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# Flooding problems in the catchment area of the River Geul

## The impact of measures on the consequences of extreme future flooding

TU Delft

Witteveen + Bos

# Flooding problems in the catchment area of the River Geul

## The impact of measures on the consequences of extreme future flooding

By

Y.H.C. van Dijk

in partial fulfilment of the requirements for the degree of

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# Abstract

The flooding of the River Geul in July 2021 was an eyeopener for the society, the government and many others involved. Besides the major structural damage as a consequence of the flooding, the emotional damage was and still is massive. Therefore, the need for measures to reduce the impact of these extreme events is bigger than ever. Many people had to temporarily leave their house and companies had to shut down. One thing became clear: the impact of comparable or even worse flooding has to be lowered, and one way to achieve that is by implementing measures in the River Geul which reduce the flood risk. The main goal of this research is to find out the impact that certain measures have on the consequences of flooding of the River Geul. Therefore, the main research question is: What is the impact of hydraulic or hydrological measures on the consequences of extreme future flooding of the River Geul? An important aspect is to consider the multidimensional impact of each measure. This can be either social, economic, or ecological impact due to flooding and the implementation of the measure itself.

The evaluation of the impact of measures is done by using different methods. First of all, an existing SOBEK model is used to simulate two extreme events: July 2021 (recurrence interval ≈ 1/100 - 1/1000 per year) and a stress test (recurrence interval ≈ 1/10.000 per year) which simulates 60% larger discharge and precipitation amounts than July 2021. Based on the bottlenecks in the River Geul, which are either bridges, weirs, culverts or orifices, measures are defined and simulated in SOBEK. A distinction is made between possible measures down- and upstream of Valkenburg and in Valkenburg, dependent on the expected effect of the measure. All the measures are simulated for both July 2021 and the stress test. The measures that significantly reduce the flooding depth and local water level nearby urban areas, which follows from the longitudinal cross-sections of the maximum simulated water level, are rated as effective. The effective measures are also evaluated with a damage victim module (SSM2017) to calculate the reduction of damage and victims, but no cost-benefit analysis is performed. Finally, expert judgement is used to estimate the costs of the effective measures. Social impact and the impact on Natura 2000 area is also examined here.

Eleven measures were considered, and four of them showed effective results and therefore their impact is compared. The effective measures are: widen the river downstream Valkenburg, bypass through Valkenburg performed as a tunnel (in-situ or drilled) or channel, remove obstacles in the River Geul along Valkenburg and enlarge the current basins in the River Geul. For the flooding of July 2021, the optimization of current basins in the River Geul scored by far the worst on damage reduction and costs. River widening and removing obstacles both reduce the amount of damage by 6 percent, while the costs are at least a factor of four lower compared to the bypass (dependent on the type of bypass). However, the bypass reduces the damage by at least 34 percent. The most expensive bypass is the drilled tunnel, but it comes with less social impact, because barely any buildings have to be removed in the city centre of Valkenburg (assuming that the subsoil in Valkenburg is suitable for a drilled tunnel). For the stress test, the damage reduction of the effective measures was not significant compared to July 2021. Thus, for extremer events the measures have no longer a considerable impact. This is not an argument to not implement measures, because the probability that a similar event as the stress test recurs is at least a factor of ten lower compared to July 2021.

Depending on the preferences of decision makers the choice for a measure can be made. Based on this research and looking at the flooding of July 2021, a bypass in Valkenburg reduces the damage along the River Geul the most with approximately one-third. For a bypass performed as a drilled tunnel the social impact is limited as maximum five buildings have to be removed but a cost estimate of 112 - 207 million euros is associated with this choice. River widening downstream Valkenburg or removing obstacles in Valkenburg comes with lower costs of 4 - 23 million euros in combination with no social impact but this results in a damage reduction of only 6 percent.

# Preface

With this thesis I am finishing my Master of Science program in Civil Engineering with the specialization ‘Hydraulic Engineering’ at the Delft University of Technology. The research project was carried out at Witteveen+Bos, a consultancy and engineering firm that provides services in the field of water, infrastructure, environment, and construction.

This research has been very educational and showed me the diversity of the field of hydraulic engineering. The road to the end was a bit of a struggle with an unknown model and many different analysing methods but I’m proud of the result and hope you enjoy reading my report.

This graduation research was conducted under the supervision of Witteveen+Bos and I would like to thank them for the expert support they provided. During my thesis I have been supervised by an inspiring committee which I would like to thank for their supervision and guidance throughout this process. I would first like to thank Matthijs for chairing the committee and the few (digital) meetings. Erik, your guidance has helped me to remain objective throughout the process. I also want to thank you for the good help when it was urgently needed. I also want to thank Joost and Laura. Joost, you guided me in the right direction by identifying the key points in my research project. Laura, thank you for all your helpful and thorough feedback. You helped me a lot in interpreting model results and took the time to think along when I was stuck in the process. Furthermore, I want to thank Michel, Bart and Joost (D.) for their guidance with SOBEK modelling. Without you I would have probably struggled even more. Finally, I want to thank Steven for the feedback on my thesis and Britt for all the mental support and believe in me throughout the whole process. You listened to all my presentations and was there for me when needed.

I wrote my thesis during the Corona pandemic. It has been a tough time but luckily, I was able to go to the office from time to time. I also spent a lot of time on the university where I could work with fellow students which kept me motivated. Thanks for that.

*Y.H.C. van Dijk*

*Delft, April 2022*

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# 1. Introduction

## 1.1. Motivation

In July 2021, the River Geul in Limburg had to deal with extreme rainfall. The discharge at the peak was even 25 times higher than the average winter discharge and 100 times higher than the average summer discharge (ENW, 2021). This is a very unusual situation, especially since a few years before the River Geul had to suffer from extreme drought during the summer (Waterschap Limburg, 2018). Eventually, the River Geul faced an extreme rise of water level. In some towns in Limburg, the inhabitants had to evacuate out of precaution as the rise of the water level could not be predicted accurately (ENW, 2021). It is safe to say that only the evacuation itself had already significant impact on the community, but the damage of the flooding even more (NOS, 2021).

The River Meuse is the primary water system into which the River Geul eventually flows. The River Meuse was not flooding due to the higher safety standard compared to the River Geul (ENW, 2021). The River Geul suffered from massive damages. The water level rose several metres and many streets were covered with river water. Not only infrastructure was destroyed but also buildings, gardens, cars, and other properties. Many people can never go back to their houses anymore and companies had to shut their doors (NOS, 2021). The impact on their life is massive. Especially in the Netherlands, people are used to safety and minimal risk when it comes to flooding. This flooding of the River Geul showed that also in the Netherlands flooding is still possible, even though the water systems in the Netherlands get so much attention (Ministerie van Infrastructuur en Waterstaat, 2018). Comparing this flooding with neighbouring countries, the Netherlands was lucky, and no deaths occurred. However, according to the report of Ministerie van Infrastructuur en Waterstaat (2018) about the flooding risks in the Netherlands it was estimated that flooding of the Geul could have led to five deaths. Comparing the results with Germany and Belgium, these countries had to face several death cases due to the flooding and one thing is for sure, the situation in the Netherlands could have been much worse. The fact that no deaths occurred in the Netherlands does not make it less important to come up with a safer design. In the future, flooding and the consequences of flooding might become even worse due to climate change and denser urban areas (Zhang, 2020).

Directly after the flooding, among others, TU Delft, KNMI and Deltares worked together on a fact-finding mission, referred to as ENW (2021), to declare what happened in water systems of Limburg during July 2021. In the research of ENW (2021) many things are already discussed and investigated. A small overview of important findings of this research regarding the flooding of the River Geul is given:

- Due to steep slopes the water level of the River Geul can rise quickly and induce unpredictable situations. Together with the local precipitation mainly above East-Belgium, the flooding happened quicker than expected.
- An issue that was also of importance is the relatively wet soil. Due to more than average rainfall during the spring the storage capacity of the catchment area had decreased. This contributed to the fact that the precipitation that normally would infiltrate in the soil went directly to the river and increased the discharge. Due to steep slopes the precipitation reached the river even faster.
- Lastly, the geographical location of the River Geul contributed to the flooding. The river is often narrow with little space to flow, because its valley has several small villages and city centres. The river becomes a straight channel in these urban areas, and the increased discharge directly leads to an increase in water level. An additional problem is related to the safety standard of 1/25 per year for the urban areas along the River Geul, while elsewhere in Limburg and the Netherlands this safety standard for urban areas along regional waters is 1/100 per year (Provinciale Staten van Limburg, 2015). The reason or cause of this lower safety standard is a cost-benefit analysis which showed that it was not effective to increase the safety standard (Ministerie van Infrastructuur en Waterstaat, 2018). However, the flooding

event in July 2021 exceeded both 1/25 and 1/100 per year safety standards which means that the flooding was likely to happen. If extreme events like July 2021 happen more often, due to for instance climate change, it can be of importance to increase this safety standard of the urban areas along the river for the safety of the inhabitants. Apparently, the discharges belonging to certain safety standards recur more often, which means that the safety standards no longer give a good image of how safe the urban areas are. Research stresses the possibility of an increase in extreme weather events in combination with urbanization (Zhang, 2020) which makes it even more important to increase this safety standard.

The above-mentioned findings express plausible causes for the flooding of the River Geul. Why so much damage was the result of this flooding has different reasons and this is also analysed in the report of ENW (2021). The elaboration of these reasons is summarized:

- No one expected a flooding during the summer and both the inhabitants, and the government were not aware of the possible impact of the flooding, with the result that there was not enough time to take emergency measures and secure for instance furniture or other properties. The predictions and warnings for the River Geul came too late or not at all which was a big issue and should be improved for the future. Another additional increase of damage during summer was because of the use of the large areas along the River Geul for campsites, harvesting and other purposes. During the winter it is considered that flooding could happen, and these areas are therefore not occupied but during summer those areas are being used.

The combination of all the above points gives reason to come up with measures to decrease the impact of a similar or even worse flooding. Overall, the research of ENW (2021) is a basis to explain what happened during the flooding of July 2021, but further research is necessary. Especially for the River Geul either information is missing, or the data still needs to be properly implemented in a model. How a similar flooding and especially the corresponding consequences can be prevented, or at least decreased, is the main unanswered question which has to be tackled.

## 1.2. Objective & research question

The main goal of this research is to find out the impact of certain measures on the consequences of extreme future flooding of the River Geul, assessed with a hydraulic model and taking into account the social, economic and ecological aspect. Therefore, the main research question is:

**What is the impact of hydraulic or hydrological measures on the consequences of extreme future flooding of the River Geul?**

The research question is focused on hydrologic and hydraulic measures in the catchment area of the River Geul. These measures could consist of for instance retaining water more upstream (for instance regreening and retention basin) and increasing discharge capacity in the downstream part (think of river widening and a bypass in Valkenburg). An important aspect is to consider the impact of each measure. This can be either social, economic, or ecological impact due to flooding and the implementation of the measure itself.

The sub-questions that have to be answered in order to give an answer to the main research question are:

1. How was the precipitation and discharge distributed over the Dutch part of the catchment area of the River Geul during the flooding of July 2021?
2. How extreme was the amount of precipitation of July 2021 in Limburg (NL) and surrounding areas in Germany compared to extreme Dutch climate scenarios?
3. What is the influence of the River Meuse and bottlenecks in the River Geul on the water level of the River Geul during flooding?
4. What type of measures can be taken where and what is the impact of these measures on the River Geul and surrounding areas during extreme future flooding?

## 1.3. Approach

The research starts with a literature review in Chapter 2. The current river basin and historical developments are analysed. A study of the flooding of the River Geul in July 2021 follows. The existing measures in the River Geul are also discussed and related to the flooding of July 2021. Chapter 3 presents a small data analysis based on the quantity and representativeness of the data. The following chapters make use of this data, and therefore the credibility of this data is important. To get a feeling for the amount of water in the catchment area of the River Geul during the flooding of July 2021 the distribution of water in the Dutch part of the catchment area of the River Geul is investigated. This is described in Chapter 4 and answers sub question 1. In Chapter 5 the precipitation in surrounding areas in Belgium and Germany, during the flooding of July 2021, is analysed and compared with Dutch climate scenarios to make sure that measures are simulated with representative scenarios for extreme future flooding. In this chapter sub-question 2 is answered.

The hydraulic model set-up and the baselines of simulations is explained in Chapter 6, which gives an answer to sub-question 3. For modelling purposes an existing SOBEK model of the River Geul, provided by waterboard Limburg, is used. The calibration of the SOBEK model is optimized by comparing the water levels from SOBEK with the maximum measured water levels during the flooding of the River Geul in July 2021. After the calibration, a small study on the influence of the River Meuse on the River Geul is performed. Some scenarios are simulated, and the response of the River Geul is analysed. Eventually, the bottlenecks in the River Geul are identified and listed as preparation for the definition of possible measures. After the simulation of the measures the impact of these bottlenecks is made clear.

A distinction between measures down- and upstream Valkenburg and in Valkenburg is made, dependent on the expected effect of the measure. Based on the bottlenecks, the location of measures is defined and simulated in SOBEK for the catchment area of the River Geul. The evaluation of the simulated measures is performed in Chapter 7, which answers sub-question 4. The measures are simulated with the July 2021 scenario and a stress test which makes use of even 60% extremer conditions than July 2021. Eventually, a damage victim module (SSM2017) is applied to give an overview of the reduction of damage and victims and expert judgement provides global calculations of the costs.

## 1.4. Restrictions of the research

The most important restrictions of the research are mentioned in this section. All the restrictions of the research are elaborated in Section 6.1.6.

- Only hydraulic and hydrologic measures in the Dutch part of the catchment area of the River Geul which can be simulated with a hydraulic model and be evaluated equally are considered. Other solutions like making buildings in Valkenburg flooding proof are not considered. To demarcate the scope measures in Belgium and Germany are also not taken into account. The used hydraulic model only contains the Dutch part of the catchment area of the River Geul, so it would cost a lot of time to expand and calibrate this model for both Germany and Belgium.
- The SOBEK evaluation of measures is only based on SOBEK simulations of the flooding of July 2021 and a stress test, which is based on the most extreme amount of precipitation that fell in Germany during the flooding of July 2021. Other less extreme but more frequent recurring events are not considered in this research. The precise recurrence intervals of the simulated events are unknown but according to ENW (2021) the flooding of the River Geul in July 2021 has a recurrence interval between 1/100 and 1/1000 per year, while for the stress test the expectation of the recurrence interval lays around 1/10.000 per year. The recurrence interval of the stress test is based on the flooding of the River Roer in July 2021 (WVER, 2021), which includes the most extreme amount of German precipitation as used for the stress test. The assumption is made that the recurrence interval of this event is also representative for the stress test of the River Geul to make comparisons between the flooding of July 2021 and the stress test.

# 2. Literature review

In order to provide sufficient background information a literate review is necessary. This forms the necessary theoretical framework to understand the necessity and starting points of this research. The literature review is subdivided into four sections. Section 2.1 shows more detailed information about the River Geul. This section visualizes the catchment area and gives general information about both the River Geul and River Gulp. Section 2.2 presents important findings from the research of ENW (2021) and the need for further research. Especially the River Geul is discussed as the River Geul is the main topic of this research. In Section 2.3 similar flooding events in the River Geul are evaluated. This gives insight into how extreme the flooding of July 2021 was compared to past flooding events. Section 2.4 elaborates on the existing measures in the River Geul. This section mainly focusses on the measures that also influence the behaviour of the river during flooding.

## 2.1. The River Geul and River Gulp

Figure 1A shows where in the Netherlands the River Geul flows and Figure 1B shows the river basin of the River Geul.

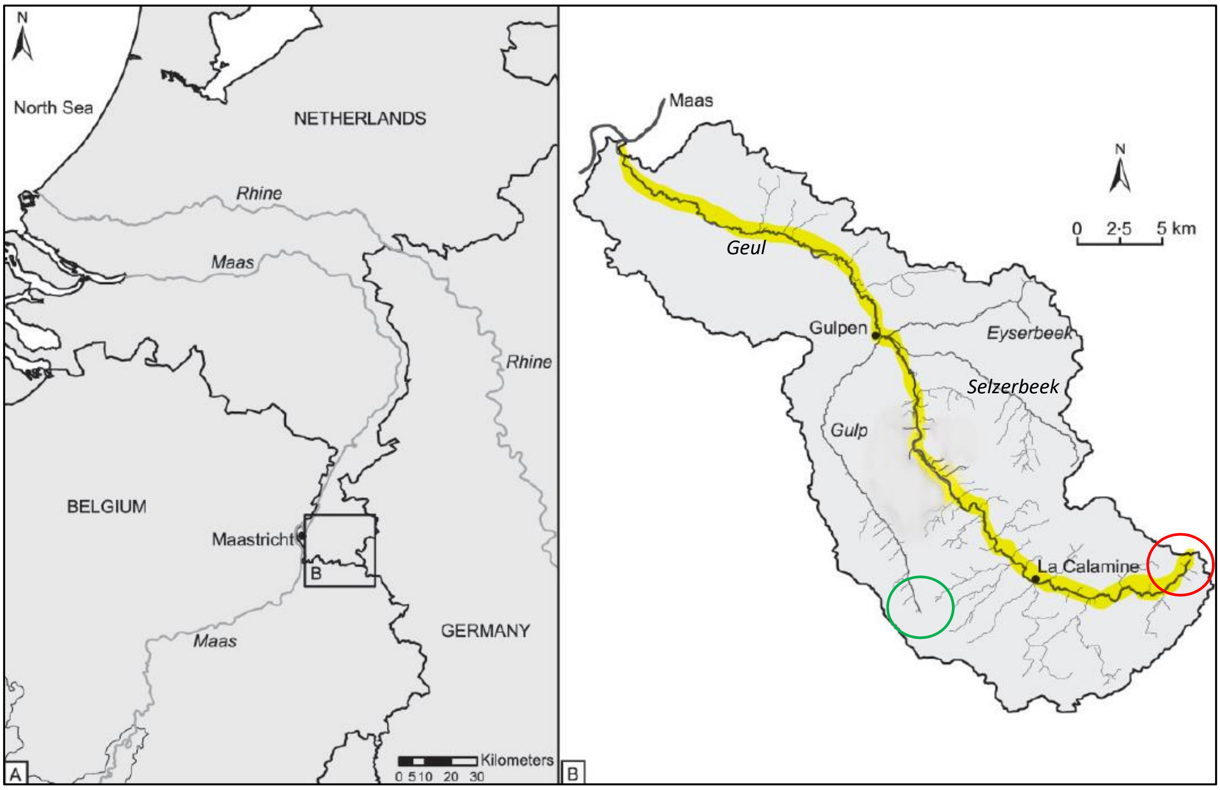



**Figure 1A Location of the River Geul with respect to the Netherlands. Figure 1B The river basin of the River Geul. The River Geul is marked yellow, the source of the River Geul is defined with a red circle and the source of the River Gulp with a green circle, adjusted from (Moor et al., 2007).**

### 2.1.1. The River Geul

The River Geul is 56 kilometres long and originates in Belgium, close to the German border (Paarlberg, 1990). In Belgium, the River Geul is steeper than in the Netherlands (see Appendix 2A, Figure 63). This steepness in Belgium contributes to a quick transport of discharge downstream, towards the Netherlands. Furthermore, the River Geul has a quick responding discharge process because water cannot infiltrate in the soil due to impenetrable stone. The River Geul has a high steady discharge due to the many tributaries flowing into the River Geul. However, in the past a few sources have been dried up for other land use purposes. This change of land use led to less storage capacity and more water flowing directly downhill, leading to more frequent mud and water nuisance. Due to this change of land use the discharge is also more fluctuating.

From Mechelen until Gulpen, which is equal to 11 kilometres, the River Geul was channelized in the second half of the 19th century. After 2010 the natural behaviour was restored to give it more freedom to move through the landscape in South-Limburg (Van Heeringen et al., 2012). In the urban areas the meandering river changes into a straight channel again. In Valkenburg this is properly visible. Eventually the River Geul flows via a culvert underneath the Julianakanaal to end up in the River Meuse.

The difference between the peak discharge of 100 $m^3/s$ during July 2021 (ENW, 2021) and the average discharge of 1-4 $m^3/s$ (Paarlberg, 1990) is massive. This is the result of the precipitation dependence of the discharge of the River Geul.

### 2.1.2. The River Gulp

The River Geul has multiple tributaries, from which the River Gulp has the largest influence. The River Gulp is seventeen kilometres long and also originates in Belgium, but in Hendrik-Kapelle more to the west (Paarlberg, 1990). A notable characteristic of the River Gulp is the elevation difference, which is almost three times higher than the elevation difference of the River Geul (see Appendix 2B, Table 30).

Due to the geohydrological conditions of the River Gulp the fluctuations are minor compared to other tributaries in South-Limburg (Paarlberg, 1990). This is also one of the reasons that the River Gulp barely experiences flooding; 70% of the discharge is the basic discharge throughout the year. Close to the source the River Gulp is very steep, and narrow compared to the River Geul and more downstream the River Gulp becomes flatter.

### 2.1.3. Safety level of the River Geul and River Gulp

The River Geul and River Gulp are regional streams and have a lower safety standard than for instance the River Meuse. Furthermore, the estimates of damages for the River Geul and Gulp are a factor of 2.5 to 5 higher than for an average Dutch river for a 1/100-year flooding. Also, the number of possible deathly victims for the River Geul and River Gulp is critical, with one to five victims for a 1/100-year flooding (see Appendix 2C, Table 31), and should be a reason to raise the safety level of those tributaries. This might also have contributed to the large amount of damage after the flooding of July 2021. The damage as a consequence of the flooding along the River Geul in July 2021 was estimated to be €200- €250 million with most of the damage in the urban areas along the River Geul (ENW, 2021). This estimate includes both physical damage and business downtime.

For the River Geul and a few other rivers, the Ministerie van Infrastructuur en Waterstaat (2018) provided damage estimates based on the recurrence interval of an event. The pre-estimated amount of damage of the River Geul ranges from €10 to €50 million for a recurrence interval of 1/100 per year and from €125 to €250 million for a recurrence interval of 1/1000 per year (see Appendix 2C, Table 32). The precise recurrence interval of the flooding in July 2021 is unknown but according to ENW (2021) the recurrence interval is between 1/100 and 1/1000 per year. Because of this uncertainty, it is also unknown whether the pre-estimated amounts of damage are representing the occurred amount of damage accurately.

## 2.2. The fact-finding mission

The research of ENW (2021) is the most important and most recent source of information about the flooding in Limburg during July 2021. This report provides not only information about river morphology and statistics but also hydrology, meteorology, functioning of weirs, damage due to flooding, health effects and so on. Only hydrology, meteorology, and damage due to flooding is used for this research.

### 2.2.1. Cause of flooding: precipitation and system characteristics

In July 2021, a massive peak discharge travelled through the River Geul and several tributaries. The main cause of this high discharge is related to intense rainfall. The precipitation happened locally and that is also visible in Figure 2, which shows the precipitation from the 13th until the 15th of July 2021. The largest amount of precipitation fell in Belgium, more upstream and in the catchment area of the River Geul, and in Germany to the east and outside the catchment area of the River Geul.

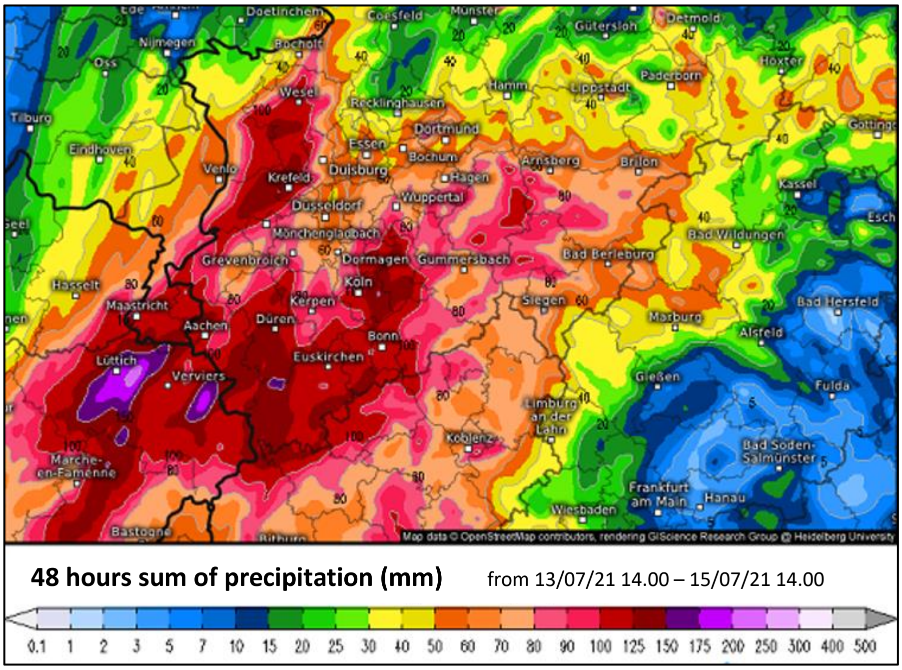



**Figure 2 48 hours sum of precipitation from 13/07/21 14.00 until 15/07/21 14.00 (Ruhnau, 2021).**

Several factors, including system characteristics, enhanced the flooding of the River Geul and an overview of them is given below (ENW, 2021):

- First of all, the geographical situation in Limburg is far from ideal. The slope is steep and in Belgium these slopes are even steeper than in the Netherlands. Due to steep slopes more upstream the water level of the River Geul can rise quickly and induce unpredictable situations: so-called flash floods. The relation between these flash floods and steep slopes is proven by the research of Moraru et al. (2021).
- Due to more than average rainfall during the spring of 2021 the storage capacity of the catchment area was decreased. This made sure the precipitation that normally infiltrated in the soil now directly went to the river and increased the discharge.
- In the valley of the River Geul there are many small villages and city centres. In these urban areas the River Geul becomes narrower, has little space to flow and becomes a straight channel. The consequence is that an increase in discharge directly leads to an increase in water level.
- Another issue in these urban areas along the River Geul is that the safety standard is particularly lower; 1/25 per year, while elsewhere in Limburg and the Netherlands this safety standard for urban areas along regional waters is 1/100 per year (Provinciale Staten van Limburg, 2015). Therefore, the flooding of the River Geul happens sooner than for other rivers.

### 2.2.2. Flood peak: Discharge and water level

The flood peak in the River Geul is explained based on several water level graphs. What the graphs in Figure 3 clearly visualize are the two peaks: on the 14th of July in the evening and on the 15th of July in the morning, when the wave peaks enter the system at the Belgium border. Comparing the graphs from upstream until downstream it is visible that it takes both flood peaks half a day to move through the River Geul. Another fact that is visible from the flood peaks is that the profile of the flood peak changes over time. Figure 3 shows that the profile of the flood peak becomes wider over time and that it flattens out. This is the result of a less steep slope more downstream of the River Geul. In the Netherlands, this phenomenon is called top flattening.

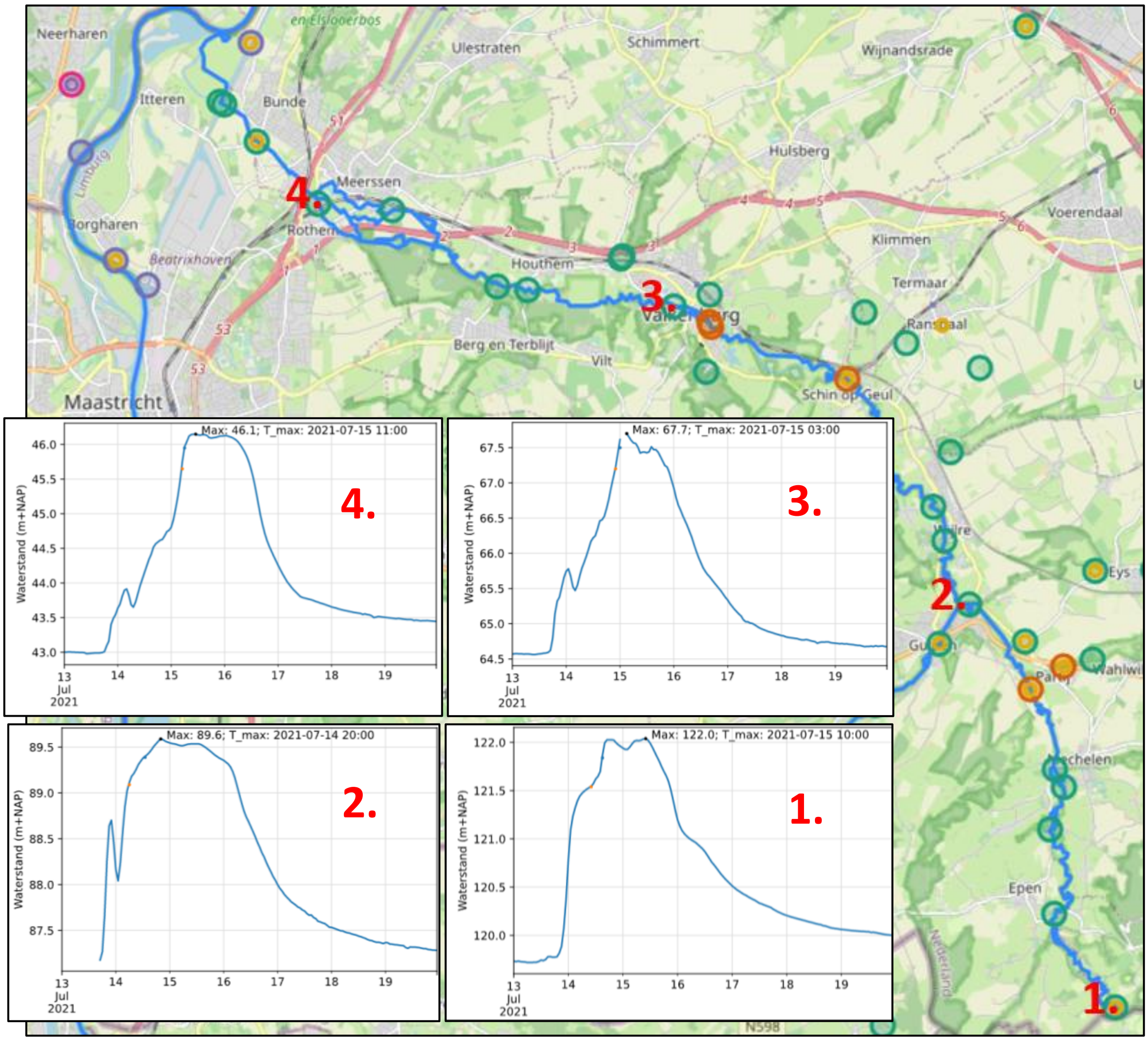



**Figure 3 Top view of the River Geul and four numbered measurement stations with corresponding water level graphs of the flooding in July 2021 (https://hw2021.surge.sh/Alle_metingen.html).**

The discharge through the River Geul is estimated to be 100 m³/s but this is a rough estimate (ENW, 2021). The estimate of the discharge is less secure than the measured water levels as the discharge depends on multiple parameters, such as water level and river profile. During peak discharge, the river flows outside it banks and becomes wider. This makes the estimate of the discharge doubtable.

In the research of ENW (2021) not only the estimate of 100 m³/s is mentioned. Model results are compared with the occurred water levels which led to the following statement:

The water levels in the River Geul valley with a probability of exceedance of 1/100 per year in the current climate have been calculated with a discharge at Cottessen of 62 m³/s and at Valkenburg of 84 m³/s. The waterboard has also calculated water levels for the WH_Center climate scenario with a target year 2050. In this situation, the discharge at Cottessen is approximately 105 $m^3/s$ and at Valkenburg 160 $m^3/s$. These model results are generally closer to the maximum water levels that occurred in the River Geul, but the probability of exceedance in the current climate is unknown (ENW, 2021, P. 166).

