flood risk management, only about the heights of the flood defences.

E.3 Box of building blocks

In total, the box of building blocks contains almost 400 potential long-term measures for the Meuse and Rhine Branches. These long-term measures (blocks) have been selected by the Delta Programme Rivers in consultation with the regional partners (Provinces, water boards, municipalities). To a large extent, they have been re-schematized and calculated using the Delta Program Rivers model instruments (Delta Model 0.1). For this research, only the river section “Onbedijkte Maas” is used as this section is from Eijsden till Mook (Kroekenstoel, 2014).

In addition to potential long-term measures, the box of building blocks contains the climate task: the rise in normative water levels as a result of higher river discharge and sea-level rise. The reference for the new Box of building blocks is the situation in 2015 (situation after implementation of Room for the River, Maaswerken, HWBP-2). Standard discharges associated with this are 16000 m^3/s for the Rhine and 3800 m^3/s for the Meuse (HR2006, 1/1250 discharge).

The aim is to select just as many long-term measures to neutralize the climate challenge. The part of the climate task that is not neutralized must be solved by raising the dike (and/or existing dike overheight/strength). The solution with dikes has to be calculated outside of the Block Box, with a different set of instruments.

Specifically for the Meuse, a distinction has been made between a 1/1250 and a 1/250 climate task. The 1/1250 climate task is available for the entire length of the Meuse (Meuse km 3 – km 247), while the 1/250 climate task is only available for the Limburg Meuse (Meuse km 3 – km 164). This is also true for the pre-calculated water level effect of a specific spatial measure were a distinction is made. When selecting the 1/250 climate task, the box of building blocks automatically selects the 1/250 water level effect of the relevant measure on the Limburg Meuse and for the 1/1250 climate task the 1/1250 water level effect. For the spatial measures along the Brabantse Maas, only the 1/1250 water level effect is available or calculated.

The water level effects of almost all measures in the box of building blocks have been calculated in advance using a 2-dimensional hydraulic model (WAQUA). In almost all cases with a recent hydraulic model that describes the 2015 reference situation (= situation after implementation of Room for the River, Maaswerken, Stroomlijn and HWBP-2). However, the effects of several measures were calculated either with a deviating 2-dimensional hydraulic model or rather with a 1-dimensional Sobek model.

In most cases, the water level effects were calculated on behalf of the Delta Program Rivers. In some cases, calculation results have been taken from calculations commissioned by regional parties or calculations from the past.

Appendix F- Water level at the Grensmaas

Rkm	Name	HW1995	HW2021	Difference
2.6	Eijsden grens	50,16	50,64	-0,48
10.8	Sint Pieter Noord	47,66	48,12	-0,46
15.2	Borgharen Julianakanaal	46,27	46,09	0,18
16	Borgharen Dorp	45,71	45,23	0,48
18.3	Lanaken	44,79	44,56	0,23
29.3	Elsoo	40,23	40,95	-0,72
44	Rotem Maas	32,92	32,42	0,5
52.7	Maaseik	29,44	30,17	-0,73
60.4	Spaanjerd	25,3	25,14	0,16
67.9	Heel boven	22,69	22,78	-0,09
70.3	Linne beneden	21,08	21,88	-0,8
79.7	Roermond boven	20,79	20,68	0,11
80.3	Heel beneden	20,59	20,49	0,1
100.7	Belfeld boven	19,16	18,89	0,27
102.7	Belfeld beneden	19,04	18,45	0,59
107.5	Venlo	18,46	18,01	0,45
132.1	Well dorp	15,43	15,48	-0,05
144.9	Sambeek boven	14,02	13,77	0,25
147.7	Sambeek beneden	13,92	13,33	0,59
155.1	Gennep	13,22	12,34	0,88