### 2.2.3. Consequences

The consequences of flooding of the River Geul are listed below (ENW, 2021):

1. Along the River Geul the amount of damage was much larger than along the River Meuse. Many houses, gardens and crops were destroyed. In Valkenburg a few bridges were also damaged due to the extreme water level rise.
2. No one expected a flood during the summer and both the inhabitants, and the government were not aware of the possible impact of the flooding, with the result that there was not enough time to take emergency measures and secure for instance furniture or other properties. The predictions and warnings for the River Geul came too late or not at all which is a big issue and should be improved for the future.
3. Another additional increase of damage during summer was because of the use of the floodplains along the River Geul for campsites, harvesting and other purposes. During the winter it is taken into account that flooding could happen but during summer those areas are being used.

Overall, the damage as a consequence of the flooding of the River Geul in July 2021 is estimated to be €200-€250 million with most of the damage in the urban areas along the River Geul (ENW, 2021). This estimate includes both physical damage and business downtime.

### 2.2.4. Discussion and recommendations future research

A part of the research of ENW (2021) describes several points of discussion and recommendation: The data from this event can be used for validation of hydrodynamic models. Furthermore, the flooding of July 2021 is far out of the calibration reach of regional models like the River Geul model. Properly calibrated and validated models are essential for future water level and discharge forecasts. The effectiveness of possible (emergency) measures is also dependent on reliable models. Lastly, the hydraulic boundary conditions have to be determined from the calibrated models and with the current models this is not on point (ENW, 2021, P. 48). These statements show that there is need for a reliable hydraulic model that is accurately calibrated for the flooding of July 2021. The current models are not calibrated for such extreme events.

## 2.3. Flooding events in the past

In this section past flood peaks are compared with the flood peak of July 2021. This gives insight into the extremeness of the flooding of July 2021.

### 2.3.1. Comparison of extreme discharge peaks on River Geul

Besides the development of the peak discharge over time, the extreme events in the past can be compared with each other. Figure 4 shows all the extreme events in the past in one graph. A fictive peak (—) is also included which has a recurrence interval of 1/100 per year in the current climate (Deuss et al., 2016). Clearly visible is that the peak of July 2021 (—) was more extreme than any of those events. The discharge peak of July 2021 (the red line in Figure 4) has not been measured exactly but an estimate based on the water level of the flood peak just upstream Valkenburg, visible in Figure 3 location 3, is used in combination with the 160 $m^3/s$ discharge upstream Valkenburg of the WH_center 2050 climate scenario (ENW, 2021), as explained in section 2.2.2. Although the estimate of the discharge of the River Geul during the flooding is not precise, it gives a feeling for the size of the occurred wave peak.

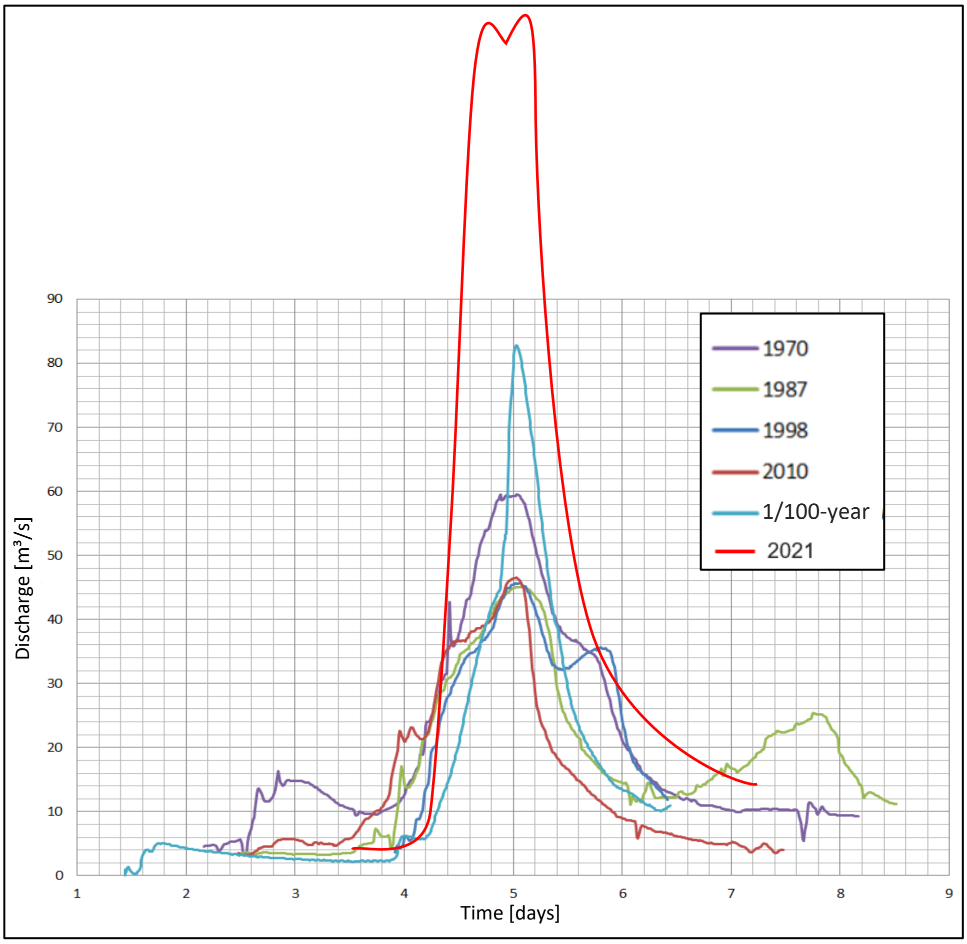



**Figure 4 Discharge peaks from the past compared with the 2021 discharge peak (red line), location upstream Valkenburg, adjusted from (Deuss et al., 2016). The red line is based on Figure 3 location 3 and 160 $m^3/s$ just upstream Valkenburg.**

Comparing the events, shown in Figure 4, the event of 1970 was the most severe compared to 1987, 1998 and 2010. Interesting to see is the fact that the peaks of 1970 and 2021 show major deviation from the 1987, 1998 and 2010 discharge peaks in Figure 4. The events from 1987, 1998 and 2010 look almost similar. Figure 4 also shows that the flooding of July 2021 exceeds the 1/100-year event in the current climate by far. Based on all the shown events it can be concluded that the maximum discharges of the River Geul fluctuated a lot over the past years and future flooding might be hard to predict as there is no clear relation visible.

## 2.4. Current measures in the River Geul

The performed hydraulic and hydrologic measures in the catchment area of the River Geul are discussed in this section. Conversations with waterboard Limburg[1] are an important source of this section, because they know the best which measures have already been taken and what the influence is.

### 2.4.1. Current measures

According to Helena Pavelkova, of waterboard Limburg, no major artificial measures have been performed that influence the flow and storage of the River Geul from the period of 2014 until now. This is partly due to the policy which holds for the inundation area which states that you may not cause any negative effects on the storage and flow of the river (H. Pavelkova, personal communications, November 4, 2021).

Another aspect of taking no measures, according to Pavelkova, has to do with the origin of the river. It is a natural freely meandering river and partly a Natura 2000 area. Pavelkova mentioned that the River Geul has a broad inundation area, so a natural retention that is not further artificially controlled. There are no structure or storage controllers to optimize because there are no significant controlled structures or controlled storages present in the River Geul basin (H. Pavelkova, personal communications, November 4, 2021).

The multiple reservoirs along the River Geul effectively influence the flooding of the River Geul. However, these reservoirs are not built by humans, but these are from origin natural storage areas without any controlling structures like weirs. Only the reservoirs of Partij and Nijswiller can be controlled but these are not significant (H. Pavelkova, personal communications, November 4, 2021).

Furthermore, the removal of the channelization in 2010 of the River Geul from Mechelen until Gulpen has had an influence on the flow of the river. After 2010 the natural behaviour was restored to give it more freedom to move through the landscape in South-Limburg (Van Heeringen et al., 2012).

In Valkenburg the 'Walramstuw' divides the River Geul in two streams, as shown in Figure 5 with the green dot. The 'Walramstuw' is a centuries old weir and was made for providing water to the mill that lies in the 'Molentak' in Figure 5. During flooding, the discharge can be divided over the two channels, which lowers the water level significantly. The weir can control the amount of water that goes to each channel (Ingenieurbüro Floecksmühle GmbH, 2015).


**Figure 5 Division of the River Geul into 'Molentak' and 'Geul' (Ingenieurbüro Floecksmühle GmbH, 2015).**

### 2.4.2. Effect of current measures during flooding of July 2021

The only measure that effectively reduced the flooding of July 2021, according to waterboard Limburg, is the division of the River Geul in Valkenburg in combination with the 'Walramstuw'. This measure spreads the discharge of the River Geul over two channels and raises the discharge capacity at Valkenburg during flooding by a factor of two (H. Pavelkova, personal communications, November 4, 2021).

[1] Waterboard Limburg has only supplied data, the SOBEK model and the info of Section 2.4. They no further contributed to this study and the findings of this study may not correspond with the findings of the waterboard.

# 3. Data collection and analysis

## 3.1. Methodology

Different types of data are used during the research. This chapter elaborates on the assessment, the availability, quality, and applicability of the data. Both the meteorological data and the input for the boundary conditions of the SOBEK model are elaborated. Table 1 shows an overview of the types of data of July 2021 that are used in this research.

| Type of data of July 2021 | Source |
|---|---|
| Meteorological grid data of the catchment area of the River Geul | Meteobase |
| Precipitation in Germany | Wetterkanal vom Kachelmannwetter |
| Water levels of the River Meuse, at the connection with the River Geul | Rijkswaterstaat |
| Water levels of the River Geul and tributaries | waterboard Limburg |
| Discharge of the River Geul and tributaries at the boundaries | waterboard Limburg, KNMI and ENW (2021) |

**Table 1 Overview of types of data and the corresponding source.**

To assess this data use is made of the detailed information that the several sources delivered regarding the used data. Section 3.2.1 focusses on the availability and accuracy of the data, while Section 3.2.2 evaluates how applicable the data is for this research.

## 3.2. Results

### 3.2.1. Availability and quality of data

- Meteorological grid data of the catchment area of the River Geul

Meteobase uses all the measurement locations and data from the KNMI. To translate precipitation amounts to a useful type of data for modelling radar composites are used. Meteobase gives the possibility to download precipitation and evaporation for a freely selectable sub-region in grid format. The precipitation volumes consist of radar data calibrated with measurements from 216 ground stations and can therefore be used for calibration purposes (*Rasterdata*, 2021).

ENW (2021) mentioned the following: However, the information on current precipitation was of insufficient quality. The number of precipitation measurement locations in the area is limited and the real-time KNMI radar product underestimated the precipitation volumes by approximately a factor of three (ENW, 2021, P. 24). This means that:

1. The measured amount of precipitation can be uncertain because of the limited amount of measurement locations. However, more measurements are not available in the catchment area of the River Geul. This data is used for simulation purposes.

   To prevent unrealistic results the SOBEK model is calibrated based on measured water levels. The calibrated model consists of the Meteobase precipitation data and the input at the boundary conditions. If the water levels after calibration of the SOBEK model are more or less equal to the measured water levels during flooding it can be assumed the flooding of July 2021 is properly simulated. This approach and the uncertainty are part of the discussion in Section 8.3.

2. The predicted amount of precipitation from the real-time KNMI radar product is unreliable, but these predictions are also not used in this research.

- Precipitation in Germany

Many measurement locations in Germany are used to publish precise precipitation amounts. The German weather channel explains it as followed: In the live weather you will see analysis maps based on observation data plus our 1x1 km² model - our SuperHD mesoanalysis. The maps are available for various parameters that you can select via the menu. The analysis is updated whenever there is sufficient new observation data, so the update interval can vary depending on the parameter. Some parameters, such as the temperature, are updated every 10 minutes, while others only update every hour. Please note that this is an analysis and that there may be local deviations in some cases. With a remarkably high resolution of 1x1 km², the analysis is very precise in most cases and also depicts mountains and valleys well (*Live wetter*, 2021, info-button).

- Water levels of the River Meuse, at the connection with the River Geul

The water levels in the River Meuse are measured by Rijkswaterstaat. All the measurements published by Rijkswaterstaat are defined applying the standard guideline, which means that the measurements are collected, processed, and published accordingly (Rijkswaterstaat, 2010). This method includes verification and makes sure that the accuracy always remains acceptable.

- Water levels of the River Geul and tributaries

Water levels during flooding represent the situation properly because they are not dependent on the width of the river. Discharges are doubtable, because the conveyance area is unsure during flooding, but water levels are not depending on this.

At the time of the flooding, the hydrological measuring network of waterboard Limburg functioned quite well (except for a few measuring points that had failed), so there was a good overview of the events (ENW, 2021, p. 21). This means that most of the measurement locations along the River Geul functioned properly during the flooding of July 2021. The few locations that did not work do not influence the accuracy of the overall system.

- Discharge of the River Geul and tributaries at the boundaries

The discharge of the River Geul of the flooding in July 2021 is estimated by waterboard Limburg. However, as mentioned before, the conveyance area during flooding is hard to estimate which makes the estimated discharge unsure. For both the River Roer and Geul, the water level measurements combined with a water level-discharge relationship are not a reliable picture of the discharge (ENW, 2021, p. 27). To deal with this uncertainty the discharge for the climate scenario WH_Center 2050 is used as defined by ENW (2021).

KNMI defined the climate scenario, while ENW (2021) defined which climate scenario was relevant. Waterboard Limburg provided the boundary discharges for the River Geul and its tributaries pertaining to this scenario. This is further explained in Section 6.2.1 where the boundary conditions are defined.

### 3.2.2. Applicability of data

- Meteorological grid data of the catchment area of the River Geul

The raster data is directly coupled to the SOBEK shape file of the catchment area of the River Geul. This coupling makes sure that the data from Meteobase is connected to the right location in SOBEK.

- Precipitation in Germany

The precipitation that fell in Germany is only used as reference amount. The provided precipitation from Meteobase is adapted to the precipitation amounts of Germany and used for the catchment area of the River Geul. In this way the data can be used for the stress test of the system.

- Water levels of the River Meuse, at the connection with the River Geul

The measurement locations of the River Meuse closest to the mouth of the River Geul are still relative far away, which is visible in Figure 6. Uikhoven lays downstream and Lanaken lays upstream the river mouth. The elevation difference over the part from Lanaken until the mouth is much larger due to the thresholds in Meers (Bureau Drift, 2005). That is why the measurements at Uikhoven represent the situation the best. The elevation difference is minimal and the situation at the mouth is representative for the available data of Uikhoven: the measured water level at Uikhoven is compared with the available water levels at the mouth of the River Geul in the SOBEK model from waterboard Limburg. On average these water levels are (almost) equal over the available time.

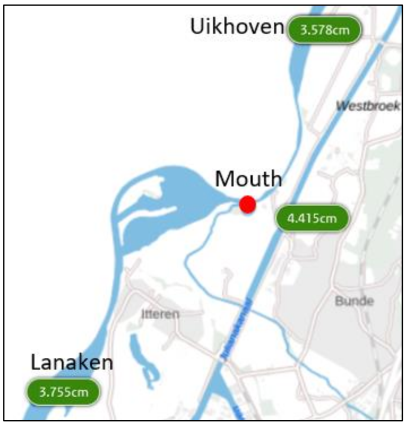



**Figure 6 Overview of several measurement locations of the River Meuse with respect to the mouth of the River Geul (Rijkswaterstaat, 2021).**

- Water levels of the River Geul and tributaries July 2021

The water levels measured along the River Geul are directly useful for the research. Calibration of the SOBEK model can be done accurately with the many water level measurements along the River Geul. Water levels during flooding represent the situation properly because they are not dependent on the width of the river.

- Discharge of the River Geul and tributaries at the boundaries

The locations of the discharges, estimated by waterboard Limburg, for the WH_Center climate scenario for the year 2050 are similar to the boundary locations within the SOBEK model. Therefore, these discharges are useful to use, not only for the River Geul itself, but also for the three tributaries.

# 4. Water distribution in the catchment area

## 4.1. Methodology

The quantification of the water distribution in the system is accomplished by investigating the amounts of discharge that came from Belgium and Germany and calculating the total amount of precipitation that fell on the catchment area of the River Geul in the Netherlands during the flooding of July 2021.

The distribution of discharges is based on the climate scenario WH_Center 2050, as explained in Section 3.2.1. Waterboard Limburg provided the boundary discharges of the River Geul and its tributaries, pertaining to this scenario. Section 6.2.2 shows how these discharges are changed for the simulation of the flooding in July 2021, but this is not taken into account in this chapter. The changed discharges are expected to not accurately represent the occurred discharges during the flooding of July 2021. The maximum measured water levels during the flooding of July 2021 are accurate (ENW, 2021) and used as a reference parameter for the simulation of the flooding. However, the discharges are only used to optimize the simulated water levels until the model represents the maximum measured water levels of July 2021 precisely.

Figure 7 shows the catchment area of the River Geul in the Netherlands and the boundary discharges for the climate scenario are included. Section 6.2.1 explains in more detail where these amounts come from. To calculate total amounts of water based on the boundary discharges the measured water level graphs, as several were already shown in Section 2.2.2, are used to determine how large the peaks were. These graphs are added in the calculations.

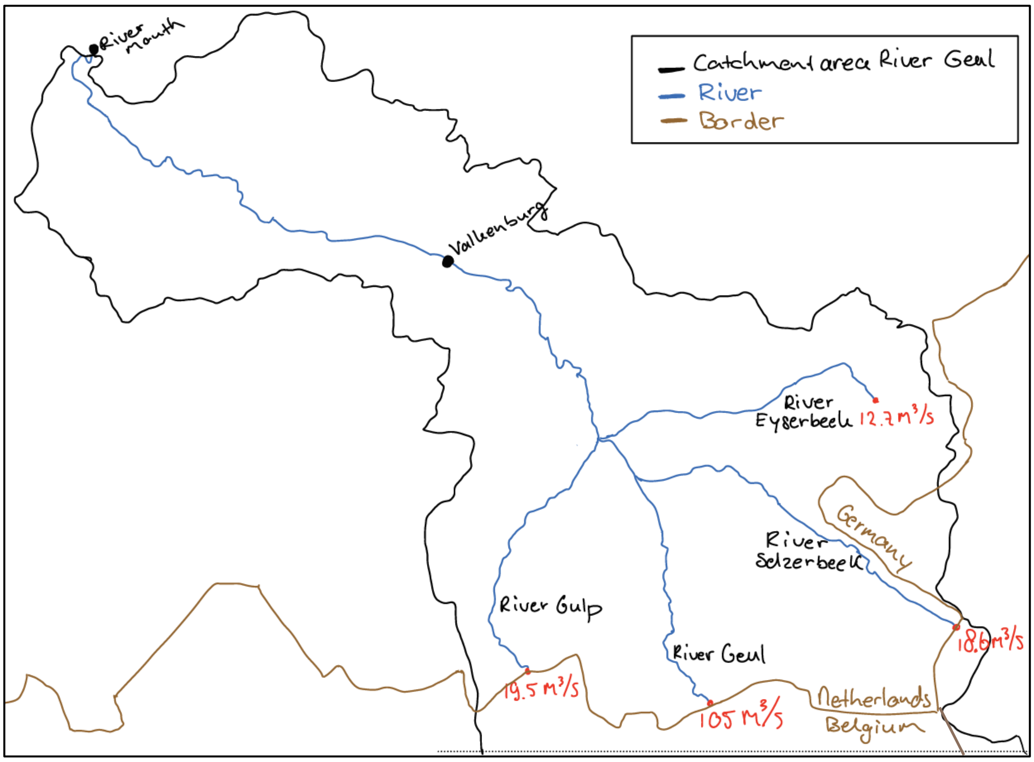



**Figure 7 Catchment area of the River Geul in the Netherlands. The discharges at the borders (and for the River Eyserbeek at the source) represent the first estimate for the flooding of July 2021 based on the climate scenario WH_Center 2050.**

To calculate the total amount of precipitation on the Dutch part of the catchment area of the River Geul the averaged maximum amount of precipitation that fell in 48 hours from the 13th until the 15th in Limburg is used. Multiplying this average amount of precipitation with the square metres of the catchment area eventually gives the total amount of precipitation in the system.

The quantification of the water distribution is expressed with a percentage that either Germany, Belgium or the Netherlands contributed to the total amount of water that enters the Dutch part of the catchment area of the River Geul during the flooding of July 2021.

Finally, a hand calculation is made to show how large a basin would be to store all the water in the Dutch part of the catchment area just upstream Valkenburg. Around 70% of the Dutch part of the catchment area of the River Geul lies upstream Valkenburg, which is used to calculate the amount of precipitation that has to be stored together with the discharges from the rivers. The research of Deuss et al. (2016) showed that the River Geul in Valkenburg is flooding at 47 m³/s. This value is subtracted from the total discharge reaching Valkenburg. This calculation gives a feeling about the size and amount of water that the River Geul and surrounding areas have to deal with during those extreme events.

## 4.2. Results

### 4.2.1. The river discharges

Figure 8 until Figure 11 show the hand calculations of the total amount of water that enters the Dutch part of the catchment area of the River Geul. The duration of the discharge peaks is estimated from the water level graphs, which are also shown in the figures.

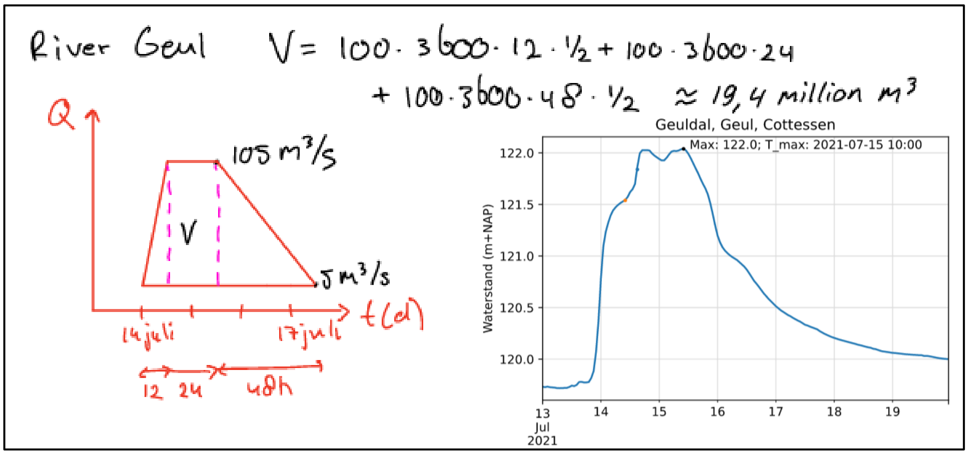



**Figure 8 Hand calculation of total amount of water during the River Geul discharge peak. Corresponding water level graph at the boundary on the left (https://hw2021.surge.sh/Alle_metingen.html).**

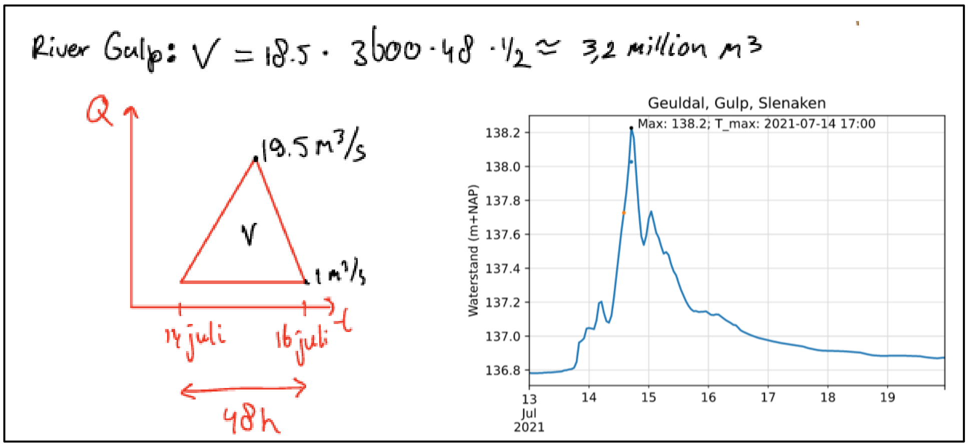



**Figure 9 Hand calculation of total amount of water during the River Gulp discharge peak. Corresponding water level graph at the boundary on the left (https://hw2021.surge.sh/Alle_metingen.html).**

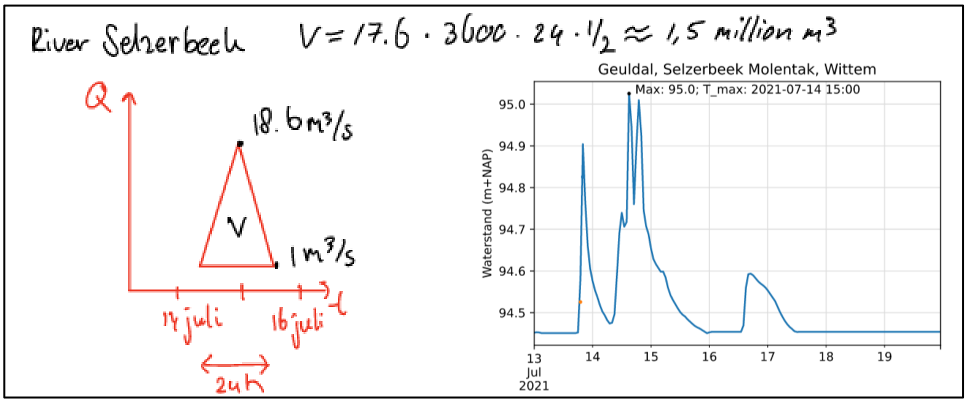



**Figure 10 Hand calculation of total amount of water during the River Selzerbeek discharge peak. Corresponding water level graph at the boundary on the left (https://hw2021.surge.sh/Alle_metingen.html).**

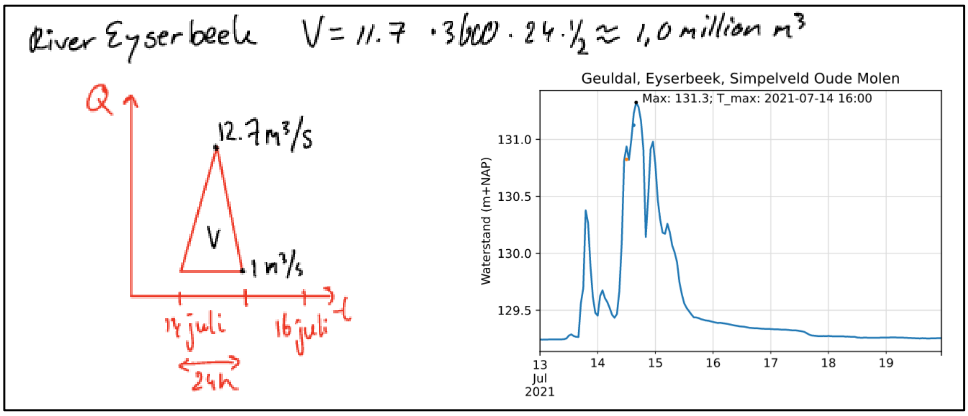



**Figure 11 Hand calculation of total amount of water during the River Eyserbeek discharge peak. Corresponding water level graph at the boundary on the left (https://hw2021.surge.sh/Alle_metingen.html).**

### 4.2.2. The precipitation of July 2021 in the Netherlands

In the research of Paarlberg (1990) the size of the catchment area of the River Geul is defined. Table 2 shows the overview of the total size and the size of the catchment area of the River Geul in the Netherlands.

| Size of the catchment area [ha] | |
|---|---|
| Total | Netherlands |
| 38.775 | 18.280 |

**Table 2 Overview size of the catchment area of the River Geul (Paarlberg, 1990)**

The most intense precipitation in the Netherlands only lasted for approximately 48 hours (ENW, 2021) and therefore only the amount of precipitation that occurred in these 48 hours is considered. An average of 150 mm precipitation in 48 hours was measured in the Netherlands during the flooding of July 2021 (ENW, 2021). The size of the catchment area of the River Geul in the Netherlands is multiplied with this 150 mm of precipitation. Figure 12 shows this calculation.

$$\text{Total amount of precipitation} = \frac{150\ \text{mm}}{10^3\ \text{mm/m}} \cdot 18.280\ \text{ha} \cdot 10^4\ \text{m}^2/\text{ha} \approx 27.4\ \text{million m}^3$$

**Figure 12 Hand calculation maximum amount of precipitation in 48 hours during the flooding of July 2021.**

### 4.2.3. The distribution of water

All the hand calculations are finished, and the water distribution is made visible in Table 3. The total amount of water that enters the Dutch part of the catchment area of the River Geul is shown and the sources of this total amount are expressed as a percentage of the total amount. In this way it is made visible how much water the Netherlands directly can control.

| Originating country | Name of the source | Duration [hours] | Amount of water [million m³] | Amount of water [%] |
|---|---|---|---|---|
| **Belgium** | Discharge River Geul | 84 | 19.4 | 43 |
| | Discharge River Gulp | 48 | 3.2 | |
| **Germany** | Discharge River Selzerbeek | 24 | 1.5 | 3 |
| **Netherlands** | Discharge River Eyserbeek | 24 | 1 | 54 |
| | Precipitation NL | 48 | 27.4 | |
| | | **Total** | 52.5 | 100 |

**Table 3 Distribution of water in the Dutch part of the catchment area of the River Geul, based on the calculations in Section 4.2.1 and 4.2.2.**

Table 3 shows that just half of the total amount of water in the Dutch part of the catchment area of the River Geul also comes from the Netherlands. This means that the discharge of the Dutch part of the River Geul is already majorly dependent on other countries. The question is how much of the precipitation in the Netherlands reaches the River Geul and increases the discharge in the River Geul. However, the contribution of the surrounding countries can only become larger when less precipitation reaches the river, which makes it almost impossible to solve the water issues at the source.

### 4.2.4. Example of necessary basin size upstream Valkenburg

To give an idea of how large a basin should be to temporarily store the discharge peak upstream Valkenburg a hand calculation is made (Figure 13).

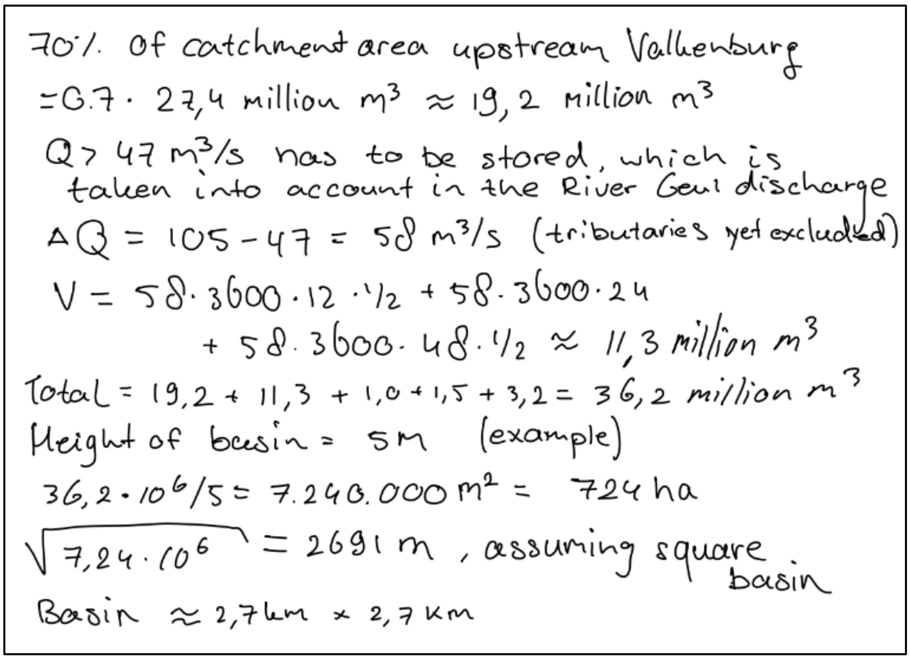



**Figure 13 Hand calculation of necessary basin size to store the discharge peak upstream Valkenburg for the flooding of July 2021.**

The calculation shows that a basin with a depth of five metres and a width of 2.7 by 2.7 kilometres would be necessary to temporarily store the wave peak. To give an impression of the size, Figure 14 shows the size of the basin on the map based on the height of five metres and an area of 724 ha.

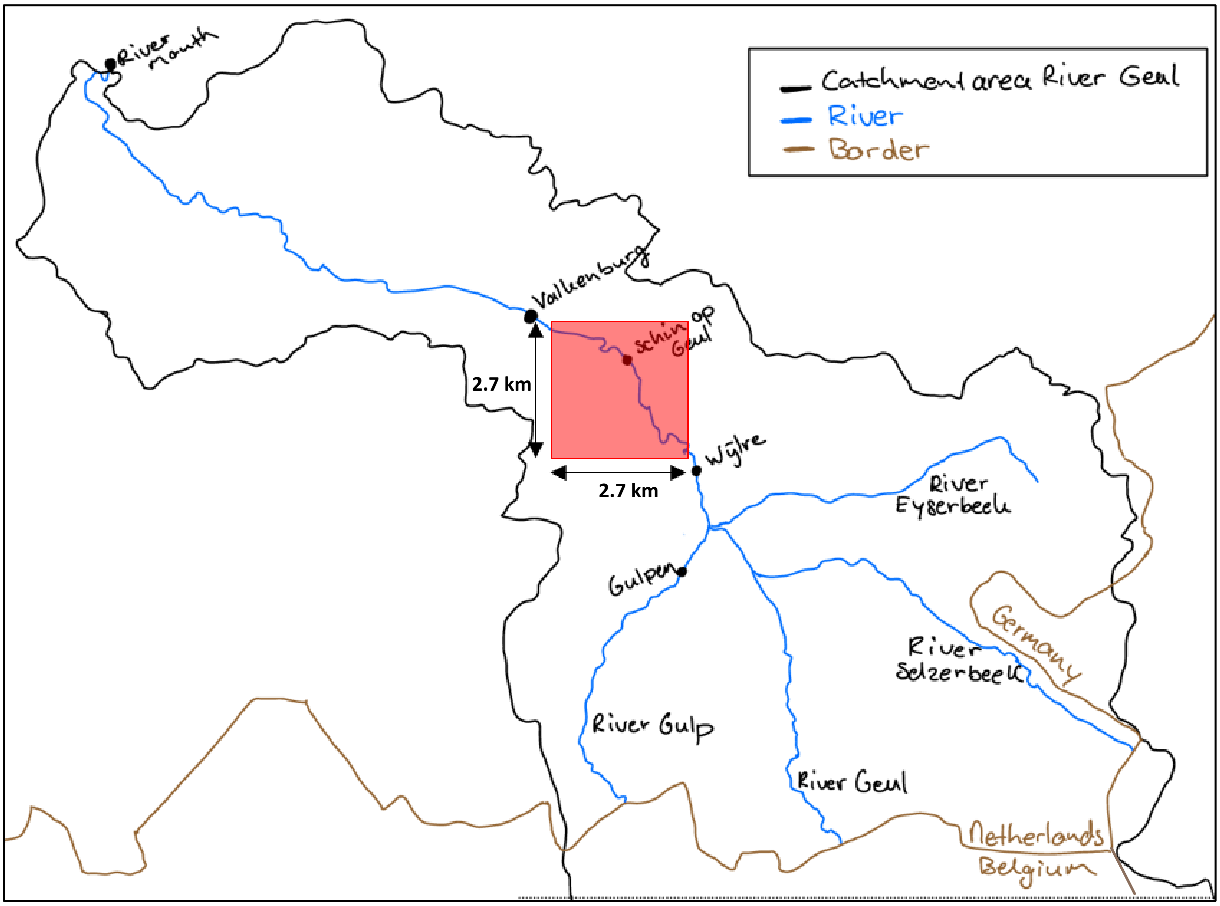



**Figure 14 The basin of 2.7 by 2.7 km in perspective on the map, drawn with a red box.**

## 4.3. Recap of Chapter 4

The contribution to the research of this chapter is showing the sources of water that entered the Dutch part of the catchment area of the River Geul during the flooding of July 2021. The sources and corresponding amounts of water show how dependent the Dutch part of the River Geul is on other countries during extreme events. This gives limitations in the possibility to apply measures at the source of the problem, because the source lies outside the Netherlands and in this research only the Dutch part of the catchment area is considered. Eventually sub-question 1 is answered in this chapter:

***SQ1 - How was the precipitation and discharge distributed over the Dutch part of the catchment area of the River Geul during the flooding of July 2021?***

The discharge of the River Geul is for a significant part dependent on the inflow from Belgium and Germany. During the flooding of July 2021 46% of the total amount of water in the Dutch part of the catchment area of the River Geul came from Belgium and Germany. The precipitation of the Dutch part of the catchment area contributed 52% of the total amount of water in the catchment area, while only 2% came from a tributary of the River Geul that originates in the Netherlands.

To get a feeling for the amount of water in the system a simple calculation is made. A basin with an area of 724 ha and 5 m depth would be necessary to temporarily store the water just upstream Valkenburg and prevent flooding in Valkenburg for an event like July 2021.

# 5. Climate scenarios versus July 2021

## 5.1. Methodology

An important aspect of designing solutions for river systems is taking into account climate change. It could be that extreme climate scenarios show an even more severe situation in the River Geul than the flooding of July 2021. Therefore, the climate scenarios are investigated.

The amount of precipitation that has fallen during the flooding of July 2021 is compared with the current climate scenarios in the Netherlands. The climate scenarios are explained according to precipitation duration lines because this is the necessary information to make a comparison with the amount of precipitation during July 2021. To compare the climate scenarios with the event of July 2021 a few investigations are performed. First, the climate scenarios are explained. Second, the amount of precipitation of July 2021 is shown and compared with the climate scenarios.

As it is already known that the most extreme precipitation that fell in Germany in July 2021 was much more intense than in the Netherlands, the precipitation of Germany is also compared with the climate scenarios. This gives insight into which stress test is the worst: the climate scenarios or the amount of precipitation that fell in Germany. Lastly, to validate the possibility that the amount of precipitation of Germany would fall on the catchment area of the River Geul, a comparison is made regarding the geographical location of the two areas.

## 5.2. Results

### 5.2.1. The climate scenarios

Climate scenarios (in the Netherlands) are possible future scenarios and are defined for the year 2050 and 2085. In the Netherlands, the climate scenarios have been adapted in 2014. The scenario WH (which was before 2014 known as W+) is being used for similar systems like the River Geul (KNMI, 2015). Where the discharges of the River Geul for the flooding of July 2021 were comparable to the WH_Center 2050, as explained in Section 3.2.1, the climate scenarios for the year 2085 showed representative amounts of precipitation for the Netherlands in July 2021. Figure 15 shows the precipitation duration lines for the climate scenario WH_Center 2085.

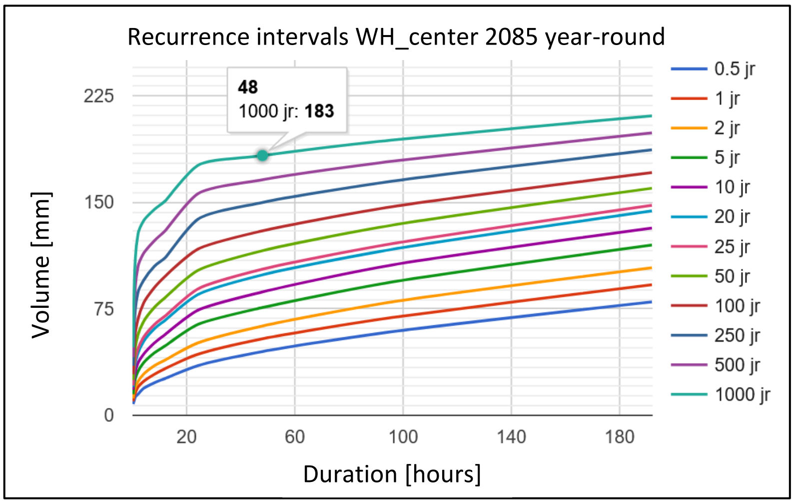



**Figure 15 Precipitation duration lines for the year 2085 year-round climate scenario WH_center, horizontal axis = duration [hours] and vertical axis = precipitation [mm] (Beersma et al., 2019).**

### 5.2.2. Precipitation of the Netherlands versus climate scenarios

The amount of precipitation that fell on the catchment area of the River Geul in July 2021 is based on measurements from waterboard Limburg and the KNMI. An average of 150 mm precipitation in 48 hours was measured in the Netherlands during the 13th until the 15th of July 2021. A local maximum of 182 mm in 48 hours was measured in Ubachsberg (the Netherlands), slightly to the east of the River Geul (ENW, 2021).

Comparing this maximum measured amount of precipitation of 182 mm in 48 hours with the precipitation duration lines of the climate scenario WH_Center for the year 2085 for a recurrence interval of 1/1000 per year shows almost the same value, with 183 mm precipitation in 48 hours (Figure 15). For the Netherlands, this 1/1000 per year precipitation line for 2085 shows that climate scenarios already take into account these amounts of precipitation. This is also in line with the estimate of the recurrence interval of 1/1000 per year in the research of ENW (2021). However, in Germany the amount of precipitation was much higher (ENW, 2021).

### 5.2.3. Precipitation of Germany versus climate scenarios

In Hagen, a place in Germany, a maximum value of 224 mm in 24 hours and 304 mm in 48 hours has been measured during the 13th until the 15th of July (Ruhnau, 2021). This is the record of July 2021 comparing the three countries, the Netherlands, Germany, and Belgium (ENW, 2021). Figure 16 shows the maximum measured amount of precipitation in Germany in 48 hours. The precipitation plume above Hagen is larger than the catchment area of the River Geul, which would mean that if the plume would be above the catchment area of the River Geul, everywhere in and around the catchment area would fall +/- 304 mm of precipitation in 48 hours.

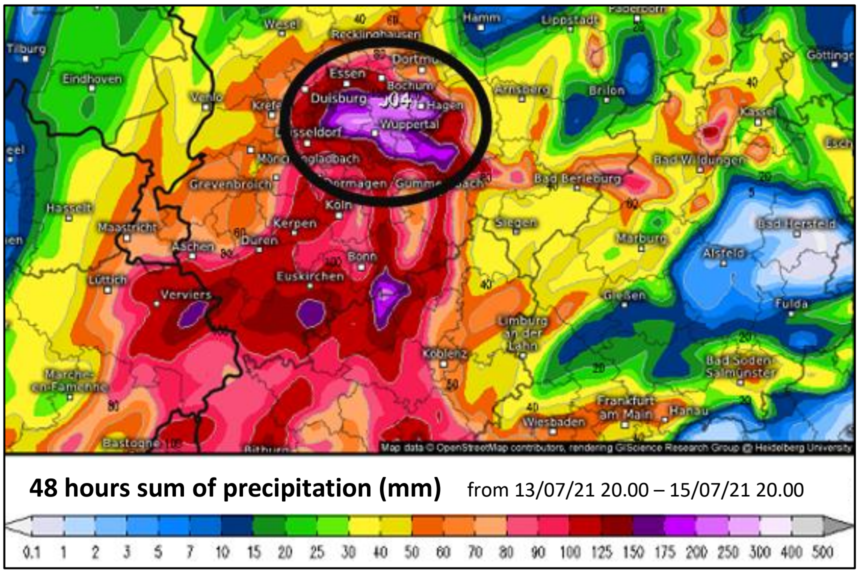



**Figure 16 48 hours sum of precipitation from 13/07/21 20.00 until 15/07/21 20.00, black circle = extreme precipitation plume (304 mm in 48 h) above Hagen (Ruhnau, 2021).**

Comparing the precipitation duration lines with the maximum measured amount of precipitation in Germany shows that there is still a major difference. The maximum amount of German precipitation in 48 hours was 60% more compared to the most extreme Dutch climate scenario (304 versus 204 mm). WH_upper 2085 is the most extreme Dutch climate scenario, with a recurrence interval of 1/1000 per year (see Appendix 5B, Figure 64).

It is safe to say that the climate scenarios are not sufficient to simulate a worse event than July 2021. The largest amounts of precipitation for the 1/1000 per year recurrence intervals for the year-round period are not even close to the amounts measured in Germany during the 13th until the 15th of July. The fact that this event happened during the summer makes the recurrence intervals of the event even lower, because during summer less intense rainfall compared to the year-round period is expected (Beersma et al., 2019).

### 5.2.4. Comparing geographical locations of precipitation

From the research of Rowe et al. (2008) it follows that precipitation is coupled to the elevation height of a certain area. Figure 17 shows the precipitation plume above Hagen (same as Figure 16) with number 1 and the catchment area of the River Geul with number 2. Because the elevation and the size of these areas is similar the assumption is made that this extreme precipitation event in Hagen could also have happened in the catchment area of the River Geul. The precipitation in Hagen was the most extreme during July 2021 and is later in this research used as a stress test for the simulation of measures.

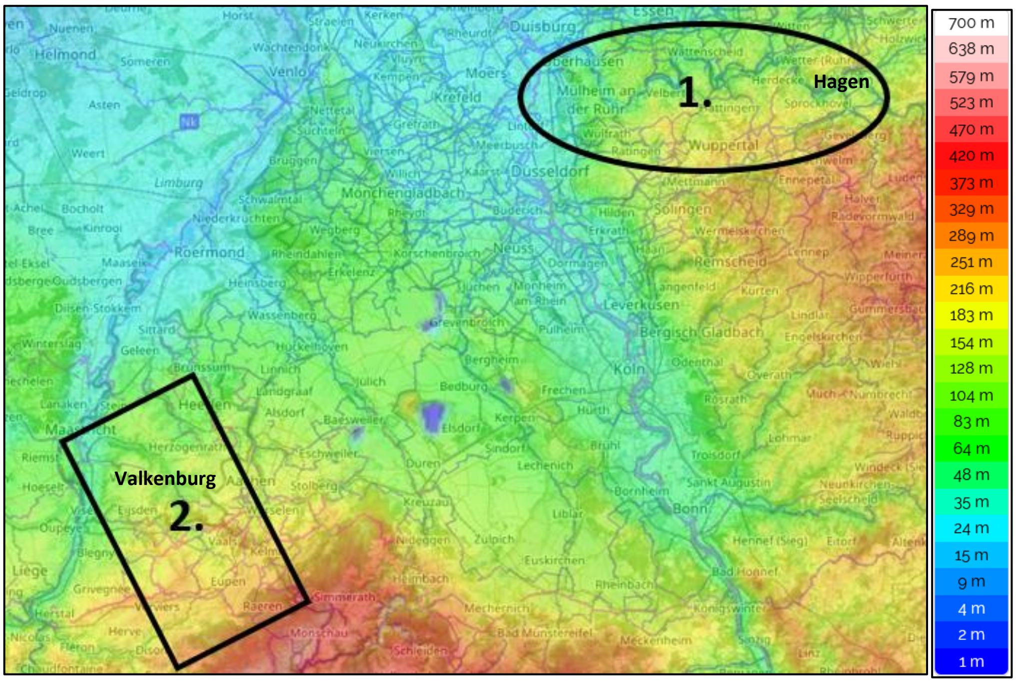



**Figure 17 Elevation map of Netherlands, Belgium, and Germany in m+NAP. Nr. 1 is the precipitation plume above Hagen. Nr. 2 is the catchment area of the River Geul (*Topografische kaart Europa, hoogte, reliëf*, 2021).**

## 5.3. Recap of Chapter 5

This chapter showed that for the amount of precipitation in Limburg (NL) in 48 hours during the flooding of July 2021 the scenario WH_Center 2085 for a recurrence interval of 1/1000 per year shows representative values, which means that the current climate scenarios already take into account similar extreme events. However, for the precipitation of Germany there are no current climate scenarios worse or similar to this event. In Germany, the precipitation in 48 hours was about 60% more compared to Limburg (NL) in July 2021. Because both the elevation and the size of the catchment area of the River Geul are comparable to the area of the extreme German precipitation the assumption is made that this extreme precipitation of Germany could also have happened in the catchment area of the River Geul (Rowe et al., 2008). Thereby, sub-question 2 is answered in this chapter:

***SQ2 - How extreme was the amount of precipitation of July 2021 in Limburg (NL) and surrounding areas in Germany compared to extreme Dutch climate scenarios?***

The amount of precipitation of Germany during the flooding of July 2021 was more extreme than the currently most extreme Dutch climate scenarios take into account. Therefore, the German precipitation is considered in this research for extreme future flooding. This event is later in this research used as a stress test for modelling purposes, together with the scenario of the flooding of the River Geul in July 2021.

# 6. Hydraulic model set-up and baseline simulations

This chapter is subdivided in three sections. Section 6.1 shows the methodology of the six subsections. Section 6.2 shows the corresponding results and Section 6.3 gives a recap of Chapter 6.

A small overview of the subsections is given. Section 6.1.1/6.2.1 elaborates on which hydraulic model is used and the input needed for this model. The calibration of the model for the flooding of July 2021 is explained in Section 6.1.2/6.2.2. In addition to the July 2021 scenario, Section 6.1.3/6.2.3 defines an even more extreme scenario, called the stress test, to represent extreme future flooding. In the next sections the baselines for the simulations are explained. Both the influence of the River Meuse (Section 6.1.4/6.2.4) and the bottlenecks in the River Geul (Section 6.1.5/6.2.5) are investigated. Section 6.1.6 explains the restrictions of the research.

## 6.1. Methodology

### 6.1.1. The hydraulic model and the input

A coupled SOBEK1D2DRR-model is used. This is a hydraulic model that combines a rainfall-runoff model with a 2D overland flow module to implement the precipitation and simulate a flooding. The use of a SOBEK model has a few reasons. First of all, the waterboard Limburg has already a calibrated and validated SOBEK model available of the River Geul, which saves a lot of time and is reliable. Secondly, a SOBEK model can combine a rainfall-runoff model with a hydrodynamic model which is important for this research. The precipitation was the main driver of the flooding of July 2021, and the implementation is an important aspect of this research. The third reason why SOBEK is used is the possibility to relatively easily simulate measures within the SOBEK model of the River Geul.

The input for SOBEK is subdivided into initial conditions, boundary conditions and precipitation:

- The initial conditions are already defined in the SOBEK model. These conditions can be used for this research because the initial conditions are only the starting point of the calculations. The initial conditions are the initial flow [$m^3/s$] and the initial depth in the channels [m]. The initial conditions do not have major influence on the eventual results. The boundary conditions do have major influence, and these are important to define for July 2021.

- The SOBEK model has five boundary conditions. Figure 18 shows the locations of these boundary conditions. The four discharge boundary conditions are:
  1. the River Geul at the Dutch-Belgium border,
  2. the River Gulp at the Dutch-Belgium border,
  3. the River Selzerbeek at the Dutch-German border,
  4. the River Eyserbeek at the source.

  The water level boundary condition is:
  5. the River Geul at the mouth.

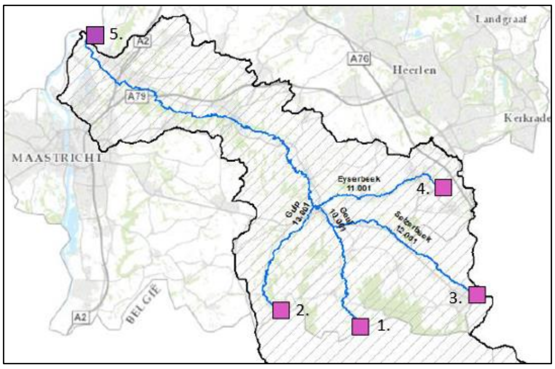



**Figure 18 Overview boundary conditions SOBEK model, nr 1-4 discharge B.C., nr 5 water level B.C.**

  The climate scenario WH_Center 2050 in combination with the existing discharge boundaries is used to define the discharge boundary conditions for July 2021. The water level boundary is based on measured water levels of July 2021.

- The precipitation is implemented as grid data coming from Meteobase. The precipitation is subdivided over multiple smaller areas of the catchment area. Figure 19 shows this division of the catchment area, the so-called shapefile. The combination of the shapefile and definition of the date is necessary to create a grid with the precipitation of July 2021.

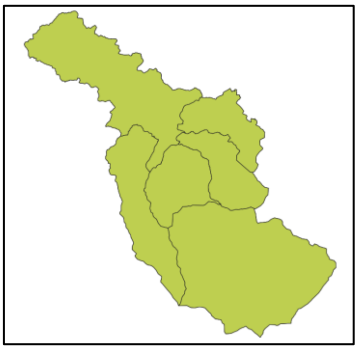


**Figure 19 Shapefile of the division of the catchment area (*SOBEK Suite*, 2013).**

### 6.1.2. Calibration July 2021

The existing SOBEK model is already calibrated but the calibration of this model needs to be optimized for the flooding of July 2021. The (improved) calibration is explained in this section and is based on the data of the flooding of the River Geul in July 2021. The goal of the calibration is to adapt the existing model such that it represents the flooding of July 2021 properly. This is done by comparing the output water levels from SOBEK with the measured maximum water levels during the flooding of July 2021. Section 6.2.1 shows the input which is used for this calibration. An iterative process of adapting the input of the discharge boundaries is performed to find an optimum between the representation of the simulated water levels in SOBEK and the maximum measured water levels during the flooding of July 2021.

### 6.1.3. Stress test

Based on the results of Chapter 5, the extreme precipitation of Germany in July 2021 is used for the stress test. The aim of this stress test is to show how the River Geul functions for even more extreme events than the flooding of July 2021. In Chapter 7 the simulation and evaluation of measures is also based on both July 2021 and the stress test to evaluate the impact of measures for extreme future flooding.

The stress test requires other boundary conditions than July 2021. Only the input of the discharge boundaries is adapted. The water level boundary at the River Meuse is assumed to remain the same as this is not part of the scope of the research. The discharge boundaries are mostly dependent on the amount of precipitation that fell upstream the boundaries, in the Netherlands, Belgium and Germany. The amount of precipitation measured upstream of the boundary conditions is used to make estimates for the discharges of the stress test. Appendix 5A, Table 33 is used for the measured amounts of precipitation over 48 hours in July 2021 upstream of the boundary conditions of the River Geul and the tributaries. The assumption is made that the discharge is directly influenced by the amount of precipitation.

Besides the input at the discharge boundary conditions, the maximum water level of the stress test is compared with the maximum water level of July 2021. A longitudinal cross section of the River Geul in Valkenburg is used to show the difference between both scenarios.

### 6.1.4. Influence of the River Meuse

In this section the influence of the River Meuse on the River Geul is investigated by simulating a few scenarios in SOBEK. The water level of the River Meuse is also simulated as a wave peak and is a boundary condition within the SOBEK model. The three scenarios that are simulated in SOBEK are:

1. both wave peaks arrive at the same time at the mouth (flooding of July 2021),
2. there is 1 day delay in between the wave peaks,
3. the wave peak of the River Meuse has double the size of July 2021.

The influence of the River Meuse is based on the water level difference in the River Geul between the three cases. The only difference between the three scenarios is the water level boundary condition: The River Geul at the mouth. To simulate these three scenarios the boundary conditions are adapted. Scenario 1 is already simulated, because this is the simulated flooding of July 2021. Scenario 1 is used as the reference scenario, and therefore the water level of the other two scenarios is compared to scenario 1. Scenario 1 makes use of the boundary conditions as defined in Section 6.2.1. For scenario 2 the wave peak of the River Meuse is moved one day back in time and for scenario 3 the wave peak of the River Meuse is doubled.

Doubling the wave peak of the River Meuse is done by subtracting the average water level at the river mouth from the wave peak of July 2021 and multiplying it with a factor of two. Table 4 shows an example of this calculation.

| Peak water level July '21 [m+CD] | Average water level July '21 [m+CD] | Peak minus average water level [m] | Difference in water level x 2 [m] | Double sized peak water level [m+CD] |
|---|---|---|---|---|
| 42.6 | 38 | 4.6 | 9.2 | 47.2 |

**Table 4 Example calculation scenario 3 with double the wave peak of the River Meuse during July 2021.**

### 6.1.5. Bottlenecks in the River Geul

A locally steeper step profile during maximum water levels, as visible in Figure 20, refers to a bottleneck in the system (Mosselman, 2007). This is the result of objects like weirs or bridges in the river. However, not each object in the river is a bottleneck. Bottlenecks are important to identify before implementing measures in a river system, because they can decrease positive effects of a measure or even increase the negative effects. Besides that, removal of bottlenecks can be a measure by itself. The definition of these bottlenecks is therefore important for the location of possible measures in Section 7.2.1.

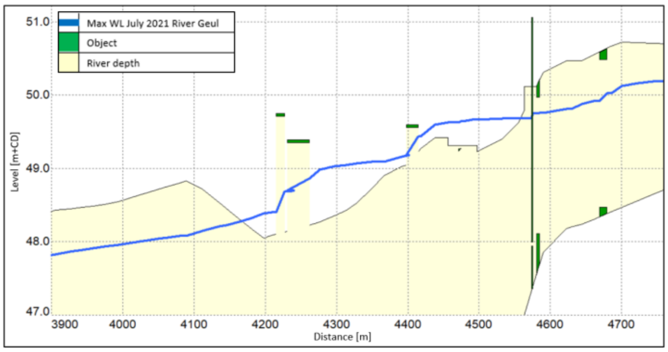



**Figure 20 Example step profile during maximum water level in the River Geul.**

To identify the bottlenecks in the system the calibrated SOBEK-model for the flooding of July 2021 is used. Longitudinal cross-sections with maximum water levels along the River Geul show these step profiles and indicate possible bottlenecks in the system. The source of the bottleneck is also given to indicate the origin of the step profile. Eventually, the backwater as a result of the bottlenecks for each river section is determined together with the length of the effect, based on the longitudinal cross-sections.

### 6.1.6. Restrictions of the research

To define the restrictions of the research a distinction is made between several topics. These topics cover the scope and the boundaries of this research. The accompanying restrictions are defined during the research and are part of the methodology to achieve certain results. The restrictions are as follows:

#### Policy-based restrictions

- The multiple Natura 2000 areas along the River Geul give limitations; within these areas it is the goal to maintain or improve the quality of biodiversity. Measures are not allowed to decrease the quality of biodiversity. Identification of the potential hydraulic and morphological effects on habitats is the task of the engineer, after which ecologists can assess the potential seriousness of the effects for the Natura 2000 areas and decision makers can make a decision.

Figure 68 in Appendix 6C shows the Natura 2000 areas in the catchment are of the River Geul. From Meerssen until Cottessen the River Geul is part of a Natura 2000 area, according to the European Habitat Guideline. Downstream Meerssen the River Geul no longer pertains to the Natura 2000 area, which is visible as an orange line in Figure 68. Multiple areas along the River Geul are also part of a Natura 2000 area as well as the River Meuse, where the River Geul eventually flows into.

- Cultural heritage should be considered when a measure requires removement of buildings. No decision is made in the research if a measure is feasible or not based on this fact. The locations of cultural heritage for the whole River Geul are available at the WebGIS Publisher – Viewer (2021).

### Measures

- Only hydraulic and hydrologic measures in the Dutch part of the catchment area of the River Geul which can be simulated with a hydraulic model and be evaluated equally are considered. Other solutions like making buildings in Valkenburg flooding proof are not considered. To demarcate the scope measures in Belgium and Germany are also not taken into account. The used hydraulic model only contains the Dutch part of the catchment area of the River Geul, so it would cost a lot of time to expand and calibrate this model for both Germany and Belgium.
- Hydraulic bottlenecks are used to define the location of the simulation of several measures. The bottlenecks of the water system are defined with a longitudinal water level profile computed with a calibrated model, which is further explained in Section 6.2.5. Only bottlenecks of the River Geul are identified. The research and the simulation of several measures is only based on these bottlenecks to limit the number of simulations. The largest discharge flows through the River Geul anyway. The possible bottlenecks in the tributaries and therefore specific measures in the tributaries are not taken into account, except for two measures which are not dependent of bottlenecks (enlarging current basins and weirs before the tributaries reach the River Geul).

### Modelling

- An existing SOBEK model of the River Geul from waterboard Limburg is used. This model was built in 2014 and has been validated and calibrated. The improvement of the calibration of this model is performed based on the flooding of July 2021. Validation or other calibrations are expected to be done already.
- Flood maps are normally used to calibrate the model, but these are not available from the peak moment at the night of the 14$^{th}$ to 15$^{th}$ of July (ENW, 2021). Only from the 16$^{th}$ of July a flood map is available (Het Waterschapshuis, 2021). That is after the peak moment and will not be used. Therefore, the calibration is only based on available measured water levels of the River Geul, River Gulp and River Eyserbeek during the flooding of July 2021. No measurements are available of the River Selzerbeek due to malfunctioning of the measurement equipment. The discharge of the River Selzerbeek cannot be calibrated because of that. The discharge of the climate scenario WH_Center 2050, as defined in Section 2.2.2, is used as a starting point for simulating the flooding of July 2021.
- The SOBEK evaluation of measures is only based on SOBEK simulations of the flooding of July 2021 and a stress test, which is based on the most extreme amount of precipitation that fell in Germany during the flooding of July 2021. Other less extreme but more frequent recurring events are not considered in this research. The precise recurrence intervals of the simulated events are unknown but according to ENW (2021) the flooding of the River Geul in July 2021 has a recurrence interval between 1/100 and 1/1000 per year, while for the stress test the expectation of the recurrence interval lays around 1/10.000 per year. The recurrence interval of the stress test is based on the flooding of the River Roer in July 2021 (WVER, 2021), which includes the most extreme amount of German precipitation as used for the stress test. The assumption is made that the recurrence interval of this event is also

representative for the stress test of the River Geul to make comparisons between the flooding of July 2021 and the stress test.

### Geotechnical

- The riverbed of the SOBEK model is calibrated for the conditions of 2014. It is expected that this is still representable, and no major changes occurred. Only close to the mouth of the River Geul some signs of erosion were visible after the flooding in July 2021 (ENW, 2021). However, these minor erosion signs are not taken into account because of the minor influence on the functioning of the River Geul system.

### Hydraulic/hydrological

- Discharges for the boundary conditions of the three tributaries and the River Geul are defined by the calibration of the SOBEK model. The maximum water levels in the River Geul during the flooding of July 2021 are known and the water levels at the mouth are known. The boundary discharges are iteratively defined, with the WH_Center climate scenario for the year 2050 as a first simulation (see Section 6.2.2).
- The SOBEK model contains several measurement stations which can give a flooding depth as output. However, this is a point measurement and does not show local flooding depths between the measurement stations. Therefore, longitudinal cross-sections of the maximum water level during flooding are compared for the cases with and without the simulated measure. In this way, the local decrease in water level is shown, but also the presence of urban areas and the length over which the water level change is defined. For the flooding depth only flood inundation maps can be used to show the local impact of measures, but these are hard to compare between different cases. Therefore, the assumption is made that an effective measure needs to decrease the local water level nearby urban areas to effectively reduce the damage as a consequence of flooding. Still, both the flooding depth at the measurement stations and the local water level are discussed for all the measures, but decisions are made based on the change in water level.

### Data

- The stress test, simulated in SOBEK, is based on the amount of precipitation that fell in Germany in July 2021. The quality and accuracy of these measurement stations in Germany is assumed to be proper. The research of ENW (2021) also made use of these values and no reports of non-functioning measurement stations are available.

### Catchment area

- The discharge of the River Geul coming from Belgium is a boundary condition in the model. The specified discharge takes into account the precipitation that fell in Belgium. This discharge is defined based on a climate scenario that is representative for the flooding of July 2021.
- The connection of the River Geul and Meuse is implemented as a boundary condition in the SOBEK model, and the influence of the River Meuse is studied separately using three scenarios. These scenarios are only implemented in this research to show what the influence of the River Meuse on the River Geul can be during flooding conditions. The impact of the River Meuse on the River Geul is rather important because the water level of the River Meuse can influence the flooding of the River Geul nearby the river mouth. It is however not the main goal of the research, but it shows the baselines of the research.

### SSM2017 & costs

- In this research only flooding depths as input for the damage functions in SSM2017 are used. SSM2017 underestimates the damages massively and therefore multiple damage and victim estimation techniques were combined for the research of ENW (2021) in 2021 (K. Slager, personal communications, February 2, 2022). However, estimating the damage and victims is only a small part of the research and therefore the choice is made to only use SSM2017 as it still can give insight into how measures reduce the amount of damage and victims compared to the current situation.

- The aim of using SSM2017 is to show the total damage in the catchment area of the River Geul and to compare the damage reduction of the several measures for the whole system. The limitation is that the damage is not assigned to a specific area in the River Geul, but for this research it gives plenty of information.
- For both SSM2017 and the cost estimates of the effective measures only the largest dimensions of the measures, simulated in SOBEK, are used for further evaluation. For example: river widening is simulated for 5, 10 and 20 m of widening, thus for the evaluation with SSM2017 and the estimation of the costs only 20 m of river widening is considered. The largest measures showed the largest impact on flooding depths and water levels in the River Geul and are therefore compared with each other.

## 6.2. Results

### 6.2.1. The hydraulic model and the input

The definition of the five boundary conditions is discussed in this section. Condition 1 until 4 are discharge boundaries and condition 5 is a water level boundary.

- The four discharge boundaries.

For boundary condition 1 until 4 the discharge is defined for the flooding of July 2021. This is done with available calculations and climate scenarios from waterboard Limburg. There are no accurate discharge measurements of the flooding in July 2021. The research from Deuss et al. (2016) is used which takes into account the 1/100 per year discharge distribution of the River Geul and the three tributaries, as defined by waterboard Limburg. ENW (2021) says that the climate scenario WH_Center for the year 2050 is a better estimate of the discharge during the flooding of July 2021 than the discharge belonging to a 1/100-year flooding event in the current climate. This is proven by comparing the water levels from the model with the measured water levels, see Appendix 7C1. This scenario takes into account a discharge of 105 m³/s at Cottessen (The River Geul at the Dutch-Belgium border). The known values from Deuss et al. (2016) for the 1/100 per year discharge distributions are used to interpolate the discharges of the tributaries for the climate scenario, which is visible in Table 5. Table 5 shows in green the interpolated discharges of the boundary conditions of the tributaries. These values are used as first input for the calibration of the SOBEK model. The available wave peak from the existing SOBEK model is adapted with the discharges as defined in Table 5. The duration of the wave peak is based on the water level measurements from waterboard Limburg.

| Boundary condition | Discharge 1/100 per year current climate [m³/s] | Discharge climate scenario WH_Center 2050 [m³/s] |
|---|---|---|
| **1 The River Geul at the Dutch-Belgium border** | 62 | 105 (given) |
| **2 The River Gulp at the Dutch-Belgium border** | 11.5 | 19.5 |
| **3 The River Selzerbeek at the Dutch-German border** | 11 | 18.6 |
| **4 The River Eyserbeek at the source** | 7.5 | 12.7 |

**Table 5 Overview of discharges boundary conditions 1-4 for the current climate scenario (Deuss et al., 2016) and the interpolated values (coloured green) for the WH_Center 2050 climate scenario based on the known 105 m³/s at B.C. 1 (ENW, 2021).**

The boundary condition, defined as a discharge, at the source of the Eyserbeek is also adapted, even though the source originates in the Netherlands. There are no accurate estimates available of the discharge during the flooding of July 2021. For the other two tributaries, the River Gulp and River Selzerbeek, the same method is applied, which makes the approach more general and reliable.

- The water level boundary at the river mouth.

For July 2021 the measured water level of the wave peak in the River Meuse at the mouth is used, because during the flooding of July 2021 the wave peak from the River Meuse and the River Geul arrived at the same time at the mouth of the River Geul. This is an additional effect that can raise the water levels in the River Geul significantly. The maximum measured water level at the River Mouth in July 2021 is 42.6 m+CD (Rijkswaterstaat, 2021). The influence of the water level of the River Meuse on the River Geul is investigated separately in Section 6.2.4.

- The precipitation

Meteobase uses the shapefile and a date, chosen from the 12th until the 16th of July 2021, to make grid data that can be used in the rainfall runoff module of SOBEK. A part of the created precipitation data is shown in Table 6. For the six areas in the catchment area, as defined in the shapefile, the amount of precipitation is shown.

| Date | Time | Sippenaeken [mm] | Hommerich [mm] | Meerssen [mm] | Eys [mm] | Partij [mm] | Azijnfabriek [mm] |
|---|---|---|---|---|---|---|---|
| **13-7-2021** | 09:00:00 | 0.26 | 0.58 | 0.89 | 0.67 | 0.68 | 0.36 |
| **13-7-2021** | 10:00:00 | 0.23 | 0.48 | 0.35 | 0.32 | 0.59 | 0.4 |
| **13-7-2021** | 11:00:00 | 0.22 | 0.31 | 0.27 | 0.22 | 0.32 | 0.27 |
| **13-7-2021** | 12:00:00 | 0.2 | 0.3 | 0.22 | 0.15 | 0.23 | 0.35 |

**Table 6 Output of precipitation for July 2021 catchment area River Geul from Meteobase (*Rasterdata*, 2021).**

### 6.2.2. Calibration July 2021

This section contains the summary of the calibration. The full explanation of the calibration can be read in Appendix 6A.

In the research of ENW (2021) the maximum measured water levels during the flooding of the River Geul and tributaries in July 2021 are given. These measurements are coming from the measurement locations of waterboard Limburg. The output of the SOBEK model of the River Geul is compared with these measured values. For each river, the average difference of the modelled and measured water levels for several locations is calculated to define how accurate the model represents the water levels. A few iterations are necessary to find an optimum. Eventually, with the following changes the model gives the best representation of the measured water levels:

1. the River Geul at the Dutch-Belgium border from 105 to 140 $m^3/s$,
2. the River Gulp at the Dutch-Belgium border from 19.5 to 16 $m^3/s$,
3. the River Eyserbeek at the source from 12.7 to 14 $m^3/s$.

Based on this calibration the input of the discharge boundary conditions for the scenario of July 2021, as defined in Section 6.2.1, are adapted. Table 7 shows the discharge boundary conditions before and after calibration.

| **Boundary Condition** | **July 2021 before calibration [$m^3/s$]** | **July 2021 after calibration [$m^3/s$]** |
|---|---|---|
| 1 The River Geul at the Dutch-Belgium border | 105 | 140 |
| 2 The River Gulp at the Dutch-Belgium border | 19.5 | 16 |
| 3 The River Selzerbeek at the Dutch-German border | 18.6 | 18.6 |
| 4 The River Eyserbeek at the source | 12.7 | 14 |

**Table 7 Discharge boundary conditions for July 2021, before and after calibration.**

### 6.2.3. Stress test

Table 8 shows the calculation of the discharges of the stress test based on the discharges corresponding to the calibrated discharges of July 2021 and the amounts of precipitation upstream the boundaries in the Netherlands, Belgium and Germany.

| Boundary condition | July 2021 discharges [m³/s] | Precipitation upstream the boundary [mm in 48 h] | Max precipitation Germany [mm in 48 h] | Stress test [m³/s] |
|---|---|---|---|---|
| **1 The River Geul at the Dutch-Belgium border** | 140 | 190 | 304 | $\frac{304}{190} * 140 = 224$ |
| **2 The River Gulp at the Dutch-Belgium border** | 16 | 190 | 304 | 25.6 |
| **3 The River Selzerbeek at the Dutch-German border** | 18.6 | 160 | 304 | 35.3 |
| **4 The River Eyserbeek at the source** | 14 | 150 | 304 | 28.4 |

**Table 8 Overview measured precipitation upstream of the boundary and maximum precipitation Germany. Calculated discharge for the stress test.**

Figure 21 shows the difference in water level between July 2021 and the stress test. Only a minor part of the River Geul is shown as an example, including Valkenburg. Overall, the water level rises with minimal 0.5 m along the whole River Geul as a consequence of the 60% higher discharge and precipitation amounts of the stress test.

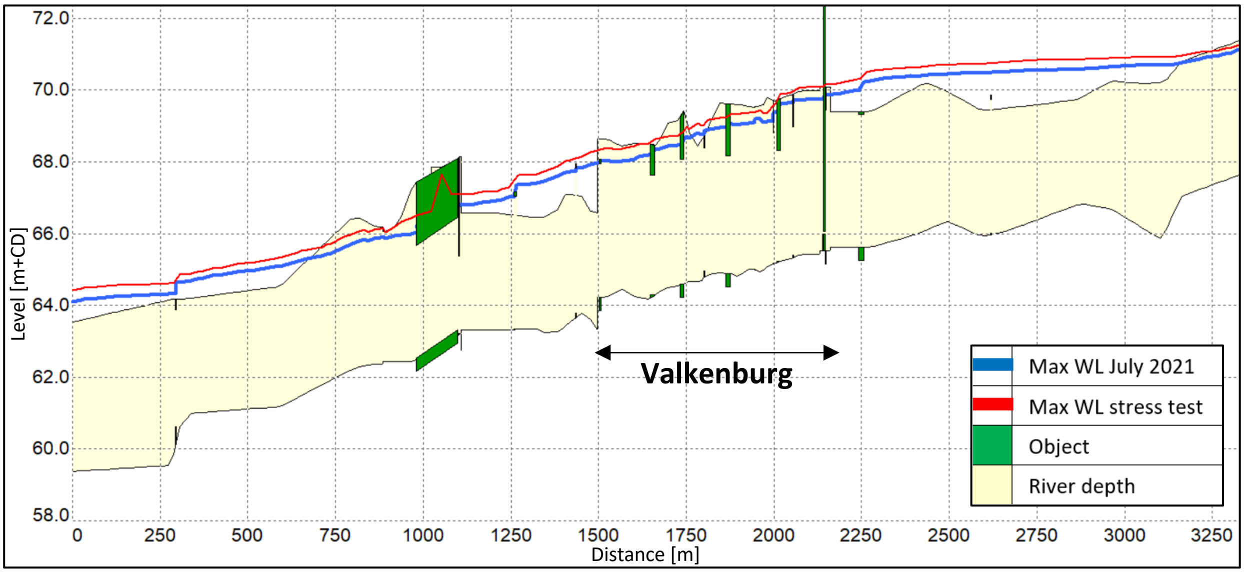



**Figure 21 Longitudinal cross-section of the River Geul along Valkenburg, comparing the maximum water level of July 2021 with the stress test.**

### 6.2.4. Influence of the River Meuse

In this section the influence of the River Meuse on the River Geul is evaluated. Table 9 shows for the three scenarios the water levels and the difference in water levels between scenario 2 and 3, compared to scenario 1. Directly visible from this table is that the influence of the River Meuse at the mouth of the River Geul only reaches until MS 2, close to Meerssen (as visible in Table 9). More upstream there is no difference in water levels between the three scenarios.

The major difference as a consequence of the peak delay or increased peak height is visible at MS 1, close to Bunde. One day delay in between the peak of the River Meuse and River Geul leads to lower water levels at MS 1 and MS 2, while doubling the peak leads to higher water levels at these locations. Despite the massive water level difference of 1.14 m at MS 1 after doubling the peak, the effect is almost gone at MS 2. In other words, the influence of the River Meuse at the mouth of the River Geul barely influences upstream water levels of the River Geul and never reaches Valkenburg during these extreme events.

| MS River Geul | Scenario 1 | Scenario 2 – 1 day delay | Scenario 3 – double the peak |
|---|---|---|---|
| | Water level [m+CD] | Difference with scenario 1 [m] | Difference with scenario 1 [m] |
| MS 1 | 46.12 | -0.11 | 1.14 |
| MS 2 | 49.75 | -0.01 | 0.02 |
| MS 3 | 52.8 | 0.00 | 0.00 |
| MS 4 | 58.88 | 0.00 | 0.00 |

**Table 9 Overview influence water level Meuse on the water level of the River Geul, based on three scenarios.**

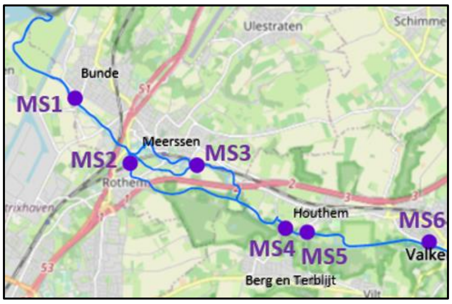



**Figure 22 Zoomed in on River Geul from Bunde until Valkenburg (MS 1 -6).**

The explanation behind the minor influence of the River Geul is illustrated with the backwater curve. The flow is subcritical (see Appendix 6B1) and the M1-backwater curve is limited in length. The book of Elger et al. (2016) explains the theory behind these backwater curves. The main driver of the backwater curve is the water level in the River Meuse, which is higher than the equilibrium depth of the River Geul for all three scenarios (see Figure 23 and Figure 67 in Appendix 6B2).

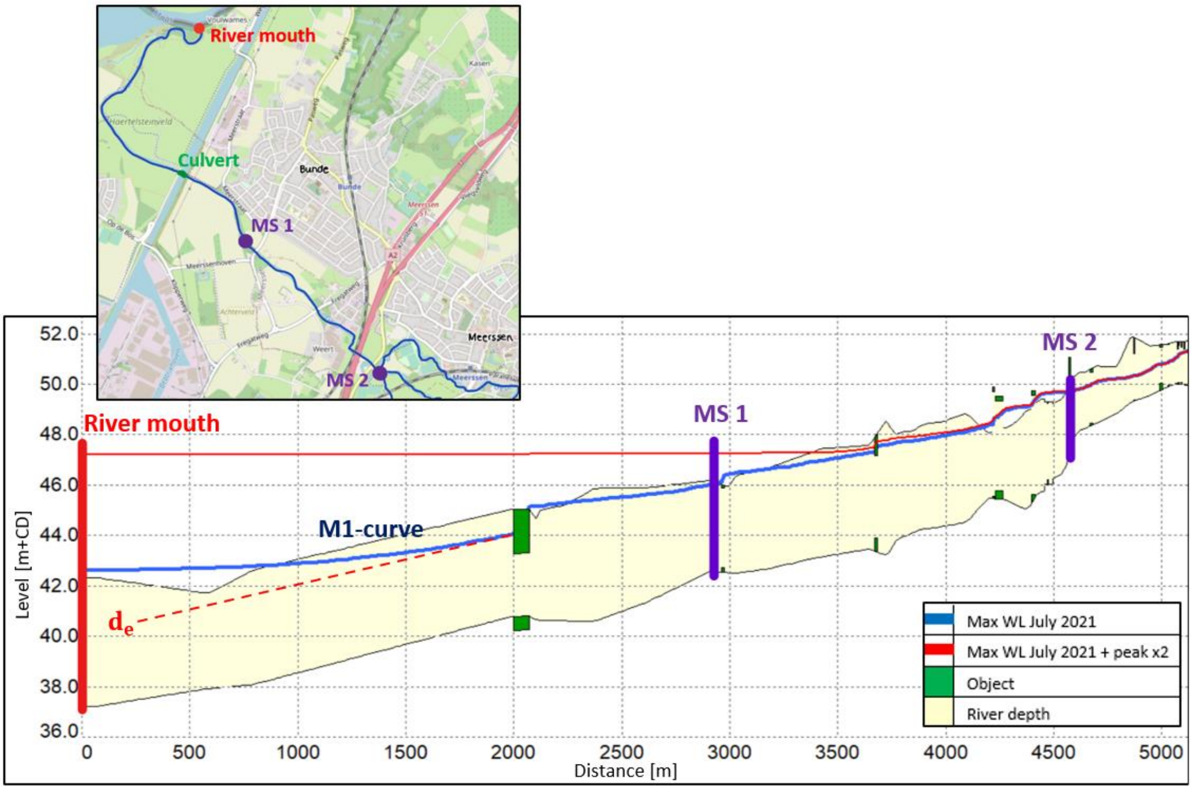



**Figure 23 Side view scenario 1 and 2: 1. Both peaks arrive at the same time at the mouth and 2. The peak of the River Meuse has double the size. The M1-backwater curve is also located.**

Figure 23 shows the M1-backwater curve and the transition towards equilibrium depth ($d_e$) properly. The River Geul adapts to the water level of the River Meuse until the water level of the River Geul is higher, which is the case more upstream. This transition happens with a M1-backwater curve until equilibrium depth is achieved. Figure 23 compares scenario 1 and 2, which shows major local differences, while the comparison of scenario 1 and 3 shows barely any differences (Figure 67, Appendix 6B2). In Figure 23 the main difference is visible downstream MS 1, where locally, the water level rises majorly. In between MS 1 and MS 2 this effect vanishes and the water level for scenario 1 and scenario 2 become the same again. Overall, the influence of the River Meuse on the water level of the River Geul is limited until just upstream MS 1 (upstream Bunde). With respect to the total length of the River Geul the influence of the River Meuse only reaches the lowest seven percent of the River Geul (4 out of 56 kilometres).

### 6.2.5. Bottlenecks in the River Geul

The catchment area is subdivided into three smaller sections: down- and upstream Valkenburg and in Valkenburg, as shown in Figure 24. The bottlenecks are investigated for each section of the River Geul.

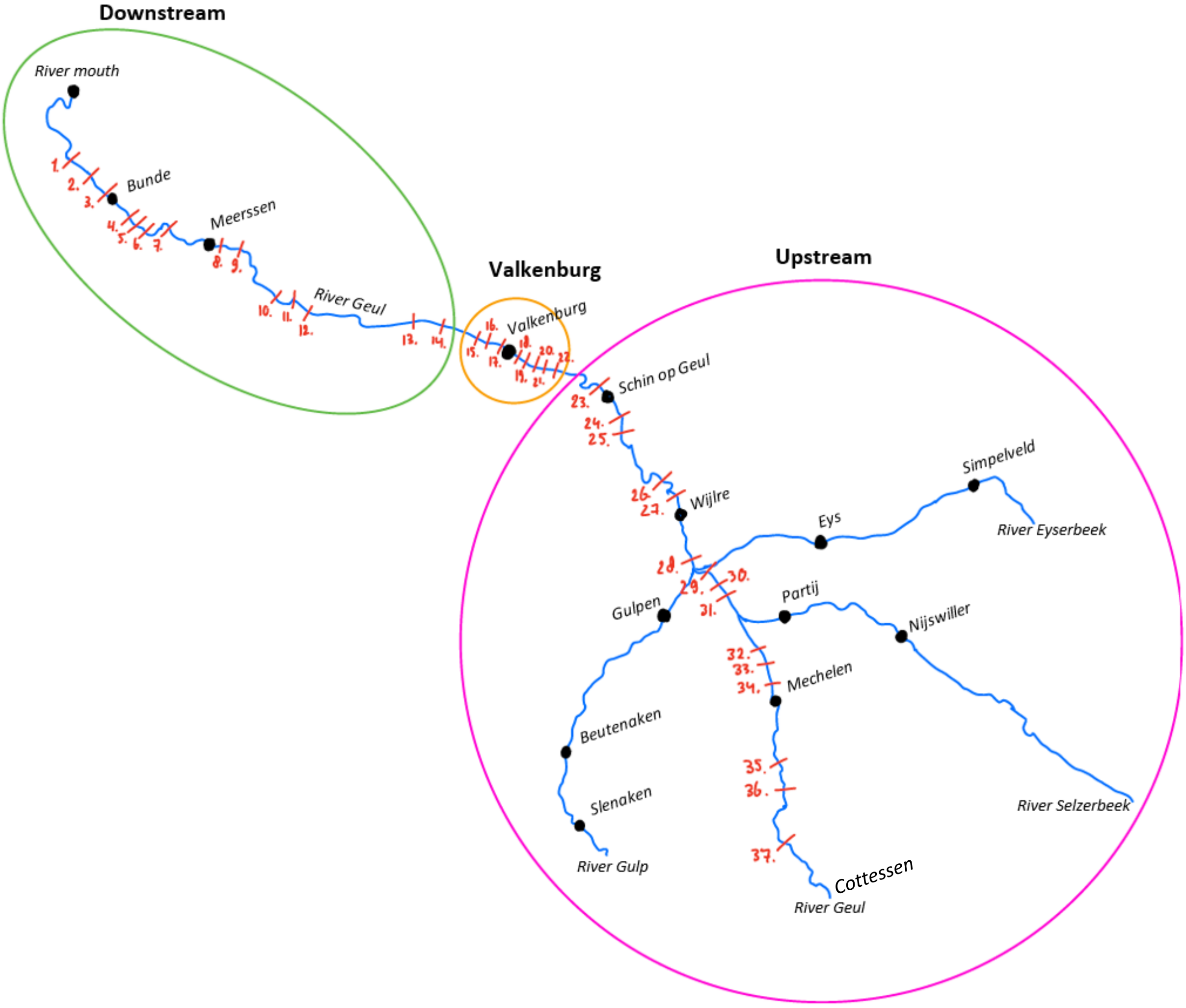



**Figure 24 Catchment area of the River Geul subdivided into three sections. The bottlenecks in the River Geul are numbered from 1 until 37.**

The bottlenecks along the River Geul are investigated prior to the definition of the measures. This is also divided into three parts, as shown in Figure 24. The bottlenecks of the River Geul are shown from the river mouth until the Belgium border in Cottessen. All the numbers of the bottlenecks are shown in both the longitudinal cross-sections (Figure 25, Figure 26 and Figure 27) and the top view of the River Geul (Figure 24). For all the bottlenecks (number 1 until 37) the source of the bottleneck is shown in Table 10. The longitudinal cross-sections of the bottlenecks along the River Geul show that these bottlenecks create major local water level differences. This is the result of changes in flow velocities due to for instance local narrowing or lower friction factors. This leads to unpredictable situations during flooding and has to be considered during the simulation of possible measures.

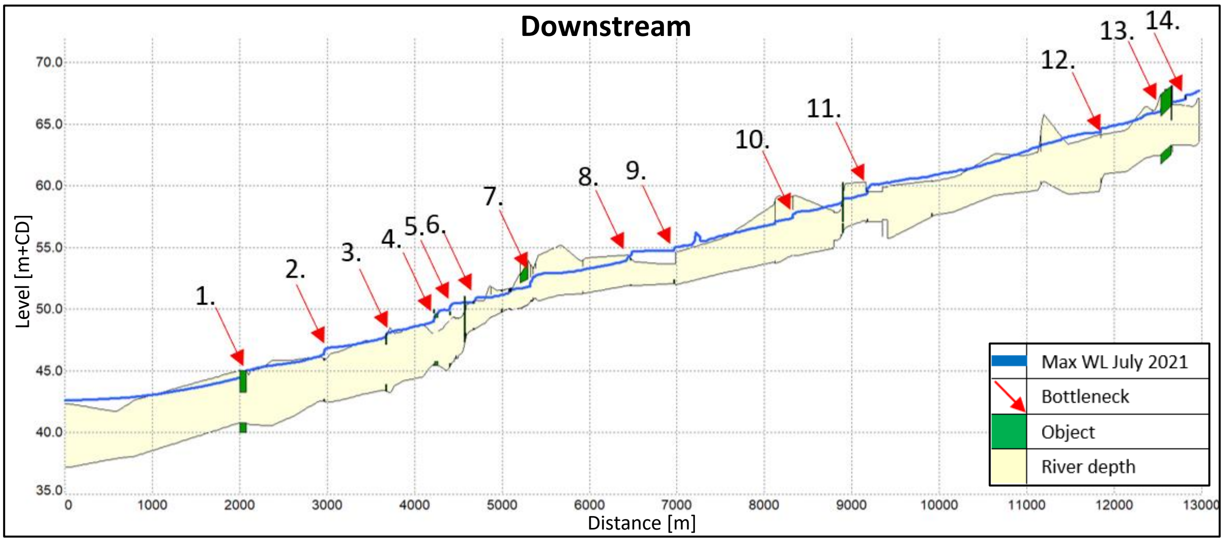



**Figure 25 Overview of bottlenecks in the River Geul from downstream Valkenburg until the river mouth.**

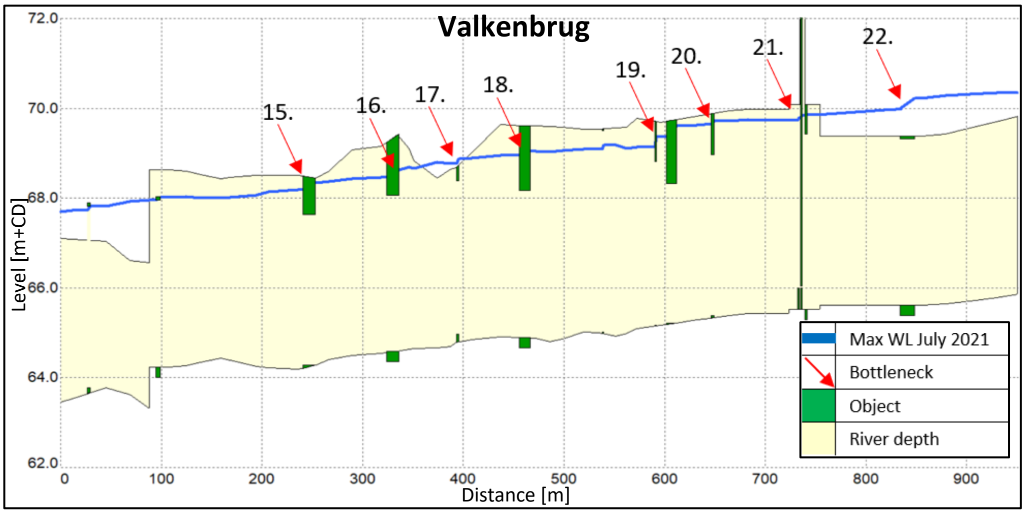



**Figure 26 Overview of bottlenecks in the River Geul along Valkenburg.**

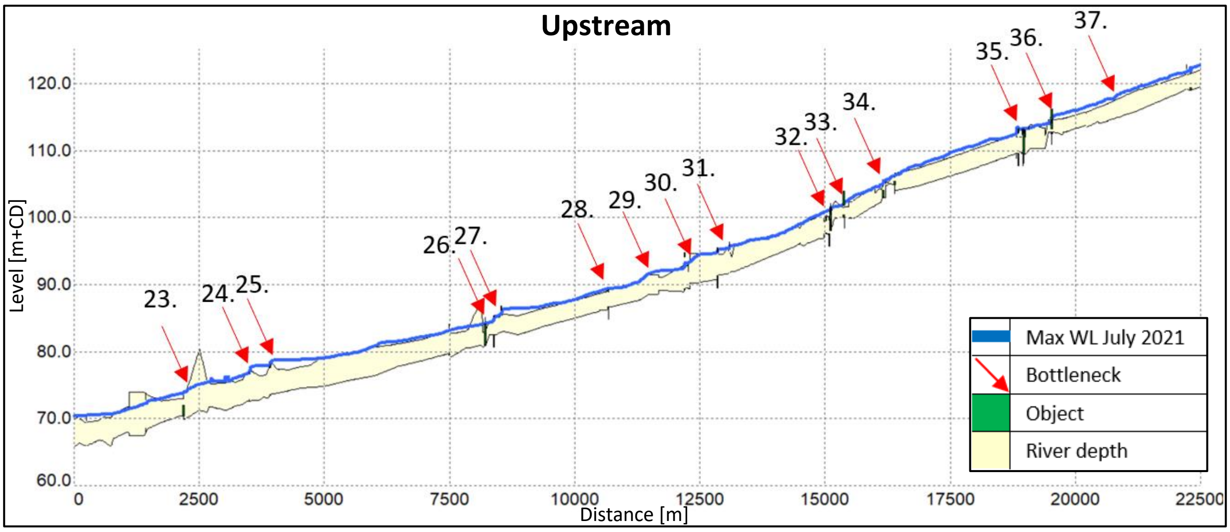



**Figure 27 Overview of bottlenecks in the River Geul upstream Valkenburg until Cottessen.**

Table 11 shows the source of the bottlenecks in the River Geul. These sources come from the SOBEK model and show what kind of bottleneck is the cause of the step profile in the longitudinal cross-sections.

| Area | Bottleneck nr. | Source of bottleneck |
|---|---|---|
| **Downstream** | 1 | Culvert Julianakanaal |
| | 2 | Bridge |
| | 3 | Bridge |
| | 4 | Bridge |
| | 5 | Weir |
| | 6 | Bridge |
| | 7 | Culvert |
| | 8 | Bridge |
| | 9 | Weir |
| | 10 | Bridge |
| | 11 | Orifice |
| | 12 | Bridge |
| | 13 | Bridge |
| | 14 | Culvert |
| **Valkenburg** | 15 | Bridge |
| | 16 | Bridge |
| | 17 | Bridge |
| | 18 | Bridge |
| | 19 | Bridge |
| | 20 | Bridge |
| | 21 | Weir |
| | 22 | Bridge |
| **Upstream** | 23 | Weir |
| | 24 | Bridge |
| | 25 | Bridge |
| | 26 | Weir |
| | 27 | Bridge |
| | 28 | Bridge |
| | 29 | Bridge |
| | 30 | Bridge |
| | 31 | Bridge |
| | 32 | Orifice |
| | 33 | Orifice |
| | 34 | Weir |
| | 35 | Culvert + bridge |
| | 36 | Bridge |
| | 37 | 4 weirs |

**Table 11 Sources of bottlenecks, based on the SOBEK model and Figure 25 until Figure 27.**

Based on Figure 25 until Figure 27 the influence of the bottlenecks on the water level of the River Geul is determined for each river section. Table 12 shows both the backwater and the length over which the backwater occurs. Eventually, the backwater per kilometre river length is calculated to make a fair comparison between each river section. From Table 12 it is clearly visible that in Valkenburg the bottlenecks cause the largest backwater per kilometre river length compared to the sections up- and downstream Valkenburg.

| River section | Backwater [m] | Length [km] | Backwater per 1 km [m/km] |
|---|---|---|---|
| **Downstream** | 6.5 | 11 | 0.6 |
| **Valkenburg** | 2 | 0.65 | 3.1 |
| **Upstream** | 10 | 20 | 0.5 |

**Table 12 Backwater as a result of bottlenecks for each river section, based on Figure 25 until Figure 27.**

## 6.3. Recap of Chapter 6

This chapter showed that an existing SOBEK model of the River Geul is available which is used for this research. The calibration of the model is optimized for the flooding of July 2021 by adapting the discharges of the WH_Center 2050 climate scenario and using the available water level measurements of the River Geul and River Meuse (near the mouth of the River Geul). Based on the simulation of the flooding in July 2021 and the measured amounts of precipitation in the Netherlands, Belgium and Germany, the stress test is also simulated. With the use of this hydraulic model, sub-question 3 is answered:

***SQ3 - What is the influence of the River Meuse and bottlenecks in the River Geul on the water level of the River Geul during flooding?***

According to the SOBEK simulations of the three different scenarios the influence of the River Meuse only reaches until Bunde in the most extreme case, which is when the peak of the River Meuse would have double the size. For this extreme scenario, the water level at Bunde goes up by over one metre. With respect to the total length of the River Geul the influence of the River Meuse only reaches until the lowest seven percent of the River Geul, which is equal to 4 out of 56 kilometres river length. Overall, the effect is very local due to the steepness of the River Geul. The influence never reaches areas upstream Bunde.

The SOBEK simulation of the flooding in July 2021 is used to identify the bottlenecks in the River Geul. A locally steeper step profile in the longitudinal water profile of the River Geul refers to a bottleneck in the system (Mosselman, 2007). This is the result of for instance a weir or bridge in the river system. The influence of these bottlenecks is creating flow velocity differences due to for instance local narrowing or lower friction factors with the consequence that during flooding the water level can locally rise or lower significantly. The influence is expressed in amount of backwater that the bottlenecks cause in the River Geul during the flooding of July 2021. In Valkenburg the backwater is about 3 m per kilometre river length, while up and downstream Valkenburg the caused backwater is only 0.5 m per kilometre. This is a major difference and shows that the bottlenecks have a much larger influence on the flooding of the River Geul in Valkenburg than elsewhere in the system. Bottlenecks also influence the effectivity of measures during flooding, which is considered in the simulated locations of measures. Section 7.2.1 elaborates on this aspect for several measures.

# 7. Evaluation of possible measures

This chapter is subdivided in three sections. Section 7.1 shows the methodology of four subsections. Section 7.2 shows the corresponding results and Section 7.3 gives a recap of Chapter 7.

In this chapter the evaluation of measures is discussed. This evaluation is subdivided into four subsections. First of all, the possible measures are defined in Section 7.1.1/7.2.1. An important aspect is which measures are simulated where, and how these measures function. Section 7.1.2/7.2.2 discusses the SOBEK output of each measure. A small sensitivity analysis of the SOBEK output is performed in Section 7.1.3/7.2.3. The measures from Section 7.2.2 that effectively reduce the flooding depth and water level nearby urban areas are evaluated on their impact in Section 7.1.4/7.2.4. SSM2017, costs, social impact, and Natura 2000 area are part of the evaluation in Section 7.1.4/7.2.4.

## 7.1. Methodology

### 7.1.1. Selection of possible measures

The goal of the measures is to reduce the impact of flooding, which can be achieved by lowering the flooding depth and water level in urban areas like Valkenburg without negatively influencing the flooding depth and water level in other urban areas along the River Geul. To fulfil this goal the catchment area is subdivided into three smaller river sections: down- and upstream Valkenburg and in Valkenburg, as already shown in Figure 24 for the bottlenecks. Downstream Valkenburg measures that lower the water level locally and upstream of the measure are useful, while in Valkenburg only a local effect is the most effective. Upstream Valkenburg the temporary retention of water and flattening of the peak wave for downstream areas is the aim.

The possible measures are based on the knowledge from the research of ENW (2021), the water distribution in the River Geul but also theory from River Dynamics. Furthermore, the bottlenecks are properly evaluated to define possible measures. The location of multiple measures down- and upstream Valkenburg is based on the bottlenecks in the system. In Valkenburg the measures are not dependent on these bottlenecks, because they either bypass the bottlenecks or can be simulated along bottlenecks (raising dikes for example).

The explanation of measures covers a few questions:

- Which measure is simulated where (and why this location)?
- How does the measure function?

The answers to these questions include statements, drawings, formulas, and top views (of the location where they are simulated).

### 7.1.2. SOBEK output of measures

In this section the results of the simulations in SOBEK are presented. For each measure the simulations are performed for two scenarios: the calibrated scenario for the River Geul of the flooding of July 2021 and the stress test which makes use of the most extreme German precipitation of July 2021 situated above the catchment area of the River Geul. A table with an overview of the results of each measure and a table which elaborates on these results is made. Further in Section 7.2.2 an elaborate explanation is given of the measures that showed effective results. A water level reduction without urban area, which thus leads to no damage reduction, is considered as not effective. These measures have no significant impact on future flooding, which does not fulfil the goal of this research.

Maximum water depths relative to street level (flooding depths) are used to show the results of measures at the measurement stations. Figure 82 in Appendix 7C shows all the measurement stations in the Dutch part of the catchment area of the River Geul. Longitudinal cross-sections of the maximum water level are used to explain certain results, show local effects and determinate the length effect of the measures. Also, maximum flow velocities are compared for several measures, but these are not considered for the effectiveness of measures, because the flow velocities are not calibrated with (none existing) measurements of July 2021. In general, only the locations are shown with significant differences relative to the simulations without measures.

### 7.1.3. Sensitivity analysis SOBEK simulations

A small sensitivity analysis is performed to show that the SOBEK-output is representing the effect of the measures properly. This is based on the change in flooding depth for the different simulations with a range of dimensions of each measure. Only one measure is elaborated as an example for this analysis.

### 7.1.4. The impact of effective measures

This section compares the impact of the measures based on the damage victim module. The measures that showed effective SOBEK results are evaluated with the damage victim module (SSM2017). A point of detail here is that only the largest dimensions of each measure are further evaluated with SSM2017 and expert judgement to show the maximum impact. The damage victim module makes use of the SOBEK output of each measure. Important to mention is that, in this case, SSM2017 only uses flooding depths as input for the damage functions. According to Kymo Slager, SSM2017 underestimates the damage and victims massively and therefore multiple damage and victim estimation techniques were combined for the research of ENW (2021) (K. Slager, personal communications, February 2, 2022). However, estimating the damage and victims is only a small part of the research and therefore the choice is made to only use SSM2017 as it still gives insight into how measures reduce the amount of damage and victims along the River Geul for both July 2021 and the stress test.

Expert judgement is used to make a first estimate of the costs of each effective measure. In this way better recommendations can be done regarding the economic benefit a measure has. To estimate the costs, use is made of SSK (standard cost estimation system, used in the Netherlands) and experts from Witteveen+Bos. The costs are based, among other things, on the buildings that have to be removed, the amount of soil that has to be removed and the material that is needed to realize the measure. Social impact is not taken into account in the costs because it is not easy to express this in amounts of money. Therefore, a comparison is made for the social impact of the effective measures. The social impact is based on the amount of buildings and objects that have to be removed. For instance, the people who have to leave their house because of a measure probably value a measure that spares their house much higher than for instance people who live in Valkenburg but do not have to sacrifice their house. Therefore, this is an important aspect to evaluate because decision makers have to take this aspect into account while comparing the measures. Furthermore, for each measure the use and flooding of Natura 2000 area and cultural heritage is researched.

## 7.2. Results

### 7.2.1. Selection of possible measures

Table 13 gives an overview of the measures that are simulated in each river section. Furthermore, the goal of the measure and the theory behind the measure is given.

| Section | Measure | Goal | Theory River Dynamics (expected effect) |
|---|---|---|---|
| Downstream | Enlarge culvert Julianakanaal | Prevent water level raise upstream of the culvert. | Higher discharge capacity leads to lower water levels close to the culvert and the backwater curve leads to lower water levels more upstream. |
| | Widen the river downstream | Decrease the water level locally and upstream of the measure. | A wider river leads to lower water levels in section Downstream, but the backwater curve can also lead to lower water levels more upstream (until Valkenburg). |

| | | | |
|---|---|---|---|
| **Valkenburg** | Remove channelization in Valkenburg | Lower the water level in Valkenburg. | Due to a locally higher discharge capacity of the river, the water level becomes lower, and the water level rises less quickly. |
| | Bypass: tunnel or additional channels around Valkenburg | | A bypass leads to lower water levels due to the division of discharge over multiple channels. The lower water level also affects the upstream part of the river. |
| | Raise dikes in Valkenburg | | Higher dikes lead locally to a higher safety level but increase the water level in the river. |
| | Remove obstacles in the River Geul, along Valkenburg | | Obstacles slow down the water, which means that removing them lowers the water level locally. |
| **Upstream** | Thresholds upstream Valkenburg | Lower the water level downstream of the measure. | Thresholds raise the water level upstream and slow down the water. A part of the wave peak is stored and spreads out. |
| | Weirs before the three tributaries reach the River Geul | | Weirs increase the water level upstream, but the peak can be spread over time by closing the weir. Therefore, maximum water levels downstream the weirs go down as the discharge of the tributaries arrives later. |
| | Add vegetation upstream Valkenburg | | Vegetation slows down the water, which induces water level raise. Flooding happens sooner (infiltration), and the peak flattens out. |
| | Raise riverbed upstream Valkenburg | | Riverbed raise induces a local water level rise. Flooding upstream happens sooner (infiltration), and the peak flattens out. |
| | Enlarge current basins | Lower the water level locally and downstream of the measure. | Enlarging basins creates additional storage capacity during flooding and therefore stores temporary a part of the wave peak which lowers water levels locally and downstream. |

**Table 13 Overview of possible measures with corresponding goal and theory of River Dynamics.**

The measures from Table 13 are further elaborated in the following subsections.

#### 7.2.1.1. Enlarge culvert Julianakanaal

***Which & where***

The location of the culvert is visible in Figure 29. The current culvert exists of five square openings. During the flooding of July 2021, two out of five openings were blocked (*Schoonmaakwerkzaamheden aan de Geulduiker*, 2021). This is a massive decrease in capacity, and this should also be investigated. The SOBEK model can show the effect of this event. Important to mention is that the report of HKV lijn in water (2009) mentions the following: The River Geul flows into the Grensmaas, after it flows with a culvert underneath the Julianakanaal. The capacity of this culvert is for any circumstances sufficient and will not give discharge limitations (HKV lijn in water, 2009, P. 27-2). In other words, the capacity of the culvert is sufficient for any future discharges. This would mean that increasing the capacity is unnecessary. This statement is validated with the SOBEK model.

***How***

Enlarging the culvert can be done by adding an additional opening, see Figure 30. The capacity increases, looking at the formula of Torricelli (Elger et al., 2016):

$$Q = \mu A \sqrt{2g\Delta h} \quad (7.1)$$

Only $A$, the cross-sectional area, changes. $\mu$, the contraction coefficient, $g$, the gravitational coefficient and $\Delta h$, the piezometric level do not change. The result is that $Q$, the discharge, goes up when $A$ goes up, according to formula 7.1.

Figure 28 shows the backwater curve in case that the discharge capacity of the culvert is too low, which is referred to as current situation. A m1-backwater curve exists (in case the discharge capacity is too low) and raises the water level upstream, dependent on the amount of obstruction of the culvert due to debris. The new situation is also visualized in Figure 28 and no backwater curve exists when the discharge capacity of the culvert is sufficient.

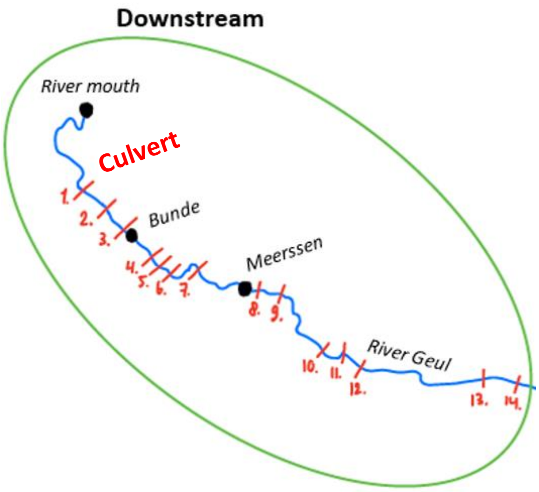



**Figure 29 Location of the culvert in the River Geul (number 1). Zoomed in on Figure 24.**

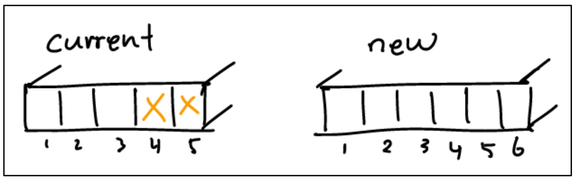



**Figure 30 Comparison current culvert with five openings, (three openings during flooding of July 2021), and an enlarged culvert with six openings.**

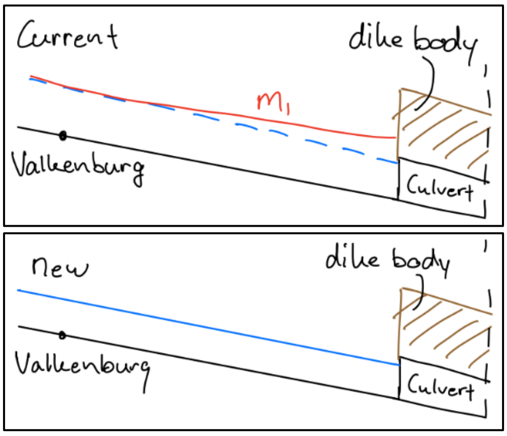



**Figure 28 Backwater curve current situation (top) and new situation (bottom), in case of limitation in discharge capacity.**

### 7.2.1.2. Widen the river downstream

***Which & where***

Widening the river downstream Valkenburg can be an effective measure to decrease the water level locally and upstream of the measure. Depending on the length of the backwater curve the water level in Valkenburg can decrease as well. The dimensions of the river widening are difficult to estimate. Therefore, several widths are simulated to show the effect. The river widening is simulated with 5, 10 and 20 m to give an overview of the influence of different widths.

The location of the river widening is based on the bottlenecks from Figure 25 and the urban areas along the River Geul. In Figure 31 the locations of the river widenings are visible, together with the length of the river widenings. These lengths are based on the cross-sections in between of the bottlenecks. This method is used for all the measures. However, the area in the green box in Figure 31 shows a part of the river without any urban area and bottlenecks nearby. As optimization this area, defined as ‘A.’ in Figure 31, is also widened for the simulation of 20 m river widening, to show the maximum effect.

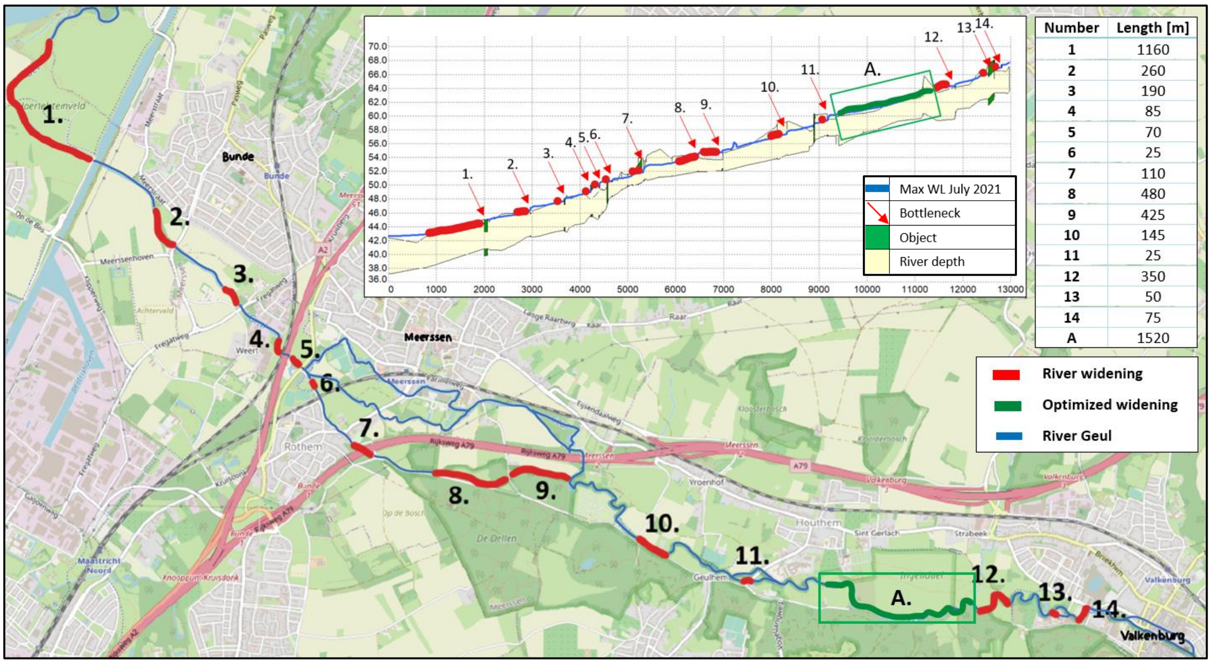


**Figure 31 Locations of river widening downstream Valkenburg, shown with a top view and longitudinal cross-section. The table shows the length of the river widening.**

### *How*

Figure 32 shows the effect of widening the river. Where the widening takes place, the water level decreases locally significant compared to the current situation. This is explained with the formula of equilibrium depth (Elger et al., 2016):

$$d_e = \left(\frac{c_f}{i_b}\frac{Q^2}{B^2 g}\right)^{\frac{1}{3}} \tag{7.2}$$

$B$, the width, goes up when widening the river. $Q$, the discharge, $g$, the gravitational constant, $c_f$, the resistance factor and $i_b$, the bed slope, remains the same. This means that $d_e$, the equilibrium depth, goes down according to formula 7.2.

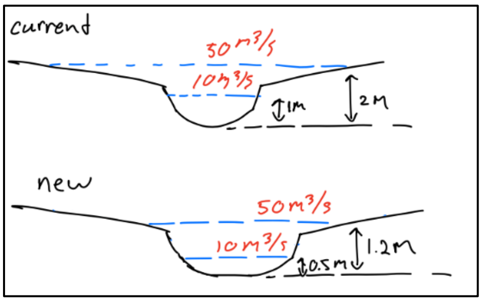


**Figure 32 Widening of the river, fictive water level change for 50 and 10 m³/s.**

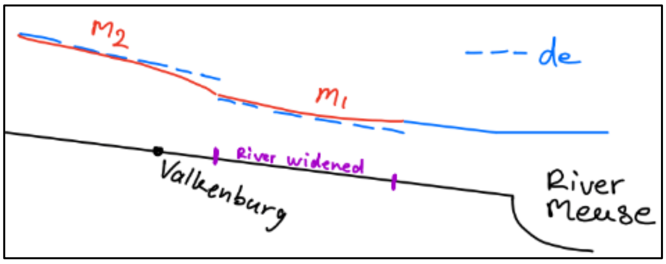


**Figure 33 Backwater curve after widening the river, fictive representation of the decrease in water level.**

Figure 33 shows the backwater curves after widening the River Geul downstream Valkenburg. Due to the lower water level as a result of widening the river, a m1-backwater curve along the widened reach takes place. Upstream the widened reach a m2-backwater curve moves along Valkenburg. If this m2-backwater curve is long enough the water level in Valkenburg decreases, which is shown in Figure 33. In that case, the river section upstream Valkenburg might also be influenced.

### 7.2.1.3. Remove channelization in Valkenburg

***Which & where***

Removing the channelization in Valkenburg is simulated for both the River Geul and the 'Molentak' in Valkenburg, as shown in Figure 34. Figure 35 shows a cross-section before and after the measure. An angle of 45 and 30 degrees is simulated to show the effect of different increases of the discharge capacity.

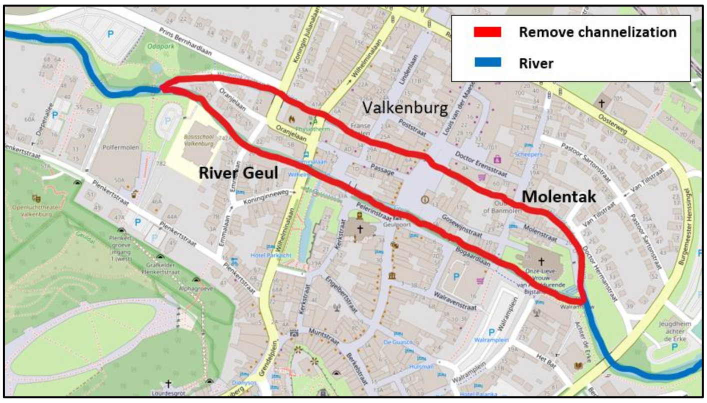



**Figure 34 Locations of removing channelization in Valkenburg.**

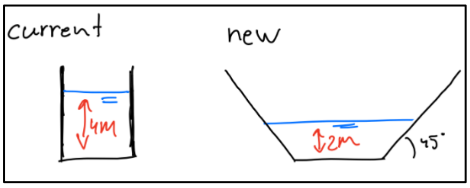



**Figure 35 Removing channelization, current and new situation. Water levels are fictive.**

***How***

Removing the channelization in urban areas and giving the river more space leads to a significant water level drop. The overall discharge capacity of the river becomes larger, and flooding happens at higher discharges. In fact, formula 7.2 can be used again in this case. The average width becomes larger which means that the equilibrium depth becomes smaller. Furthermore, the water level rises less quickly due to the higher capacity which leads to more time to evacuate in urban areas. However, removing the channelization requires a lot of space and in an urban area this might not be an option.

### 7.2.1.4. Bypass: tunnel or channel through Valkenburg

***Which & where***

The major damage as a consequence of the flooding of the River Geul in July 2021 happened in Valkenburg (ENW, 2021). However, in Valkenburg limited amount of space is available due to the many buildings. A bypass in the form of a tunnel or additional channel could be the solution.

The exact location of the bypass has to be further analysed, but this is not part of the scope of this research. However, a few options are investigated to explain certain choices. According to Figure 36 Valkenburg lays in a valley. Directly when the urban area changes into rural area, the steep hills surround Valkenburg from both sides of the River Geul. Therefore, a bypass around Valkenburg is not considered as an option.

A tunnel underneath the River Geul in Valkenburg, which requires deepening of the River Geul, is also investigated, but due to the instable soil (see Figure 69, Appendix 7A) and many buildings directly along the River Geul in Valkenburg this is also no option because the foundation would have to be improved. This would mean that around fifty buildings along the River Geul in Valkenburg have to be removed to implement this measure. There is not enough space to construct a tunnel in the current situation (Tessa Deggeller, personal communications, February 9, 2022).

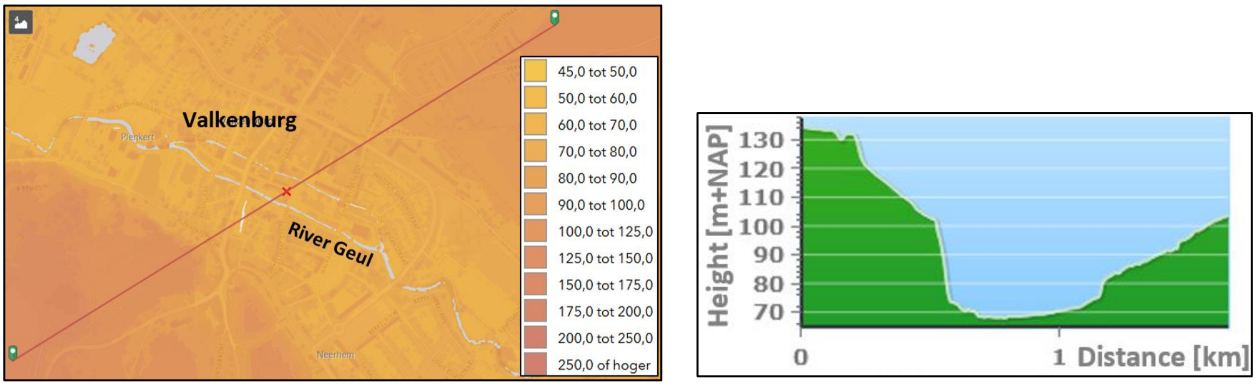



**Figure 36 On the left, an AHN4 top view (in m+NAP) of Valkenburg. On the right, a cross-sectional view, which is defined with a red line in the AHN4 top view (*ArcGIS Web Application*, 2021).**

According to the previous statements a bypass around Valkenburg is no option and a tunnel under the River Geul would be an even more extreme operation to realize because of the packed city centre around the River Geul. The remaining options in this research are:

1. tunnel through Valkenburg, either in-situ or drilled,
2. channel through Valkenburg.

Important to mention is that a drilled tunnel requires a specific subsoil. According to Jeroen de Leeuw (Witteveen+Bos) a drilled tunnel is feasible, because the deeper subsoil consists of marl and flint. The first few metres consist out of a mixture of marl, clay and sand which is also no problem for drilled tunnels. Only rough gravel would lead to problems, but this is not located in this area (J. de Leeuw, personal communications, February 14, 2022).

Figure 38 shows a 3D drawing of how this channel or tunnel would look like. Figure 37 shows a top view of the location of the bypass with respect to Valkenburg which is based on a Google Street View investigation of the area. The location of the in- and outflow of the bypass is visible in Google Street View (Google, n.d.) in Appendix 7A, Figure 70 and Figure 71. The location is based on the number of buildings in the area and the angle with the current river. Therefore, the bypass is not completely straight.

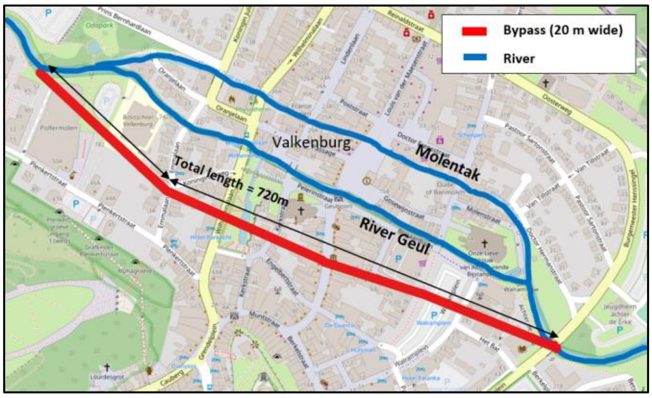



**Figure 37 Location of bypass through Valkenburg.**

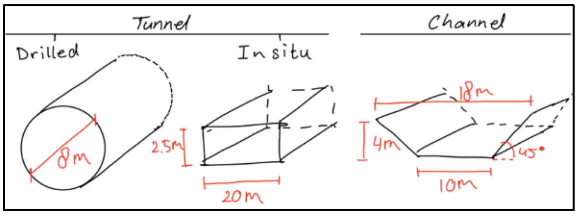



**Figure 38 3D drawing bypass, tunnel, and channel.**

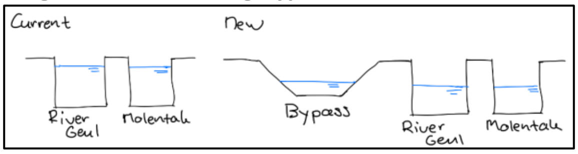



**Figure 39 Example division of water in Valkenburg, on the left the current situation and on the right the new situation with a bypass.**

The necessary dimensions of the bypass are difficult to estimate. Appendix 7A, Figure 73 shows a hand calculation that estimates the amount of discharge that has to go through the bypass. This is used as a starting point to compare the bypass with the culvert underneath the Julianakanaal. The size of the culvert underneath the Julianakanaal is 12.5 by 2.5 m. After running a simulation with this size a few alternatives are defined to show the effect of the bypass for different sizes. For both the tunnel and channel the cross-sections of the different sizes are in the same order of magnitude to make a fair comparison. The length of the bypass is 720 m, and the following dimensions of cross-sections are used:

- tunnel in-situ: 10x2.5 m, 15x2.5 m and 20x2.5 m or drilled: inner diameter D = 5.5, 6.75 and 8 m (two drilled tunnels next to each other can increase the feasibility but this is not further discussed),
- channel: bottom width of 2 m and top width of 10 m, bottom width of 5 m and top width of 13 m and bottom width of 10 m and top width of 18 m (see Figure 38). Depth of 4 m for all dimensions.

A smaller bypass of 5x2.5 m is also simulated but this bypass showed barely any water level reduction compared to the current situation and is therefore not used in this research (see Appendix 7A, Figure 72).

***How***

The bypass takes a part of the discharge away of the main river, which leads to lower water levels in the River Geul and Molentak. Figure 39 shows what happens with the water levels. This is just a fictive example, but it explains the way that the discharge is divided over the several channels. In formula 7.2 only $Q$, the discharge, changes for the existing channels with the result that $d_e$, the equilibrium depth, changes. The upstream part of the river is also affected because flooding and slowing down of the water happens at higher discharges. This induces an additional water level drop compared to the current situation. The disadvantage of a bypass is the amount of space it requires and the difficulties of implementing the bypass in a dense urban area.

#### 7.2.1.5. Raise dikes in Valkenburg

***Which & where***

Raising dikes can be beneficial to delay or even prevent flooding in Valkenburg. Figure 40 shows a typical situation in Valkenburg with a dike on the left and a house on the right, which also functions as a dike. The location of raising the dikes is the same as removing channelization, as shown in Figure 34. The calibration showed that the maximum flooding depth just upstream Valkenburg was 0.8 m during July 2021. Therefore, the dikes are simulated with a raise of 0.5 and 1.0 m to show the effect of different dike raises.

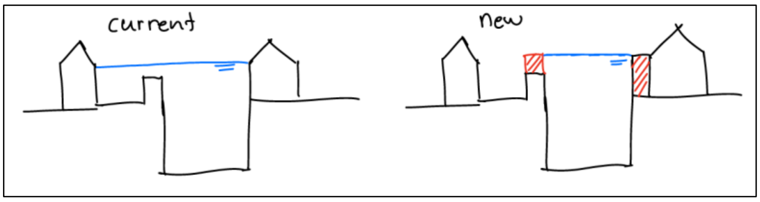



**Figure 40 On the left a typical example in Valkenburg with a dike on the left and house on the right, which also functions as a dike. On the right, the new situation with a raised dike.**

***How***

Raising the dikes increases the discharge capacity in Valkenburg, because the cross-sectional area of the River Geul becomes larger, as shown in Figure 40. Furthermore, the up- and downstream part of the river is affected because flooding and slowing down happens at higher discharges. This induces a water level drop upstream Valkenburg, but a water level raise downstream Valkenburg compared to the current situation. A disadvantage of raising dikes in urban areas is the blockage of the view in the city, and the possible requirement of removing buildings.

#### 7.2.1.6. Remove obstacles in the River Geul, along Valkenburg

***Which & where***

In the River Geul in Valkenburg many bridges are present. The columns and deck of these bridges slow down the water significantly and during the flooding of July 2021 some bridges even flushed away due to the large forces on these bridges. Removing the old bridges and building new bridges in a slimmer way without obstructions in the river reduces backwater. Figure 41 shows a visualization of the current and new situation in Valkenburg. Figure 42 shows all the obstacles (bridges) in the river along Valkenburg.

For this research, the bridges are completely removed in the hydraulic model, without simulating slimmer bridges. Similar effects are expected, because slimmer bridges barely slow down the water and thus lead to an insignificant increase in water level during flooding.

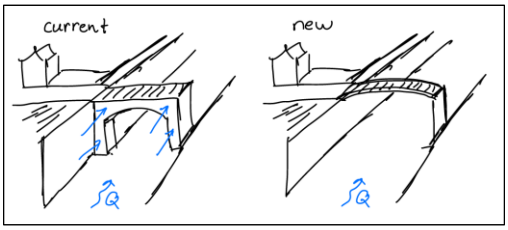



Figure 41 On the left the old bridge with resistance, on the right the new bridge without resistance.

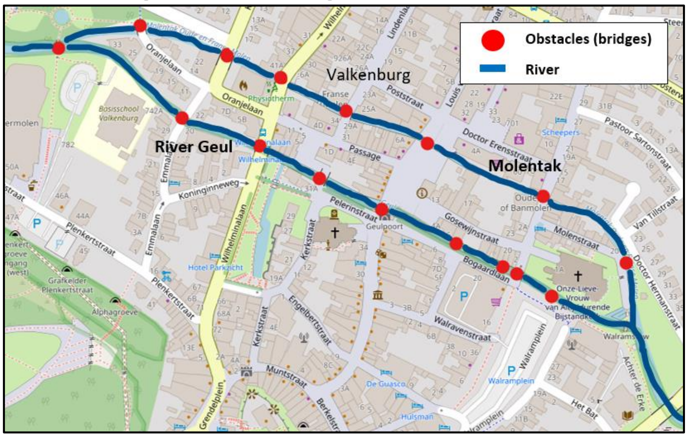



Figure 42 Locations of obstacles (bridges) in Valkenburg (red dots).

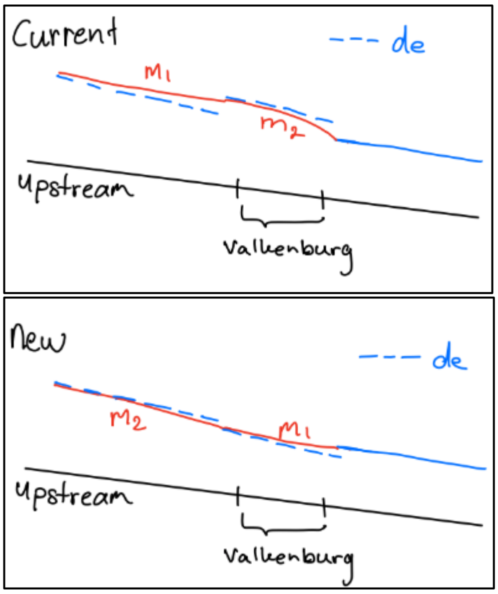



Figure 43 Backwater curve of the current situation with obstacles (top) and estimate of backwater curve without obstacles (bottom).

***How***

Formula 7.2 is used to prove the effectivity of the measure; removing the obstacles lowers $c_f$, the resistance factor, which induces a lower $d_e$, the equilibrium depth. Figure 43 shows on the top the backwater curves for the case that Valkenburg still has obstacles in the River Geul, and on the bottom the situation after removing the obstacles. The assumption is made that after removing the obstacles the water level decreases even under the water level upstream Valkenburg, because upstream of Valkenburg no obstacles are removed.

#### 7.2.1.7. Thresholds upstream Valkenburg

***Which & where***

A goal to prevent flooding in Valkenburg is to retain water upstream Valkenburg. One way to do this is placing many thresholds in the River Geul. The simulated thresholds are 0.5, 1.0 and 1.5 m high to show the effect for different heights. Figure 44 and Figure 45 show the location of the five simulated thresholds upstream Valkenburg. These locations are based on both the present bottlenecks (see Figure 45) and distance towards urban areas.

***How***

Thresholds upstream raise the water level at each step and make sure the flood plains are used earlier. This is shown in Figure 46. More water can infiltrate, and the peak flattens out due to slowing down of the water. The disadvantage of these thresholds is that it raises the water level locally significant. This can induce flooding of other urban areas. During extreme discharges, the effectivity of these thresholds is also limited because the wave peak might not even notice the thresholds, because of the limited height.

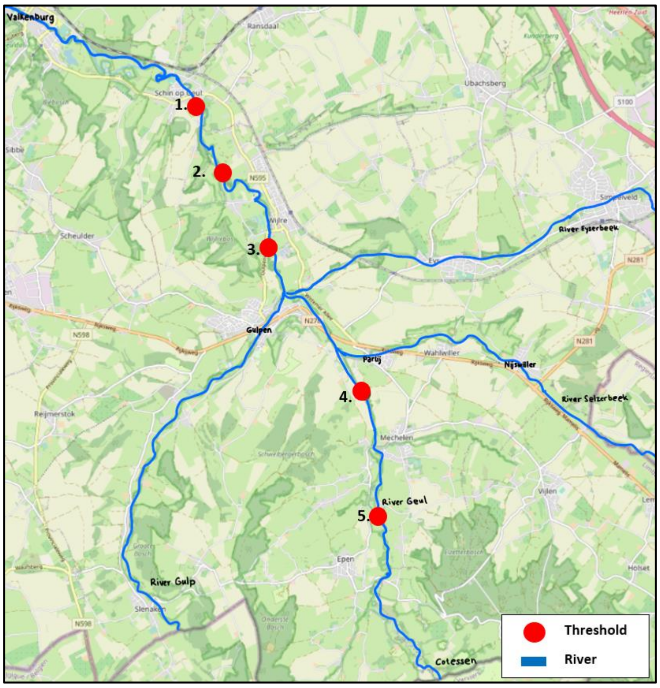



Figure 44 Locations of the thresholds upstream Valkenburg, numbered from 1 to 5.

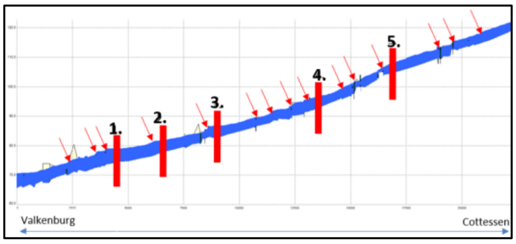



Figure 45 Longitudinal cross-section, with the location of the thresholds (red bars) and bottlenecks (red arrows).

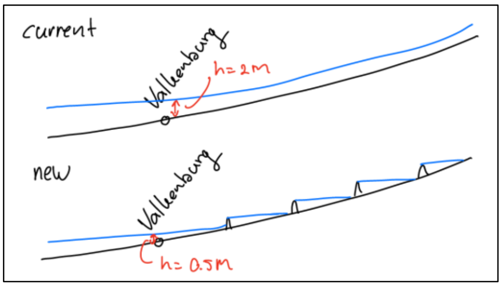



Figure 46 Implementation of several thresholds upstream Valkenburg and a fictive height reduction.

### 7.1.2.8. Weirs before the three tributaries reach the River Geul

***Which & where***

Figure 47 shows the River Geul with the tributaries and the location of the simulated weirs. These weirs are located just before the tributaries flow into the River Geul. The weirs are simulated to be closed for 12 and 48 hours, starting just before the wave peak arrives to see what influence these weirs have on the flooding of the River Geul.

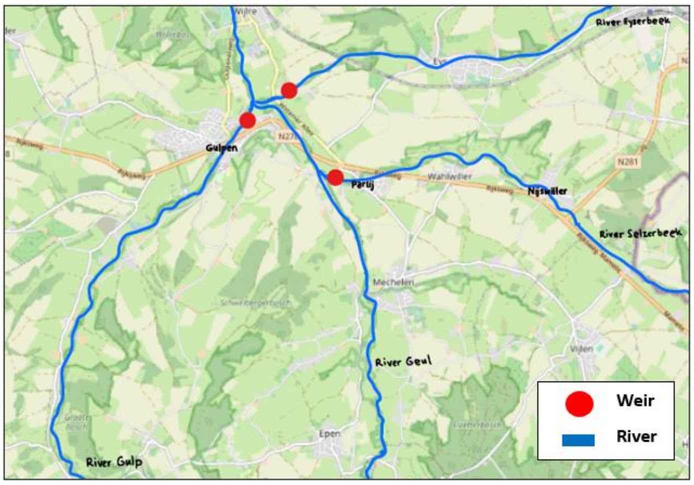



Figure 47 Locations of the weirs, before the tributaries flow into the River Geul.

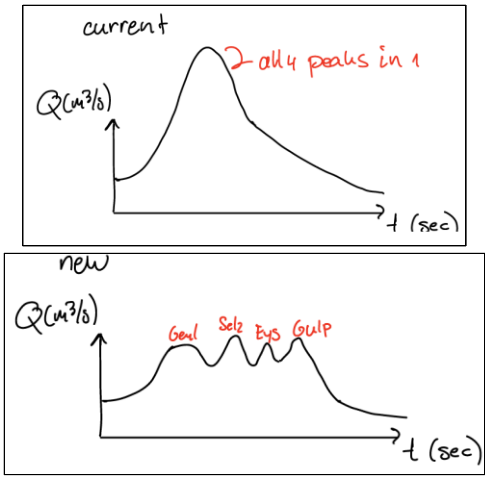



Figure 48 On the top the current discharge peak, on the bottom the new fictive spread of the discharge peak.

***How***

Implementing weirs in the system of the River Geul gives more control over the discharge distribution. The tributaries contribute for 25% to the discharge of the River Geul (based on Table 6). Having control over the three largest tributaries, the Gulp, Eyserbeek and Selzerbeek, gives the freedom to adapt a part of the discharge peak in the River Geul. Figure 48 shows the current discharge peak and the discharge peak after implementing the weirs. The distribution of the peak is fictive, but it shows how the current discharge peak can be spread over time. This lowers the flooding depth along the River Geul downstream the weirs.

Appendix 7A2 shows a calculation of the necessary retention capacity upstream the weirs to give a feeling for amounts of water. A couple million cubic metres have to be temporarily stored, which seems unrealistic to be successful. However, if only a part of this total amount of water can be stored the flooding depth can already go down. The disadvantage of these weirs is that it raises the water level locally significant during the arrival of the wave peak. This can induce flooding of other urban areas. On the other hand, during low discharges the distribution of water can also be controlled to prevent the river from drying up.

### 7.2.1.9. Add vegetation upstream Valkenburg

#### *Which & where*

An effective way to slow down the water upstream Valkenburg and temporary retain water is to increase the resistance of the riverbed by adding vegetation. Figure 49 shows the location where the simulated vegetation is added in the system. The measure is taken just upstream the bottlenecks, as shown in Figure 45. However, the vegetation is simulated in SOBEK as a resistance and can only be changed for a whole reach. Therefore, the length over which the vegetation is added, is much longer than the length of the defined cross-sections. The cross-sections from location 1 and 2 in Figure 45 belong to the same reach, which is shown in Figure 49 as '1+2'.

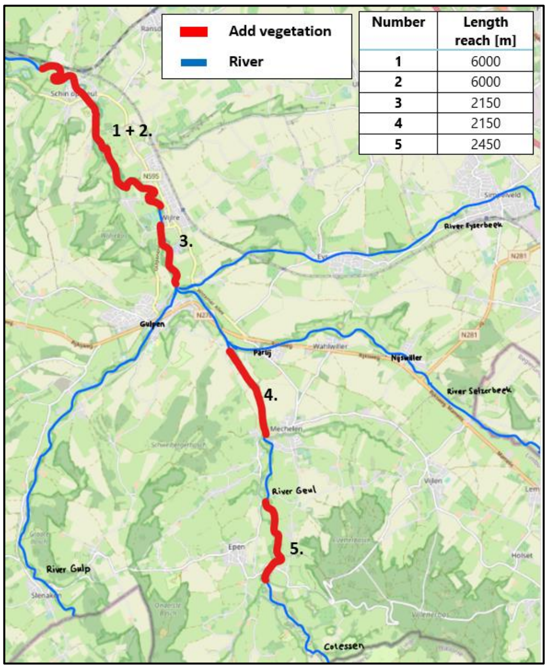


**Figure 49 Locations of adding vegetation upstream Valkenburg.**

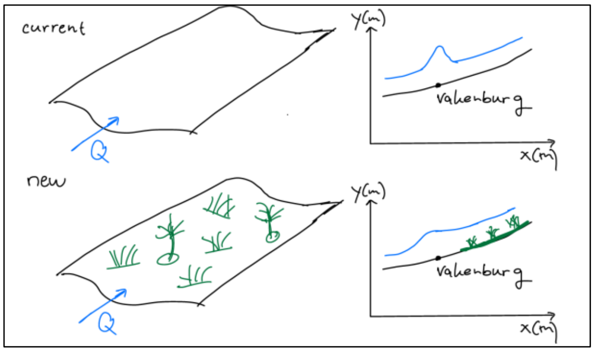


**Figure 50 Add vegetation showing on the left the current and new situation of the riverbed, right the accompanying discharge peak.**

#### *How*

The vegetation is simulated by increasing the friction factor. The standard friction factor in the hydraulic model is equal to 0.05 [-]. The adjustment factor for the Manning friction value of vegetation is investigated by Philips & Tadayon (2006). Two situations are simulated to show the influence of different amounts of vegetation:

- medium amount of vegetation; Manning = 0.05 (std) + 0.025 = 0.075,
- large amount of vegetation; Manning = 0.05 (std) + 0.05 = 0.100.

Figure 50 shows both the current and the new situation of the riverbed. Furthermore, the discharge peaks for both situations are visualized. The discharge peak becomes spread over time due to simulating vegetation. As a consequence, the local water level rises, but at Valkenburg the height during the discharge peak becomes lower.

In this case in formula 7.2 the value of $c_f$, the resistance factor, goes up, which leads to a higher $d_e$, the equilibrium depth. This local water level rise leads to slowing down the water:

$$v = \frac{Q}{A} \tag{7.3}$$

$Q$, the discharge, remains the same, but due to the increase of $d_e$, $A$, the conveyance area, goes also up. The result is that $v$, the flow velocity, goes down. Slowing down of the water leads to slowing down and spreading of the discharge peak over time, because the peak is time dependent. The disadvantage of adding vegetation is that it raises the water level locally significant during a flood. This can induce flooding of other urban areas.

### 7.2.1.10. Raise riverbed upstream Valkenburg

***Which & where***

Figure 51 shows the location where the riverbed is raised in the simulations. Again, the measure is implemented just upstream the bottlenecks, as shown in Figure 45. In this case, only the cross-sections are changed. Therefore, the length over which the riverbed is raised is much shorter compared to adding vegetation. The riverbed is raised with 0.5, 1.0 and 1.5 m.

***How***

Raising the riverbed may sound weird as a measure to reduce flooding depths but upstream Valkenburg the goal is to slow down the water. Riverbed raise induces local water level rise, which is good in this case. The floodplains are used earlier, and more water can infiltrate. This is shown in Figure 52. Furthermore, the peak flattens out due the slowdown of water, which is visible in Figure 53. The slowing down happens due to the additional resistance of the floodplains. These are covered with vegetation. The same explanation with formula 7.2 and 7.3, as explained for adding vegetation, holds for raising the riverbed.

The disadvantage of rising the riverbed is that it raises the water level locally significant during flooding. This can induce flooding of other urban areas. Furthermore, the characteristics of the river changes, which may affect ecology.

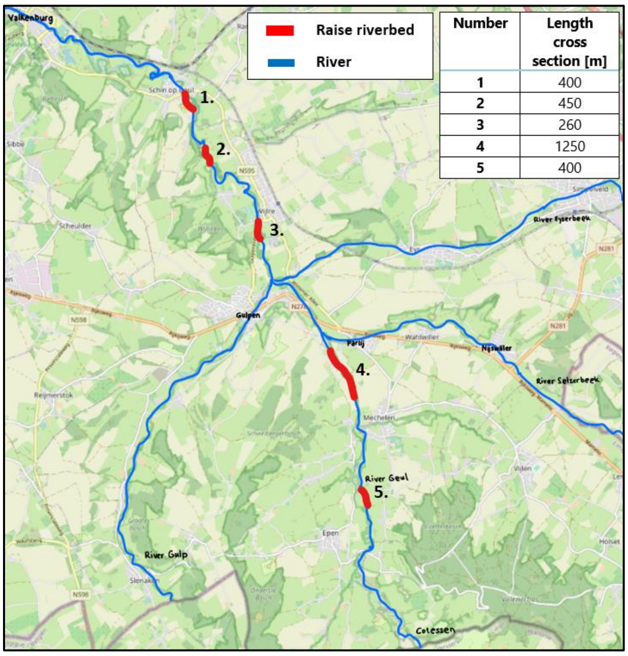



Figure 51 Locations for raising the riverbed (red lines).

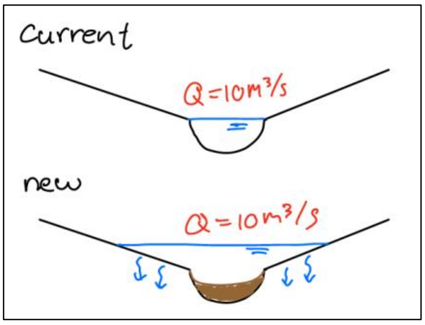



**Figure 52 Raising the riverbed, fictive example with a discharge of 10 m³/s.**

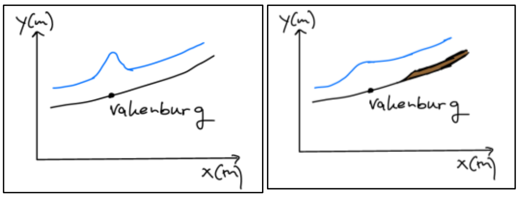



**Figure 53 Current discharge peak on the left, discharge peak with riverbed raised on the right.**

### 7.2.1.11. Enlarge current basins

***Which & where***

Figure 54 shows with a simple schematization how the capacity of current basins can be increased. The basins are multiplied with a factor of 1.5, 3 and 5 to show the effect of this measure for different sizes. The locations of the current river basins, which are also modelled in the hydraulic model, are shown in Figure 55.

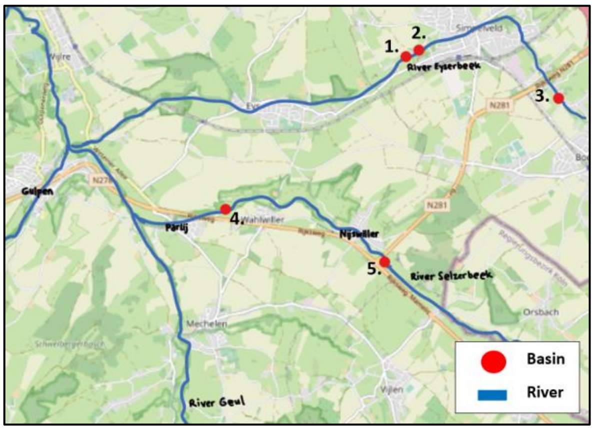



**Figure 54 Locations of the current basins (in the SOBEK model) that are enlarged.**

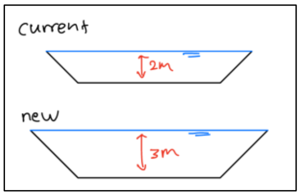



**Figure 55 Example of enlarging the current basins.**

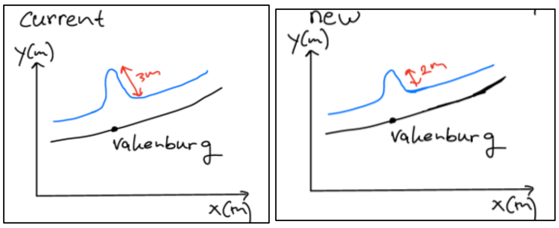



**Figure 56 On the left, the current discharge peak. On the right, the discharge peak with additional basins.**

Comparing the total basin sizes in Table 14 with the calculated necessary basin size of 36 million $m^3$ (Section 4.2.4) the difference is still large, but the existing simulated basins are only located in the tributaries. According to the hand calculation for measure 8 (see Appendix 7A2), for the River Selzerbeek a basin of 2.4 million $m^3$, and for the River Eyserbeek a basin of 1.2 million $m^3$ would be sufficient to temporary store the peak. By multiplying the current basins with a factor of five, these calculated basin sizes are accomplished (see Table 14).

| Basin | Current size [$m^3$] | X1.5 | X3 | X 5 |
|---|---|---|---|---|
| **1** | 548 | 822 | 1644 | 2740 |
| **2** | 12.374 | 18.561 | 37.122 | 61.870 |
| **3** | 352.421 | 528.632 | 1.057.263 | 1.762.105 |
| **4** | 117.726 | 176.589 | 353.178 | 588.630 |
| **5** | 948.617 | 1.422.926 | 2.845.851 | 4.743.085 |
| **Total** | 1.979.138 | 2.968.707 | 5.937.414 | 9.895.690 |

**Table 14 Overview of the current basin sizes and the new basin sizes, as defined in the SOBEK model of the River Geul.**

***How***

To buffer additional water enlarging basins can be effective. The discharge peak can be decreased in height and the inundation depth in Valkenburg can be decreased significantly due to this lower peak height. Figure 56 visualizes the decrease in peak height.

Enlarging the current basins is expected to have the same effect as building new basins. However, the amount of space is limited upstream Valkenburg and raising the additional basins with one metre might be more beneficial. Especially with the large amount of Natura 2000 areas and cultural heritage along the River Geul makes enlarging the current basins an attractive solution.

### 7.2.2. SOBEK output of measures

Table 15 shows with colours a quick overview of the results of each measure and Table 16 gives a small explanation of the results of each measure. The measures from Table 15 that overall score a '++' or '+' are rated as effective. All the other overall scores are rated as ineffective.

| Measure description & size | Water level change [m] | | River length effect [m] | Type of area water level change | Overall score |
|---|---|---|---|---|---|
| | July 2021 | Stress test | | | |
| Enlarge culvert Julianakanaal (15x2.5 m) | 0 | 0 | 0 | Bunde | +/- |
| Widen the river downstream (+20 m opt) | -0.5 until -1.0 | -0.5 until -1.0 | 5000 | Bunde, Meerssen | + |
| Remove channelization in Valkenburg (30 degrees) | -0.05 | -0.05 | 300 | Valkenburg | +/- |
| Bypass: in-situ tunnel through Valkenburg (20x2.5 m or (⌀ 8 m) | -0.1 until -1.5 | -0.1 until -0.5 | 1750 | Valkenburg | ++ |
| Raise dikes in Valkenburg (+1 m) | -0.05 until +0.1 | -0.05 until +0.1 | 300 | Valkenburg | +/- |
| Remove obstacles in the River Geul along Valkenburg | -0.1 until -0.4 | -0.1 until -0.25 | 800 | Valkenburg | + |
| Thresholds upstream Valkenburg (1.5 m) | 0 | 0 | 0 | None | +/- |
| Weirs before the 3 tributaries reach the River Geul (48 h closed) | 0 | 0 | 0 | None | +/- |
| Add vegetation upstream Valkenburg (Manning + 0.05) | 0 until +0.2 | 0 until +0.2 | 5000 | Rural area | -- |
| Raise riverbed upstream Valkenburg (+1.5 m) | 0 until +0.05 | 0 until +0.05 | 3000 | Rural area | - |
| Enlarge current basins (x5) | -0.1 until -1.0 | -0.05 until -0.1 | 7000 | Wahlwiller, Nijswiller | + |

**Table 15 Score table of each simulated measure based on the SOBEK output. The water level change, the length effect, and the location where changes occurred are taken into account. An overall score of '++' or '+' is rated as effective and all the other overall scores are rated as ineffective.**

The effective measures from Table 15 are further elaborated in this section. The ineffective measures and their SOBEK results are explained in Appendix 7B and are also not further evaluated in Section 7.2.4.

| Section | Measure description & size | Brief explanation of the result of the measure | Full explanation |
|---|---|---|---|
| Downstream | Enlarge culvert Julianakanaal (15x2.5 m) | Only when two openings of the culvert are blocked, major differences in water level are visible. The effect of largening the culvert is unnoticeable. The current culvert shows comparable results as the culvert of 15 m width, which means that enlarging the culvert is unnecessary. | Appendix 7B1 |
| | Widen the river downstream (+20 m opt) | River widening is effective for both July 2021 and the stress test but shows only a local decrease of water level in between the bottlenecks. Lowering of water level upstream of the river widening is blocked by bottlenecks in the system. | Section 7.2.2.1 |
| Valkenburg | Remove channelization in Valkenburg (30 degrees) | The effect of removing channelization is small due to the minor increase in discharge capacity, while the amount of discharge in the system remains the same. | Appendix 7B2 |
| | Bypass: in-situ tunnel through Valkenburg (20x2.5 m or ⌀ 8 m) | The bypass reduces the water level along and upstream Valkenburg the most of all measures (for July 2021). This holds for both the tunnel and channel, for the largest dimensions. | Section 7.2.2.2 |
| | Raise dikes in Valkenburg (+1 m) | Raising the dikes with either 0.5 or 1.0 m has almost no influence on the flooding depths in Valkenburg. The reason behind this is that the flooding already happens | Appendix 7B3 |

| | | | |
|---|---|---|---|
| | | upstream Valkenburg, and the dikes cannot fulfil their function. The increase in discharge capacity is also limited. | |
| | **Remove obstacles in the River Geul along Valkenburg** | The impact of removing obstacles on the water level along Valkenburg is large compared to removement of channelization and raising the dikes. This makes it an effective measure compared to the other two. | Section 7.2.2.3 |
| **Upstream** | **Thresholds upstream Valkenburg (1.5 m)** | Thresholds do not have any effect during flooding conditions (as expected) and show no differences in flooding depth and water level. | Appendix 7B4 |
| | **Weirs before the 3 tributaries reach the River Geul (48 h closed)** | The weirs raise the flow velocity and do not decrease the flooding depth. The weirs are also not capable of temporarily retaining the water, because after a while the water flows around the weir overland. | Appendix 7B5 |
| | **Add vegetation upstream Valkenburg (Manning + 0.05)** | After adding vegetation, the flooding depths go up slightly. This is the result of lower flow velocities. The wave peak does not spread out due to the bottlenecks downstream of the measure and therefore no lower water levels in Valkenburg occur. | Appendix 7B6 |
| | **Raise riverbed upstream Valkenburg (+1.5 m)** | Comparable results and the same theory hold as for adding vegetation. Also in this case, the wave peak does not spread out and the flooding depth downstream is not lowered. | Appendix 7B7 |
| | **Enlarge current basins (x5)** | Larger basins show no difference in water level of the River Geul. The River Selzerbeek shows major differences in water level. This is only for July 2021, for the stress test the effect vanishes. | Section 7.2.2.4 |

**Table 16 Overview of the explanation of results for each simulated measure.**

#### 7.2.2.1. Widen the river downstream

Widening the river shows positive effects for the flooding depths downstream Valkenburg (MS 1-6), which is visible in Table 17 for July 2021. Table 43 in Appendix 7C2 shows similar results for the stress test. The largest effect is visible at MS 1, close to Bunde. For the flow velocities, the largest effect also occurred at MS 1 with a maximum decrease of 0.42 m/s (Table 44 and Table 45, Appendix 7C2). This is the result of the long-widened reach downstream of the culvert underneath the Julianakanaal, which is visible as nr. 1 in the top view of Figure 57. The figure shows a flatter backwater curve downstream MS 1 after widening the river, which explains the lower flooding depth (Elger et al., 2016).

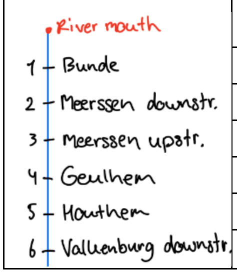
| **Difference in flooding depth [m] for different river widenings and conditions** | | | | | | |
|---|---|---|---|---|---|---|
| Location MS | MS River Geul | July 2021 (140 m³/s) | | | | |
|  | | D [m] for std case | Δh [m] for +5 m | Δh [m] for +10 m | Δh [m] for +20 m | Δh [m] for +20 m Opt |
| | MS 1 | 0.33 | -0.17 | -0.27 | -0.33 | -0.33 |
| | MS 2 | 0.40 | -0.03 | -0.06 | -0.09 | -0.09 |
| | MS 3 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | MS 4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | MS 5 | 0.29 | -0.02 | -0.03 | -0.03 | -0.03 |
| | MS 6 | 0.79 | -0.02 | -0.03 | -0.06 | -0.06 |

**Table 17 Flooding depths for different river widenings relative to the std case for July 2021. Red cell = flooding depth increase and green cell = flooding depth decrease.**

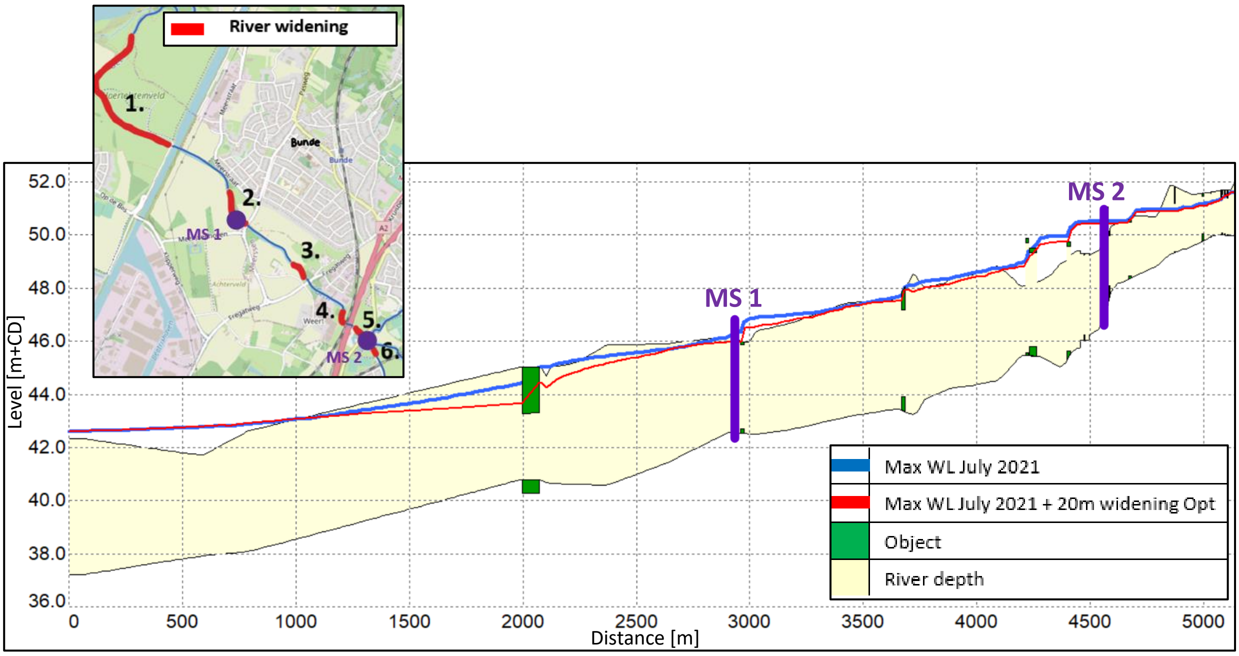



**Figure 57 Longitudinal cross-section of the River Geul comparing the std river with the river widened by 20m + optimization for the flooding of July 2021. Location = from river mouth until Meerssen.**

To find out the local effects of the widening, several longitudinal cross-sections are drawn. These are visible in Figure 57 and Figure 58 and show the maximum water level for July 2021 with and without the river widening. Both figures clearly show that the water level drops at the measurement stations are much lower than the areas in between as shown in the longitudinal cross-sections. Locally, the difference in water level is ranging from 0.5 until 1.0 metre over 5000 m river length. Figure 57 and Figure 58 also show that these water level drops are mainly in between the bottlenecks, which proves the statement that the bottlenecks make sure that the influence of the measure is blocked by the bottlenecks. Therefore, widening the river does not reach until Valkenburg. However, several urban areas are located along the locations where the water level is lowered. For the stress test similar local differences occur as shown for July 2021 in Figure 57 and Figure 58.

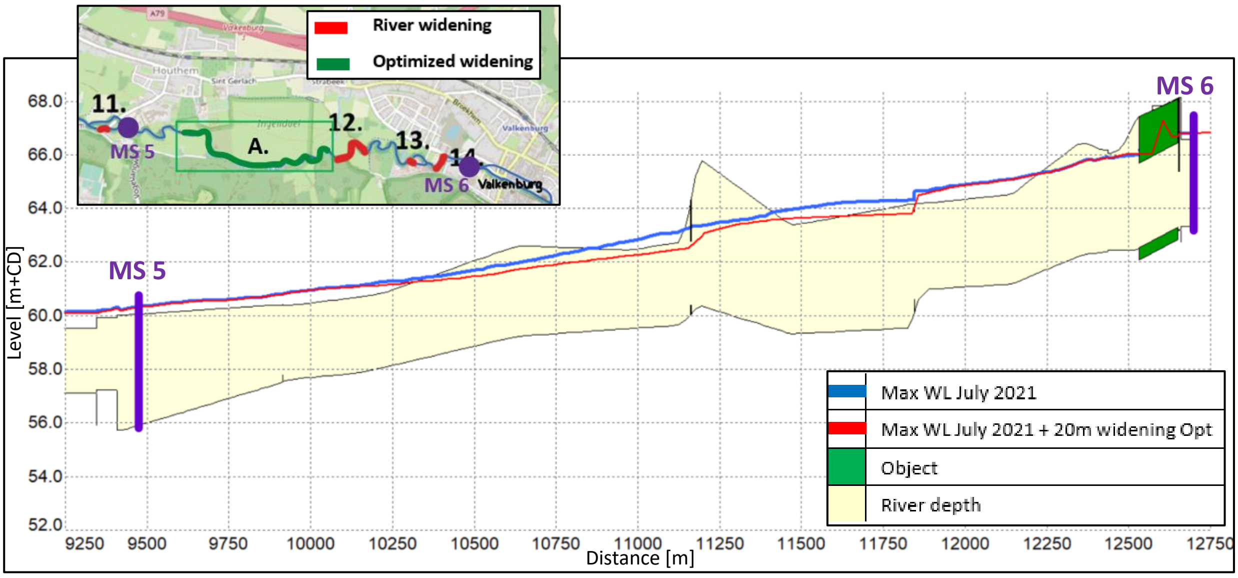



**Figure 58 Longitudinal cross-section of the River Geul comparing the std river with the river widened by 20m + optimization for the flooding of July 2021. Location = from Houthem until Valkenburg downstream.**

## Conclusion

River widening is only effective in between bottlenecks, which means that this measure is not effective to decrease the water level in Valkenburg. However, the urban areas of Bunde and Meerssen also suffered from flooding in July 2021. The flooding depths in these areas are definitely decreased due to the river widening. Based on the findings the measure is effective.

### 7.2.2.2. Bypass: tunnel or additional channel through Valkenburg

The results of the bypass show major differences in flooding depth compared to the current situation. The most effective bypasses are the culvert of 20m wide (or tunnel of D = 8m) and the channel of 10m wide, according to Table 18 and Table 19. These two are the largest bypasses and can transport the largest discharge. It is in line with the expectations that these bypasses lower the flooding depths in Valkenburg the most. Figure 59 shows a longitudinal cross-section of the River Geul in Valkenburg and compares the maximum water level of July 2021 for the standard situation and the situation with a tunnel of 20 x 2.5m simulated through Valkenburg. Figure 59 shows that the water level not only decreases at the measurement stations, but all along and upstream Valkenburg. This makes this measure very effective. Locally, the decrease in water level is ranging from 0.1 until 1.5 m over 1750 m river length. The influence of the bypass reaches until 1-kilometre upstream Valkenburg, while downstream Valkenburg no effects are visible in Figure 59. For the stress test the local effects are much smaller and ranging from 0.1 until 0.5 m (see Figure 84, Appendix 7C4).

The results of the largest dimensions of the bypass performed as a tunnel and a channel are similar. Therefore, the choice is made to only show the longitudinal cross-section of the bypass tunnel and for the same reason in the rating of effectivity of measures (see Table 15) only the bypass tunnel is mentioned.

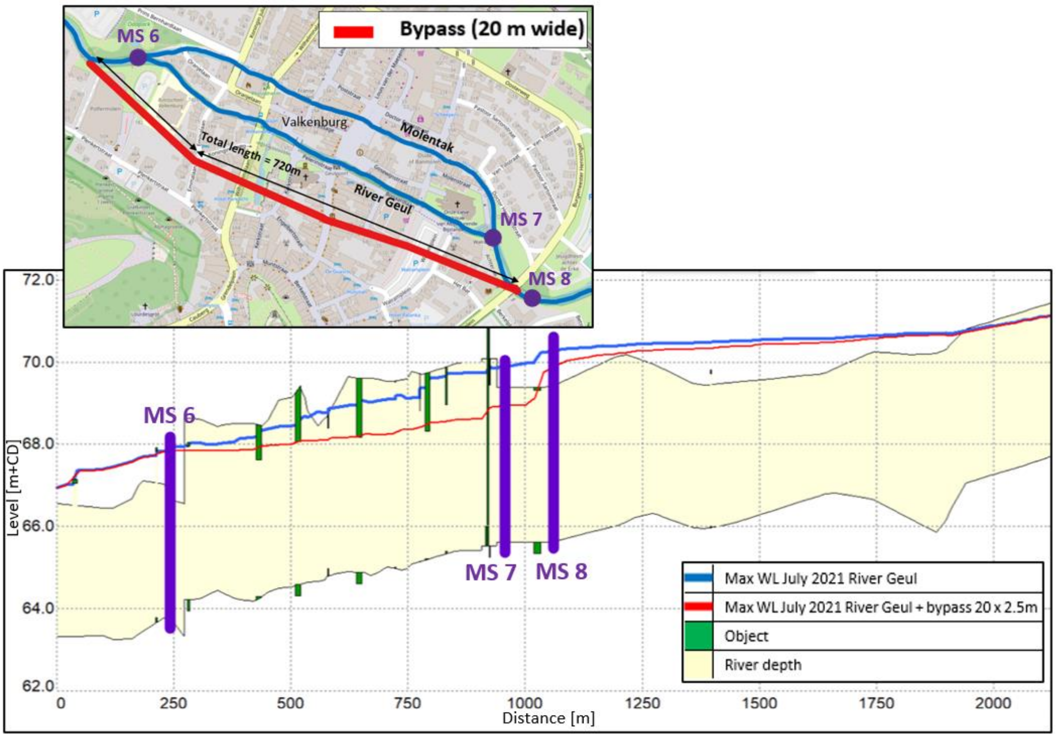



**Figure 59 Longitudinal cross-section of the River Geul, comparing the max water levels of July 2021 for the std case and the case with a bypass of 20 x 2.5 metres or ⌀ 8 m. Location = along Valkenburg.**

The reason that the channels reduce the flooding depth already more for smaller dimensions is because the SOBEK model allows flooding of a channel, while for a tunnel (culvert in the model) flooding cannot happen in the SOBEK model. Therefore, more discharge flows towards Valkenburg for the simulations with a tunnel and the flooding depths remain higher compared to the simulations with a channel.

| Difference in flooding depth [m] for different bypasses and conditions | | | | | | | |
|---|---|---|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | | | | | |
| | D [m] for std case | Δh [m] for channel 2 m | Δh [m] for channel 5 m | Δh [m] for channel 10 m | Δh [m] for tunnel 10 m | Δh [m] for tunnel 15 m | Δh [m] for tunnel 20 m |
| MS 6 | 0.79 | -0.04 | -0.03 | -0.01 | 0.02 | 0.03 | 0.03 |
| MS 7 | 0.49 | -0.49 | -0.49 | -0.49 | -0.14 | -0.33 | -0.49 |
| MS 8 | 0.85 | -0.25 | -0.35 | -0.56 | -0.07 | 1.45 | -0.48 |

**Table 18 Flooding depths for different bypasses relative to the std case for July 2021. Red cell = flooding depth increase and green cell = flooding depth decrease. The results of the bypass tunnel apply for both in-situ and drilled.**

| Difference in flooding depth [m] for different bypasses and conditions | | | | | | | |
|---|---|---|---|---|---|---|---|
| MS River Geul | Stress test (224 m³/s) | | | | | | |
| | D [m] for std case | Δh [m] for channel 2 m | Δh [m] for channel 5 m | Δh [m] for channel 10 m | Δh [m] for tunnel 10 m | Δh [m] for tunnel 15 m | Δh [m] for tunnel 20 m |
| MS 6 | 1.12 | 0.03 | 0.03 | 0.04 | 0.06 | 0.08 | 0.08 |
| MS 7 | 0.77 | -0.25 | -0.40 | -0.66 | -0.18 | -0.28 | -0.40 |
| MS 8 | 1.11 | -0.12 | -0.18 | 1.37 | -0.10 | -0.14 | -0.19 |

**Table 19 Flooding depths for different bypasses relative to the std case for the stress test. Red cell = flooding depth increase and green cell = flooding depth decrease. The results of the bypass tunnel apply for both in-situ and drilled.**

Table 18 and Table 19 show two striking values with more than one metre flooding depth increase at MS 8. This is the result of a numerical error and is not part of this research. However, Appendix 7C4 elaborates on the results regarding these errors.

#### Conclusion

Both the channel and the tunnel reduce the flooding depths and water levels significantly. Therefore, the bypass is an effective measure based on the SOBEK output. However, for July 2021 the water level decrease is about three times higher than for the stress test. The effects of this measure are therefore limited to a certain extreme event.

### 7.2.2.3. Remove obstacles in the River Geul along Valkenburg

Removing obstacles reduces the flooding depth at the measurement stations by maximum 0.08 m (Table 20) and increases the flow velocity by maximum 0.55m/s (Table 52, Appendix 7C6). This is almost the same decrease in flooding depth at the measurement stations as for the removement of channelization or raising the dikes. The increase of flow velocity was expected, because the obstacles don't slow down the water anymore.

| Difference in flooding depth [m] for removing obstacles and different conditions | | | | |
|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | Stress test (224 m³/s) | |
| | D [m] for std case | Δh [m] no obstacles | D [m] for std case | Δh [m] no obstacles |
| MS 6 | 0.79 | -0.01 | 1.12 | -0.01 |
| MS 7 | 0.49 | -0.08 | 0.77 | -0.06 |
| MS 8 | 0.85 | -0.03 | 1.11 | -0.02 |

**Table 20 Flooding depths for removing obstacles relative to the std case for July 2021 and the stress test. Red cell = flooding depth increase and green cell = flooding depth decrease.**

Looking at Figure 60, the local decrease in water level is ranging from 0.1 until 0.4 m over 800 m river length for July 2021. Slightly smaller local water level decreases are achieved for the stress test, ranging from 0.1 until 0.25 m (Figure 86, Appendix 7C6).

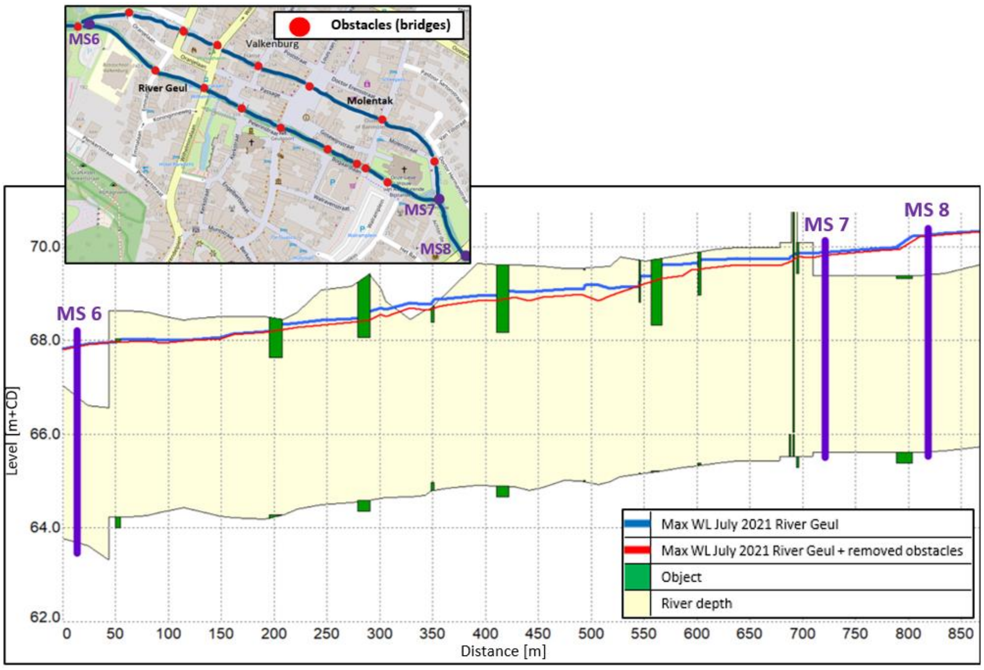



**Figure 60 Longitudinal cross-section of the River Geul, comparing the max water levels during the Flooding of July 2021 for the std case and the obstacles removed. Location = along Valkenburg.**

### Conclusion

The impact of removing obstacles on the water level along Valkenburg is large compared to removement of channelization and raising the dikes. This makes it an effective measure compared to the other two.

### 7.2.2.4. Enlarge current basins

Enlarging the current basins shows no differences in flooding depths in the River Geul. The flow velocity only changes locally at the first measurement station upstream in the River Geul before the River Eyserbeek and River Selzerbeek flow into the River Geul (Table 55, Appendix 7C6). This has no further local influence on the downstream part of the River Geul.

For the River Selzerbeek, the differences in flooding depths and flow velocities are larger for July 2021. Upstream the river basins the water level rises and downstream the flooding depth decreases, which is visible in Table 21 (MS 2 and 3 versus MS 4). The same holds for the flow velocity (Table 56, Appendix 7C11). This effect does however not reach the River Geul. For the stress test the differences in flooding depths are much lower according to Table 21.

| Difference in flooding depth [m] for different river basin sizes and conditions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MS River Selzerbeek | July 2021 (140 m³/s) | | | | Stress test (224 m³/s) | | | |
| | D [m] for std case | Δh [m] for x1.5 | Δh [m] for x3 | Δh [m] for x5 | D [m] for std case | Δh [m] for x1.5 | Δh [m] for x3 | Δh [m] for x5 |
| MS 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MS 2 | 0.33 | -0.04 | -0.33 | -0.33 | 0.46 | 0.00 | -0.01 | -0.16 |
| MS 3 | 0.12 | -0.01 | -0.12 | -0.12 | 0.23 | 0.00 | -0.01 | -0.12 |
| MS 4 | 0.18 | 0.00 | 0.04 | 0.04 | 0.47 | 0.00 | 0.00 | 0.00 |

**Table 21 Flooding depths for different basin sizes relative to the std case for July 2021 and the stress test. Red cell = flooding depth increase and green cell = flooding depth decrease.**

Figure 61 shows the longitudinal cross-section of the River Selzerbeek with both the current situation and the enlarged basins for July 2021. The local decrease of the water level is in the range of 0.1 until 1.0 m over 7000 m river length. For the stress test this local decrease is much lower and ranges from 0 until 0.15 m water level decrease (Figure 87, Appendix 7C11).

Several basins are also located in the River Eyserbeek. At the measurement stations no differences are visible compared to the current situation. However, Figure 62 shows a local water level decrease in the River Eyserbeek after enlarging the basins for July 2021. The local decrease of the water level is in the range of 0.05 until 0.1 m over 2000 m river length and is much smaller than the local decreases in the River Selzerbeek. The reason for that is the fact that the basins in the River Selzerbeek are already much larger compared to the River Eyserbeek and by multiplying them, the differences become even bigger (See section 7.2.1).

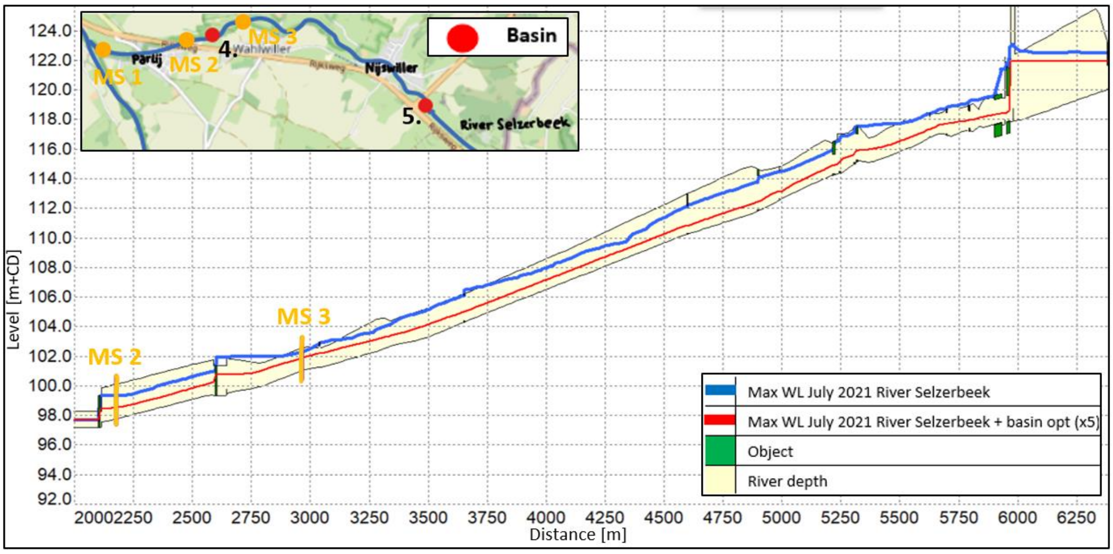



**Figure 61 Longitudinal cross-section of the River Selzerbeek, comparing the max water levels for July 2021 for the std case and the case with enlarged basins (x5). Location = downstream Partij until upstream Nijswiller.**

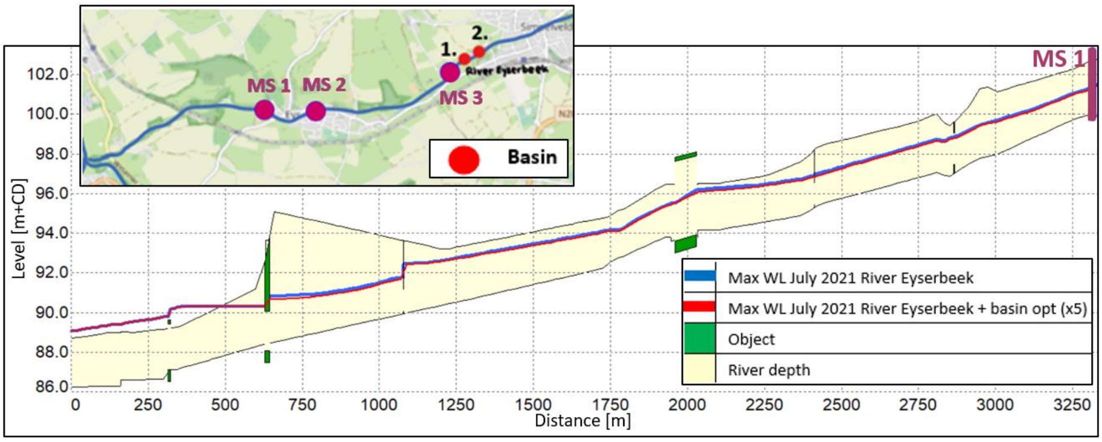



**Figure 62 Longitudinal cross-section of the River Eyserbeek, comparing the max water levels for July 2021 for the std case and the case with enlarged basins (x5). Location = connection tributaries with River Geul until downstream Eys.**

### Conclusion

Enlarging the current basins is not effective to decrease flooding depths in the River Geul. However, the water level decreases locally at the River Selzerbeek and River Eyserbeek nearby urban areas, for the scenario July 2021. Therefore, the measure is effective based on the SOBEK results.

### 7.2.3. Sensitivity analysis SOBEK simulations

For all the measures multiple dimensions and scenarios are simulated to make sure that the SOBEK model is representing the simulated measures properly. Only for the bypass around Valkenburg and the thresholds upstream Valkenburg the SOBEK model showed some numerical errors for a few cases, but overall, the model simulated all the measures according to the expectations. The expected effect of most of the measures occurred in the SOBEK output and shows that the SOBEK model is capable of representing the impact of certain measures on the river system.

All the measures are simulated with multiple dimensions to research the sensitivity and accuracy of the SOEBEK-simulations. A small sensitivity analysis is shown for one measure as an example. The measure river widening downstream is chosen in this case. All the measures are simulated for two scenarios': July 2021 and the stress test. Furthermore, the river is widened with three different widths and one optimization of the 20 m widening. It is expected that the flooding depth decreases more when the river is wider. According to Table 22 the SOBEK simulations show that the decrease in flooding depth is larger for a wider river. Only the optimization has no additional effect on the flooding depth, but after further investigation the water level additionally decreased locally in between the measurement stations. Overall, the result is that the SOBEK model functions properly and simulates the different measures and scenarios accordingly.

| July 2021 (140 m³/s) | | | | | Stress test (224 m³/s) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| std | 5 m | 10 m | 20 m | 20 m Opt | std | 5 m | 10 m | 20 m | 20 m Opt |
| D [m] | Δh [m] | | | | D [m] | Δh [m] | | | |
| 0.33 | -0.17 | -0.27 | -0.33 | -0.33 | 0.53 | -0.14 | -0.23 | -0.33 | -0.32 |
| 0.40 | -0.03 | -0.06 | -0.09 | -0.09 | 1.08 | -0.05 | -0.07 | -0.08 | -0.04 |

**Table 22 Flooding depths for different river widenings relative to the std case for July 2021 and the stress test. Red cell = flooding depth increase and green cell = flooding depth decrease.**

### 7.2.4. The impact of effective measures

#### 7.2.4.1. SSM2017 damage and victims

Table 23 shows the results of SSM2017 for the area along the River Geul for both July 2021 and the stress test. For all the measures the SOBEK output of the largest dimensions are used to give the maximum result. Clearly visible are the bypass tunnel and bypass channel which are reducing the amount of damage and victims along the River Geul the most of all measures for July 2021, while river widening and removing obstacles both show a significant but smaller reduction in damage and victims. Enlarging the current basins scores the worst of all effective measures. For the stress test the results are different, and the impact of the measures is barely visible in Table 23. In comparison with the flooding depths in the River Geul for July 2021 the flooding depths of the stress test remain much higher, even after implementing measures. Therefore, the measures barely reduce the damage as a consequence of flooding for the stress test. The impact of the measures on damage reduction is therefore limited to the scenario of July 2021. For extremer events the measures are no longer damage reducing. Appendix 7D1 further analysis with flood inundation maps why the results from Section 7.2.2 and 7.2.4 do not coincide, because the SOBEK output showed effective, but in general lower, water level and flooding depth decreases for the stress test simulations.

| July 2021 (140 m³/s) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Difference compared to standard case | | | | | |
| | Standard | Widening of 20 m Opt | Bypass tunnel 20x2.5 m or ⌀ 8 m | Bypass channel 10 m | Remove obstacles | Enlarge basin x5 | |
| **Total damage** | 62.000 | -4000 | -21.000 | -23.000 | -4000 | -2000 | €(x1000) |
| **Total victims*** | 3 | -1 | -2 | -2 | -1 | 0 | persons |
| Stress test (224 m³/s) | | | | | | | |
| | | Difference compared to standard case | | | | | |
| | Standard | Widening of 20 m Opt | Bypass tunnel 20x2.5 m or ⌀ 8 m | Bypass channel 10 m | Remove obstacles | Enlarge basin x5 | |
| **Total damage** | 110.000 | 0 | 0 | -10.000 | 0 | 0 | €(x1000) |
| **Total victims*** | 6 | -1 | -1 | -2 | -1 | 0 | persons |
| *without evacuation | | | | | | | |

**Table 23 Overview of change in damage and victims along the River Geul for both July 2021 and the stress test, according to SSM2017.**

The number of victims is estimated based on no evacuation during extreme flooding, which is unrealistic with properly working early warning systems (ENW, 2021). Table 23 shows that the largest decrease in number of victims coincides with the largest decrease in total damage for July 2021. This shows that the amount of damage and total victims are related for all the effective measures. Based on these facts only the change in damage is referred to in the further evaluation of effective measures to prevent an abundance of different evaluated impact parameters.

Appendix 7D2 shows how the amount of damage is divided over the different subcategories for each effective measure.

#### 7.2.4.2. Calculation of the costs

The decrease of damage has to be related to the costs of a measure to implement it. Even if the measure is effectively reducing the damage, the costs can lead to a no go. Table 24 shows an overview of the costs of each measure, combined with the most influencing factors for the costs: number of buildings and amount of soil that has to be removed and the material needed. The calculation of the values in Table 24 is visible in Figure 89, Appendix 7D3.

According to the costs in Table 24 the most expensive measure is enlarging the current basins. The main reason is that soil removement is extremely expensive. For both river widening and removing obstacles the costs of the measures are relatively low (see Table 24). For the bypasses, the costs are higher compared to the other measures (Enlarging the basin excluded), because several buildings have to be removed. A distinction for the bypass tunnel is made in the way it can be built, either in-situ or by drilling. The main difference is that a drilled tunnel does not require as many buildings to be removed. Therefore, the impact for Valkenburg is much smaller compared to an in-situ tunnel or a channel. However, the costs of a drilled tunnel are at least two times higher compared to the other two bypasses according to Table 24, as a result of extremely expensive equipment.

| Measure | Buildings to remove [-] | Soil removement [m³] | Material needed [-] | Costs [€] |
|---|---|---|---|---|
| **Widen the river downstream (20 m Opt)** | None | 400.000 | None | 12 - 23 million |
| **Bypass tunnel in-situ (20x2.5 m)** | +/-25 buildings | 57.600 | Building pit, 20 x 2.5 x 720 m, foundation building pit, concrete for walls, floors and roofs, crossings (K&L) and furnishment area above tunnel | 68 – 126 million |
| **Bypass tunnel drilled (⌀ 8 m)** | +/- 5 buildings | 46.000 | Drill, shafts, and facilities drilled tunnel | 112 – 207 million |
| **Bypass channel (10 m)** | +/-25 buildings | 43.200 | +/-14 bridges, riverbed protection, vertical walls, and crossings (K&L) | 42 – 77 million |
| **Remove obstacles in the River Geul along Valkenburg** | +/-16 bridges | None | +/-16 adapted bridges | 4 – 7 million |
| **Enlarge current basins (x5)** | None | 8.000.000 | None | 243 - 451 million |

**Table 24 Overview of the costs of each measure, combined with the amount of buildings that have to be removed, the amount of soil that has to be removed and the material needed (Appendix 7D3).**

#### 7.2.4.3. Social impact

Table 24 shows an overview of the costs of each measure. However, social impact is not taken into account in the costs because it is not easy to express this in amounts of money. Therefore, Table 25 is made to compare the social impact of the effective measures. The social impact of both river widening and enlarging the current basins is minimal compared to removing obstacles in Valkenburg and the bypasses through Valkenburg. The main reason for this is that the city centre of Valkenburg is packed with many old objects and buildings, which have to be removed for several measures. The bypass tunnel in-situ and bypass channel score by far the worst according to Table 25. The drilled tunnel scores much better, because at most only a few buildings have to be removed. Removing obstacles in Valkenburg brings some nuisance during construction, but the bridges are replaced by other ones so there is no long-lasting effect. Therefore, some impact is considered in Table 25. Either way, the consideration to allow a large social impact has to be weighed against the positive impact of a measure.

| Measure | Social impact |
|---|---|
| **Widen the river downstream 20 m Opt** | None |
| **Bypass tunnel in-situ 20 x 2.5 m** | +/-25 buildings to remove, major impact on society |
| **Bypass tunnel drilled D = 9 m** | +/- 5 buildings to remove, significant impact but manageable |
| **Bypass channel 10 m** | +/-25 buildings to remove, major impact on society |
| **Remove obstacles in Valkenburg** | +/-16 bridges to replace, but only temporary nuisance |
| **Enlarge current basins x5** | None |

**Table 25 Social impact of each effective measure, based on the impact of removing objects or buildings.**

### 7.2.4.4. Natura 2000 area & cultural heritage

The last part of the evaluation of the effective measures is evaluating how much of the measure covers Natura 2000 area and cultural heritage. Furthermore, the results from SSM2017 are used to show how much Natura 2000 area and cultural heritage is flooding during July 2021 and the stress test.

A top view of the catchment area of the River Geul with the assigned Natura 2000 areas is used to evaluate the measures on these aspects (Appendix 6C, Figure 68). The locations of cultural heritage along the River Geul are checked at the WebGIS Publisher – Viewer (2021). Table 26 shows the results of the evaluation. According to Table 26 only the bypass and removing obstacles in Valkenburg barely occupy Natura 2000 area in the River Geul. Widening the river and enlarging the current basins both occupy a large amount of the Natura 2000 area in the catchment area of the River Geul. However, it is questionable whether the impact is positive or negative because this depends on the type of Natura 2000 area (Junk et al., 1989). This is not part of the scope and therefore not rated in this research. Regarding cultural heritage, all the effective measures do not interfere with any buildings that are assigned as cultural heritage.

| Measure | Natura 2000 | Cultural heritage |
|---|---|---|
| **Widen the river 20 m opt** | Widening section 7 until A is part of Natura 2000 area, which is 3180 out of 4970 m length of 20 m widening which is about 64.000 m². | None |
| **Bypasses (largest)** | Only the in- and outlet of the bypass are part of the Natura 2000 area. This is about 20 x 4 = 80 m² each side. | None |
| **Remove obstacles** | Partly Natura 2000 area, only the River Geul with 9 out of 16 bridges. Size = 5 m x 12 m x 9 = 540 m². | None |
| **Enlarge current basins x5** | Only basin nr. 4 lays within a Natura 2000 area. Size increase = 25.400 x 5 – 25.400 = 101.600 m² | None |

**Table 26 Overview Natura 2000 area and cultural heritage. Based on locations + size of the measures.**

| **July 2021 (140 m³/s)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Difference compared to standard case | | | | | |
| | Standard | Widening of 20 m Opt | Bypass tunnel 20x2.5 m or ⌀ 8 m | Bypass channel 10 m | Remove obstacles | Enlarge basin x5 | |
| Natura 2000 area | 1.677.000 | -76.000 | -7000 | -6000 | -1000 | -40.000 | m² |
| Cultural heritage | 54 | -5 | -9 | -10 | -1 | -1 | objects |
| **Stress test (224 m³/s)** | | | | | | | |
| | | Difference compared to standard case | | | | | |
| | Standard | Widening of 20 m Opt | Bypass tunnel 20x2.5 m or ⌀ 8 m | Bypass channel 10 m | Remove obstacles | Enlarge basin x5 | |
| Natura 2000 area | 1.854.000 | -16.000 | 1000 | 0 | 0 | -2000 | m² |
| Cultural heritage | 83 | -2 | 1 | -2 | 0 | 0 | objects |

**Table 27 Overview of change in flooding Natura 2000 area and cultural heritage according to SSM2017.**

Table 27 shows the Natura 2000 areas and number of cultural heritage objects that are flooding for the different measures and scenarios, according to SSM2017. River widening shows the largest differences out of the presented measures. Again, the question is what the influence of flooding is on a Natura 2000 area or cultural heritage objects, and therefore this aspect is not rated. This is not expressed with money in SSM2017 and is up to the ecologists and decision makers.

## 7.3. Recap of chapter 7

The evaluation of the impact of measures is done by using different methods. First of all, a hydraulic model is used to simulate the possible measures. SOBEK is used for this, and the most important output is the reduction of the flooding depths at the measurement stations and the longitudinal cross-sections which show the local decrease in water level along the River Geul. Secondly, a damage victim module is used called SSM2017. SSM2017 calculates the amount of damage and victims that occurs during a flooding. The calculation is made for the four effective measures and the case without implemented measures. This is done for both scenarios: July 2021 and the stress test. The result gives insight into the reduction of damage and victims affected by a flooding. Finally, expert judgement is used to make global estimates of the costs of effective measures. Together with the social impact and the impact on Natura 2000 area for the effective measures the evaluation of the measures is complete. The final sub-question is answered with the evaluations of Chapter 7.

***SQ4 - What type of measures can be taken where and what is the impact of these measures on the River Geul and surrounding areas during extreme future flooding?***

The location of the measures is divided in three sections: downstream Valkenburg, in Valkenburg and upstream Valkenburg. The distinction between those sections is made, because for each section different measures are effective. The goal of the measures is to reduce the impact of flooding, which can be achieved by lowering the flooding depth and water level in urban areas like Valkenburg without negatively influencing the flooding in other urban areas along the River Geul. For instance, river widening leads to an upstream backwater curve, which lowers the water level along and upstream of the river widening. Therefore, this measure is simulated in the section downstream Valkenburg. A bypass creates a local water level lowering, which is beneficial to locate along Valkenburg. A last example is enlarging the current basins; these basins are already located in the section upstream Valkenburg and by enlarging them, additional storage capacity is created to temporarily store a part of the wave peak.

Based on the mentioned goals of measures in each river section the location relative to bottlenecks in the river section is defined. Measures downstream Valkenburg are located in between and far from downstream bottlenecks to induce local and upstream water level decrease, while measures upstream Valkenburg are located close to downstream bottlenecks to induce local and upstream water level rise with the goal to flatten out the wave peak. Only for enlarging the current basins and enlarging the culvert underneath the Julianakanaal bottlenecks are not determining the location. The measures in Valkenburg are different in that aspect because they either bypass (or remove) the bottlenecks or can be simulated along bottlenecks (raising dikes for example) to induce a local water level decrease.

Several measures did not significantly decrease the flooding depths or water levels in urban areas and are therefore not further evaluated with SSM2017 and expert judgement. This explains the empty columns of measures in Table 28 . Some measures showed effective results, which means that they lowered the water level and flooding depth significantly nearby urban areas (the effective measures are completely elaborated in Table 28). The water level change and the corresponding location mainly occur locally in between bottlenecks where the measure is simulated as bottlenecks block the positive effects of the measures. This is explained in Section 7.2.2 where the longitudinal cross-sections of the maximum water level are shown for each effective measure, together with top views of the location of the measure.

Table 28 shows the total overview of the evaluation of the largest dimensions of each simulated (effective) measure for July 2021. This overview contains the water level change with the affected river length, type of affected area, damage decrease, costs of the measure, social impact, Natura 2000 area that is used to implement the measure and decrease of flooding Natura 2000 area. For the stress test the results are much different compared to July 2021. The SOBEK output shows effective but in general lower water level and flooding depth decrease for the stress test simulations. However, in comparison with the flooding depth of the River Geul for July 2021 the flooding depth of the stress test remains much higher, even after implementing measures. Furthermore, the measures are dimensioned for the flooding of July 2021 and not for the stress test. Therefore, the measures barely reduce the damage as a consequence of flooding for the stress test. Because of this lack of impact for the stress test the total evaluation of measures is only based on the scenario July 2021.

| Scenario July 2021 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Section** | **Measure description & size** | **Change in water level [m]** | **River length effect [m]** | **Type of area water level change** | **Damage decrease along River Geul [%]** | **Costs of the measure [€]** | **Social impact** | **Natura 2000 area used [m²]** | **Change in flooding Natura 2000 area [m²]** |
| **Downstream** | **Enlarge culvert Julianakanaal (15x2.5 m)** | 0 | 0 | Bunde | | | | | |
| | **Widen the river downstream (+20 m opt)** | -0.5 until -1.0 | 5000 | Bunde, Meerssen | 6 | 12 - 23 million | none | 64.000 | -76.000 |
| **In Valkenburg** | **Remove channelization in Valkenburg (30 degrees)** | -0.05 | 300 | Valkenburg | | | | | |
| | **Bypass: in-situ tunnel through Valkenburg (20x2.5 m)** | -0.1 until -1.5 | 1750 | Valkenburg | 34 | 68 – 126 million | +/- 25 buildings removed | 80 | -7.000 |
| | **Bypass: drilled tunnel through Valkenburg (⌀ 8 m)** | -0.1 until -1.5 | 1750 | Valkenburg | 34 | 112 – 207 million | +/- 5 buildings removed | 80 | -7.000 |
| | **Bypass: additional channel through Valkenburg (base 10 m, top 18 m)** | -0.1 until -1.5 | 1750 | Valkenburg | 37 | 42 – 77 million | +/- 25 buildings removed | 80 | -6.000 |
| | **Raise dikes in Valkenburg (+1 m)** | -0.05 until +0.1 | 300 | Valkenburg | | | | | |
| | **Remove obstacles in the River Geul along Valkenburg** | -0.1 until -0.4 | 800 | Valkenburg | 6 | 4 – 7 million | +/-16 bridges replaced | 540 | -1000 |
| **Upstream** | **Thresholds upstream Valkenburg (1.5 m)** | 0 | 0 | None | | | | | |
| | **Weirs before the 3 tributaries reach the River Geul (48h closed)** | 0 | 0 | None | | | | | |
| | **Add vegetation upstream Valkenburg (Manning + 0.05)** | 0 until +0.2 | 5000 | Rural area | | | | | |
| | **Raise riverbed upstream Valkenburg (+1.5 m)** | 0 until +0.05 | 3000 | Rural area | | | | | |
| | **Enlarge current basins (x5)** | -0.1 until -1.0 | 7000 | Wahlwiller, Nijswiller | 3 | 243 - 451 million | none | 101.600 | -40.000 |

**Table 28 Overview evaluation of the largest dimensions of each simulated measure for July 2021, only the effective measures are fully evaluated with SSM2017 and expert judgement.**

A small elaboration of the results in Table 28 is given for the effective measures. The optimization of current basins in the River Geul scores by far the worst on damage decrease and costs. The other three measures, river widening, bypass through Valkenburg and removing obstacles, all score well on various aspects. River widening leads to the same damage decrease as removing obstacles but the social impact for river widening is unnoticeable. The costs of river widening are three times higher than removing obstacles, but removing obstacles also lowers the water level by only 0.1 until 0.4 m over 800 m, where river widening lowers the water level by 0.5 until 1.0 m over 5000 m. The location of the water lowering as a result of removing objects is however more valuable (city centre of Valkenburg) and flooding can lead to more damage. Therefore, a smaller decrease in water level can lead to the same decrease in damage. The bypass lowers the water level by far the most with a decrease of 0.1 until 1.5 metre locally over 1750 m. Also, the bypass reduces the damage by at least 34% compared to 6% for the other two measures while the costs are at least a factor of four higher, depending on the type of bypass; a tunnel (in-situ or drilled) or a channel. Furthermore, a bypass tunnel in-situ and channel lead to major social impact in the city centre of Valkenburg because many buildings have to be removed. For the drilled tunnel, the social impact is limited, but the costs are double as high compared to the other two bypasses. The importance of the results regarding the Natura 2000 area is not evaluated in this research and requires more research before any useful comparisons can be made.

# 8. Discussion

This study focuses on the simulation and evaluation of measures in the Dutch part of the catchment area of the River Geul to reduce the impact of flooding. The research has certain limitations and the meaning, importance, and relevance of these are discussed in this chapter.

## 8.1. Recurrence interval of simulated events

As a consequence of climate change and more frequent heavy rainfall (Zhang, 2020) extremer events increase the risk for people living in the vulnerable areas nearby the River Geul. Therefore, the SOBEK evaluation of measures is only based on SOBEK simulations of the flooding in July 2021 and a stress test based on the amount of precipitation that fell in Germany during the flooding of July 2021. The precise recurrence intervals of the simulated events are unknown. According to ENW (2021) the flooding of the Geul in July 2021 has a recurrence interval in between 1/100 and 1/1000 per year, while for the data used for the stress test (the most extreme German precipitation of July 2021) the expectation of the recurrence interval of this event lies around 1/1000 per year. Other less extreme but more frequent events are not considered in this research. This influences the results, because only measures that have impact during the most extreme events are further analysed. However, the effective measures based on the flooding of July 2021 would also be effective for less extreme events. The research thus gives insight into the river response to possible extreme future flooding, but this does not mean that the measures are not functioning for more frequently recurring events than July 2021.

## 8.2. The use of meteorological data

For this research meteorological data from Meteobase is used to simulate the flooding of July 2021. Meteobase uses all the measurement locations and data from KNMI. However, during the flooding of July 2021 the information on precise precipitation was of insufficient quality. The number of precipitation measurement locations in the area is limited, and the real-time KNMI radar product underestimated the precipitation volumes by approximately a factor of three (ENW, 2021). Important to mention is that the meteorological data is used during the calibration of the SOBEK model, but to prevent unrealistic results the SOBEK model was calibrated based on maximum measured water levels in the River Geul during the flooding of July 2021. The input of this calibrated model consists of the Meteobase precipitation data and the discharge and water level input at the boundary conditions. The variated parameter to perform this calibration is the discharge at the boundary conditions. The goal of this calibration is to simulate the flooding of July with a SOBEK model based on measured water levels. If the water levels after calibration of the SOBEK model are more or less equal (+/- 0.02 m) to the maximum measured water levels the assumption is made that the flooding of July 2021 was properly simulated. In this way the accuracy of the meteorological data is no longer important if the flooding is represented accurately.

## 8.3. Accuracy of SOBEK model

The SOBEK model forms an important aspect of this research because it translates the thoughts of measures towards a simulation of measures which shows the actual effect of a measure on the River Geul. The accuracy of the simulated water levels for the flooding of July 2021 is guaranteed by the optimization of the calibration of this model. The existing model, provided by waterboard Limburg, was calibrated in 2014. This calibration is performed by variating the roughness parameter. However, the parameter variated for the calibration in this research is the discharge at the boundary conditions. The WH_Center 2050 climate scenario is used as a base point and from there on the discharge is optimized until the output of SOBEK at the measurement stations showed the same maximum water levels as measured during the flooding of July 2021. In this way the SOBEK model represents the water levels accurately, but the discharge of the River Geul is probably overestimated. Measured flow velocities of the flooding of July 2021 are also not available so the model is not calibrated on this output parameter. Consequently, for the evaluation of impact only the simulated water levels are used because these are accurately calibrated. Yet, the goal of this research is fulfilled by considering the limitations of available (accurate) data.

## 8.4. Implementation of measures; dimensions and locations

Several measures are simulated in this research. These measures are simulated with certain dimensions at various locations in the catchment area of the River Geul. The dimensions of the measures are defined during modelling because it is hard to predict what dimensions would be effective to reduce flooding depths at certain locations in the system. For each measure, several different dimensions are simulated in SOBEK to evaluate the functioning of the measure without having to choose one dimension. The sensitivity of the model is also investigated in this way.

The distinction between the sections up- and downstream Valkenburg and in Valkenburg is made because most of the damage during July 2021 occurred in Valkenburg. Therefore, the focus in the research lies on reducing the water levels along Valkenburg, which directly limits the locations where certain measures can be effective. However, multiple urban areas along the River Geul also contribute to the amount of damage and therefore the total river system is considered when it comes to effective or ineffective measures. For instance, a water level lowering close to Meerssen also leads to a damage reduction as a consequence of flooding for the entire system of the River Geul.

The location of the measures in the sections up- and downstream Valkenburg is mostly based on the bottlenecks in the River Geul. To identify these bottlenecks the calibrated SOBEK model is used to run a simulation on the flooding of July 2021. Use is made of a longitudinal cross-section of the complete River Geul, starting in Cottessen at the Belgium border until the mouth where the River Geul flows into the River Meuse. In this way an overview of the bottlenecks in the system is provided by looking at local water level drops. This method is sensitive for errors but by knowing where the bottlenecks are, the location where the measures can be implemented is done more precisely, which leads to better results.

## 8.5. Evaluation of measures

The simulated measures are first evaluated on the SOBEK output of each measure. Based on the local reduction of the water level and the location where the water level is reduced, either urban or rural area, the measures are rated on effectiveness. Only effective measures are further evaluated with the damage-victim module. A water level reduction without urban area, which thus leads to no damage reduction, is considered as not effective. The simulated flow velocities are not taken into account to decide if a measure is effective or not, because the model is not calibrated with measurements of July 2021 as no measurements are available. Therefore, the flow velocities are not considered in the damage-victim module. This is limiting the capabilities of SSM2017 but gives more credible results.

The damage-victim module makes use of several cost damage functions and is widely used in the Netherlands to evaluate the amount of damage in certain situations. However, this module is made for polders which is not comparable with the River Geul. Polders are flat while the River Geul is steep. Therefore, the accuracy of the estimates of damage and victims with SSM2017 is doubtful. However, for this research SSM2017 is only used to give insight into the reduction of damage and victims after implementing measures relative to the current situation. In this way, SSM2017 can still give insight into the impact of measures.

After the calculations of SSM2017 the global costs for the effective measures are estimated and the social impact is defined. The biggest question marks arise when costs are shown based on undetailed designed measures. It is important to bear in mind that the actual costs can differ from these estimates, even though expert judgement is used to substantiate these estimates. However, the global estimates of the costs show how much money the government approximately has to spend to implement a measure. Also, the social impact is an estimate but can influence certain choices.

# 9. Conclusions and recommendations

In Section 9.1, the research questions as presented in Section 1.2 are answered in order to conclude this thesis. Thereafter, Section 9.2 introduces recommendations on SOBEK simulations, field research, a cost benefit analysis, ecologic research, and use of the results of this thesis are presented.

## 9.1. Conclusions

### SQ1 - How was the precipitation and discharge distributed over the Dutch part of the catchment area of the River Geul during the flooding of July 2021?

During the flooding of July 2021, 46% of the total amount of water in the Dutch part of the catchment area of the River Geul came from discharges which originate in Belgium and Germany. The precipitation above the Dutch part of the catchment area contributed 52% to the total amount of water in the catchment area, while only 2% came from a discharge of a tributary of the River Geul that originates in the Netherlands. The discharge of the River Geul is thus strongly dependent on the inflow of discharges from Belgium and Germany, which is for this research limiting the possibility to apply measures at the source. Only the Dutch part of the catchment area of the River Geul is taken into account.

### SQ2 - How extreme was the amount of precipitation of July 2021 in Limburg (NL) and surrounding areas in Germany compared to extreme Dutch climate scenarios?

For the maximum amount of precipitation in Limburg (NL) in 48 hours during the flooding of July 2021 the climate scenario WH_Center 2085 for a recurrence interval of 1/1000 per year shows representative values, which means that the current climate scenarios already take into account a similar extreme event. In Germany, the amount of precipitation in 48 hours was about 60% more compared to Limburg (NL) during July 2021 (Ruhnau, 2021). Because both the elevation and the size of the catchment area of the River Geul are comparable to the area of the extreme German precipitation the assumption is made that this extreme precipitation of Germany could also have happened in the catchment area of the River Geul (Rowe et al., 2008). No current extreme Dutch climate scenarios consider worse or similar amounts of precipitation than the extreme precipitation of Germany during July 2021. A maximum of 304 mm fell in 48 hours in Germany (Ruhnau, 2021) while the most extreme Dutch climate scenario for the year 2085 considers only 204 mm in 48 hours (Beersma et al., 2019). Therefore, the maximum amount of precipitation of Germany during July 2021 is used as a stress test for the simulated measures, instead of the most extreme Dutch climate scenario.

### SQ3 - What is the influence of the River Meuse and bottlenecks in the River Geul on the water level of the River Geul during flooding?

According to the SOBEK simulations of three different scenarios the influence of the River Meuse only reaches until Bunde for the most extreme scenario, which is when the peak of the River Meuse would have double the size. For this extreme scenario, the water level at Bunde goes up by over one metre. With respect to the total length of the River Geul the influence of the River Meuse only reaches until the lowest seven percent of the River Geul, which is equal to 4 out of 56 kilometres river length. Overall, the effect is very local due to the steepness of the River Geul, and the influence never reaches areas upstream Bunde. Therefore, the impact of the River Meuse is not further taken into account in the simulations of different measures.

The SOBEK model is used to identify the bottlenecks in the River Geul. A locally steeper step profile in the longitudinal water profile of the River Geul refers to a bottleneck in the system (Mosselman, 2007). This is the result of for instance a weir or bridge in the river system. The influence of these bottlenecks is thus creating significant local water level differences during flooding due to for instance local narrowing or higher friction factors. The influence is expressed in amount of backwater that the bottlenecks cause in the River Geul during the flooding of July 2021. In Valkenburg the backwater is about 3 m per kilometre river length, while up and downstream Valkenburg the caused backwater is only 0.5 m per kilometre. This is a major difference and shows that the bottlenecks have a much larger influence on the flooding of the River Geul in Valkenburg than elsewhere in the system.

Another effect that bottlenecks have is blocking the water level lowering of measures according to the longitudinal cross-sections of the maximum water level during July 2021 and the stress test. Measures only effectively reduce water levels between bottlenecks, with a significant distance away from a downstream bottleneck. This effect is considered during the simulation of measures.

## SQ4 - What type of measures can be taken where and what is the impact of these measures on the River Geul and surrounding areas during extreme future flooding?

The type of measures is related to the location within the River Geul. Therefore, a distinction is made between three sections: downstream Valkenburg (until the river mouth), in Valkenburg and upstream Valkenburg (until the Belgium border at Cottessen). The goal of the measures is to reduce the impact of flooding, which can be achieved by lowering the flooding depth in urban areas like Valkenburg without negatively influencing the flooding of other urban areas along the River Geul. For each section different type of measures are effective. In the section downstream Valkenburg measures that lower the water level locally and upstream of the measure are useful, while in Valkenburg a local effect is the most effective. Upstream Valkenburg the temporary retention of water and flattening of the peak wave for downstream areas is the aim. Based on the mentioned goals of measures in each river section the location relative to bottlenecks in the river section is defined. Measures downstream Valkenburg are located in between and far from downstream bottlenecks to induce local and upstream water level decrease, while measures upstream Valkenburg are located close to downstream bottlenecks to induce local and upstream water level rise with the goal to flatten out the wave peak. For measures in Valkenburg the bottlenecks are either removed, bypassed, or not influencing the effectivity of a measure.

The impact of measures is first evaluated on the simulated reduction of water level and flooding depth nearby urban areas for both July 2021 and the stress test. The measures are divided over the three sections and only the largest dimensions of the measures are compared with each other to show the maximum impact. Four measures showed effective results (for July 2021), which means that they all lower the water level and flooding depth significantly nearby urban areas. This holds for the following measures, subdivided into the three sections:

1. *Downstream Valkenburg*
    - Widening the river (+ 20 m), which lowers the water level by 0.5 to 1.0 m over 5000 m.
2. *In Valkenburg*
    - Bypass through Valkenburg with a tunnel (in-situ (20x2.5 m) or drilled (⌀ 8 m)) or channel (base 10 m and top 18 m wide), which lowers the water level by 0.1 to 1.5 m locally over 1750 m.
    - Removing obstacles in the River Geul along Valkenburg, which lowers the water level by 0.1 to 0.4 m over 800 m.
3. *Upstream Valkenburg*
    - Enlarging the current basins (x5), which lowers the water level by 0.1 to 1.0 m over 7000 m.

Several measures did not (significantly) decrease the flooding depth and water level in urban areas for both scenarios and are therefore not further discussed as the measures are not effective. This holds for the following measures, subdivided into the three sections:

1. *Downstream Valkenburg*
    - Enlarge the culvert underneath the Julianakanaal; the current culvert is already sufficient.
2. *In Valkenburg*
    - Remove channelization in Valkenburg; a low increase in discharge capacity relative to the extreme discharge during flooding.
    - Raise dikes in Valkenburg; a relatively low increase in discharge capacity and upstream Valkenburg the river suffers already from flooding.
3. *Upstream Valkenburg*

- Thresholds upstream Valkenburg; they only function during low (average) discharges.
- Weirs before the three tributaries; a low contribution of the tributaries relative to the total discharge. Furthermore, the weirs cannot retain the water like a basin.
- Add vegetation upstream; only a local water level increase due to additional resistance, but no lowering of water levels downstream due to bottlenecks so the peak does not spread out.
- Raise the riverbed upstream; the same result as adding vegetation.

The four effective measures have been further analysed with SSM2017 and expert judgement to evaluate the impact on damage decrease, costs, social impact, and the use of and flooding of Natura 2000 area. Again, only the largest dimensions of the measures are compared with each other to show the maximum impact. The impact of each measure is elaborated for the four topics for July 2021:

1. *Damage decrease along the River Geul*
   - The bypass reduces the damage by at least 34%, while both river widening and removing obstacles reduce the damage by 6%. Enlarging current basins has the smallest impact and reduces the damage by only 3%.
2. *Costs*
   - Removing obstacles is the cheapest measure. River widening is a factor of 3 more expensive, while a bypass a factor of 10 (channel) to 25 (tunnel drilled) and enlarging the current basins a factor of 60.
3. *Social impact*
   - Only the bypass tunnel in-situ and bypass channel have major social impact, because approximately 25 buildings have to be removed, while for the bypass tunnel drilled this is at most 5 buildings. The measure removing obstacles only gives temporary social nuisance.
4. *Natura 2000 area*
   - River widening lowers the amount of Natura 2000 area that experiences flooding the most, while removing obstacles in the River Geul along Valkenburg has the smallest effect. Enlarging the current basins requires a lot of Natura 2000 area, which also holds for river widening. However, depending on the type of area, the flooding and use of Natura 2000 area can have positive and negative effects (Junk et al., 1989). These expected effects have to be investigated by ecologists and are not part of this research.

## MQ - What is the impact of hydraulic or hydrological measures on the consequences of extreme future flooding of the River Geul?

With the answers to the four sub-questions the impact of measures on the consequences of extreme future flooding can be explained. Measures upstream Valkenburg do not have any major impact on the consequences of extreme future flooding. The main damage as a consequence of the flooding of July 2021 occurred in Valkenburg (ENW, 2021). Only a few measures lowered the water levels in Valkenburg significantly due to bypassing the discharge in Valkenburg or preventing the slowdown of the water in Valkenburg and therefore showed a considerable impact regarding damage reduction. Downstream Valkenburg several urban areas also experienced flooding during July 2021 and therefore a measure in this section which lowers the water level locally, due to an increase in discharge capacity, also showed a damage reduction.

Depending on the preferences of decision makers the choice for a measure can be made. Based on this research and looking at the flooding of July 2021, a bypass in Valkenburg reduces the damage along the River Geul the most with approximately one-third. A bypass performed as a channel is associated with a cost estimate of 42 - 77 million euros and +/- 25 buildings that have to be removed, while for a bypass performed as drilled tunnel the social impact is limited (maximum 5 buildings have to be removed) but a higher cost estimate of 112 - 207 million euros is the consequence. River widening downstream Valkenburg or removing obstacles in Valkenburg comes with lower costs of 4 - 23 million euros in combination with no social impact but this results in a damage reduction of only 6 percent.

For extremer events than July 2021, even the effective measures for the July 2021 scenario do no longer decrease the damage along the River Geul. All measures can no longer decrease the water level enough to decrease the damage, even though the measures lead to a decrease in water level nearby urban areas. This is the result of the large increase in water level in the whole River Geul compared to July 2021, as the stress test makes use of 60% more discharge and precipitation. Furthermore, the measures are dimensioned for the flooding of July 2021 and not for the stress test. This outcome does not mean that measures should not be implemented, because the chance that a similar event as the stress test recurs is at least a factor of ten smaller compared to July 2021 (July 2021 ≈ 1/100 - 1/1000 per year, stress test ≈ 1/10.000 per year). Overall, the stress test shows that the impact of measures really depends on the recurrence interval of events and that the rating of effective measures for July 2021 is no guarantee that measures always lead to a significant impact.

## 9.2. Recommendations

This research has explored the impact of measures on the consequences of extreme future flooding of the River Geul. During this research, several simplifications are made which provide recommendations for future research. Also, interesting findings during the research, which are not part of the scope of this research are described here. The recommendations are split up into recommended SOBEK simulations, field research, cost-benefit analysis, ecologic research, and the application of this research.

### 9.2.1. SOBEK simulations

In this research, several measures are simulated in SOBEK for July 2021 and the stress test. The SOBEK simulations that are not performed in this research, but which are recommended are:

- the combination of effective measures;

A combination of certain measures is recommended because it is expected that it can lead to larger water level lowering and thus a larger impact. After the evaluation of measures in Chapter 7 only four effective measures are left (for July 2021): widening the river downstream Valkenburg, bypass through Valkenburg, removing obstacles in the River Geul along Valkenburg and enlarging the current basins.

River widening in combination with either a bypass through Valkenburg or removing obstacles in Valkenburg are the two recommended combinations. The most effective measure regarding flooding depth and damage reduction is the bypass through Valkenburg. River widening itself leads to a local water level decrease just downstream Valkenburg while the effect of the bypass directly downstream Valkenburg vanishes. The combination of the two measures is expected to lead to a larger water level decrease along and downstream Valkenburg which induces an overall damage reduction along the River Geul. Combining removing obstacles with river widening downstream Valkenburg has the same (but less intense) expected effect as combining the bypass with river widening. However, the combination of river widening and removing obstacles is much cheaper than only implementing a bypass.

No combination with enlarging the current basins is recommended, because the measure showed barely any damage reduction. A combination with this measure has no additional advantage.

- more frequently recurring events.

The research is focused on extreme future floodings. The flooding of July 2021 and the stress test represent these extreme future floodings. It is recommended to also run the simulations of measures with less extreme events to see if the ineffective measures are still ineffective, because the recurrence interval of both July 2021 and the stress test are very low (July 2021 ≈ 1/100 - 1/1000 per year, stress test ≈ 1/10.000 per year). When for instance the goal is to decrease the damage for events with a minimum recurrence interval of 1/50 per year, cheaper and less drastic measures can already be effective. The recommendation is to run simulations with multiple larger recurrence intervals (1/25, 1/50, 1/100 per year) to find out how large the recurrence intervals have to be before measures effectively reduce the water level and damage. Based on that, measures can be compared on the impact related to a recurrence interval.

### 9.2.2. Field research

Several aspects cannot be modelled in SOBEK, for instance the spatial planning or the buyout of a farm. Also, the feasibility of certain dimensions of measures in this research have to be further evaluated. Field research would be the key to make a translation from the modelled measures towards reality and is therefore recommended for future research. Knowledge about licenses and governmental budgets are of importance here, but also knowledge about the local river characteristics and surrounding scenery are meaningful aspects to get more insight into the feasibility of possible measures. All the measures are simulated with certain dimensions, but proper field research would show which dimensions are possible. This would change the conclusions if the dimensions of measures have to change. For example, if the river can be widened over a longer reach but the bypass has to be smaller, the impact of river widening increases, while the impact of the bypass decreases. However, the costs of a bypass will always remain much higher than river widening (I. de Jong, personal communications, February 10 2022). These findings might influence the choice of decision makers.

### 9.2.3. Cost-benefit analysis

In this research the evaluation of effective measures with SSM2017 and a cost estimate is only performed for the largest simulated dimensions of each measure for the flooding of July 2021 and the stress test. Furthermore, the rating of effective and ineffective measures is purely based on the change in water level and flooding depth nearby urban area. For this research, these assumptions have led to a variety of insights for several measures, but for decision makers it is recommended to perform a cost-benefit analysis to achieve the optimal cost-benefit ratio for a variety of measures, dimensions and scenarios. A cost-benefit analysis attempts to estimate the (positive and negative) effects of a project (or policy option) for the entire society of the Netherlands (in this case). This does not only concern financial costs and benefits, but also social effects such as the effects of a project on noise pollution or nature. Both the direct and indirect effects of different variants are systematically made transparent and expressed in monetary units, so that policymakers and administrators can make a well-considered decision about which project or variant is preferred (Ministerie van Financiën, n.d.). Because all the effects are expressed in the same unit, all the different variants can be compared equally. Not only the different measures are recommended to be compared, but also the different dimensions of each measure in combination with more frequently recurring events is recommended to evaluate with this cost-benefit analysis to fairly make comparisons and decisions. Based on the outcome of the analysis, it can be decided which measure has to be analysed more detailed and which measure does not fulfil the preferences of decision makers.

### 9.2.4. Ecologic research

For several measures, the change in the use and flooding of Natura 2000 areas is investigated in this research, but the effect of measures on Natura 2000 area is not rated because ecology and the possible impact on Natura 2000 area is a whole different type of study. However, along the River Geul several Natura 2000 areas are located and therefore before implementing measures in the River Geul the impact on Natura 2000 areas as a consequence of implementing measures is recommended to investigate. The use of Natura 2000 area comes with strict rules and high costs, but also the impact of flooding on Natura 2000 area is of importance (Junk et al., 1989). Ecologists need to properly analyse the area and make recommendations based on the use and flooding of Natura 2000 areas, as defined in this research. This can drastically impact the feasibility and costs of a measure. Especially for river widening and enlarging the current basins the use and flooding of Natura 2000 area is large compared to the bypass and removing obstacles. Therefore, the conclusions of these measures are recommended to be revised after the ecologic research.

### 9.2.5. Application of this research

This research provides several insights regarding the impact of measures. For waterboard Limburg, which is the operator of the catchment area of the River Geul, these insights are useful to decide which next steps can be taken. A recommendation on these steps is given. First, it is recommended to design the bypass in more detail because this measure shows the largest decrease in damage along the River Geul and requires proper drawings, calculations, and field research. For the simulation of this measure several assumptions are made for the location, size, and materials, based on the available knowledge and SOBEK output. These assumptions can be improved by designing (and researching) the measure in more detail. Second, for removing the obstacles in the River Geul along Valkenburg it is recommended to further investigate the possibility of implementing slimmer bridges, because the urban area of Valkenburg is dense and new innovative techniques are required to achieve no slowing down of the water during flooding. Removing bridges also affects the functionality of the infrastructure during the construction, which is important to consider.

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WVER (2021, August 18). *Faktencheck zum Hochwasser*. WVER | Damit Leben im Fluss bleibt. Retrieved February 24, 2022, from https://wver.de/faktencheck-zum-hochwasser/

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# Appendix Chapter 2

## Appendix 2A
## The River Geul

| Overview hydrological details River Geul | | | | | | |
|---|---|---|---|---|---|---|
| Size of the catchment area [ha] | | Length [km] | | Elevation difference [m] | Slope [m/km] | Discharge [m³/s ] |
| Total | Within Limburg | Total | Within Limburg | | Average | Average |
| 38775 | 18280 | 56 | 36 | 242 | 4.3 | 1-4 |

**Table 29 Hydrological details of the River Geul, adjusted from (Paarlberg, 1990).**

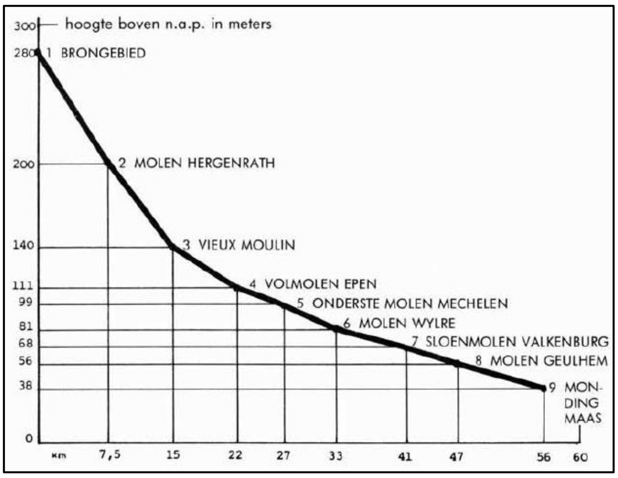


**Figure 63 Elevation difference of the River Geul from source till mouth (Paarlberg, 1990).**

## Appendix 2B
## The River Gulp

| Overview hydrological details River Gulp | | | | | | |
|---|---|---|---|---|---|---|
| Size of the catchment area [ha] | | Length [km] | | Elevation difference [m] | Slope [m/km] | Discharge [m³/s] |
| Total | Within Limburg | Total | Within Limburg | | Average | Average |
| 4640 | 2080 | 17 | 10 | 197 | 11.6 | 0.3-0.6 |

**Table 30 Hydrological details of the River Gulp, adjusted from (Paarlberg, 1990).**

# Appendix 2C

## Safety level River Geul and River Gulp

| Criteria | Main water system unprotected area (type A) | | | Main water system protected area (type B) | | |
|---|---|---|---|---|---|---|
| Flooding risk [1/year] | 1/10 | 1/100 | 1/1000 | 1/10 | 1/100 | 1/1000 |
| Economic damage [M€] | 50-100 | 100-250 | 500-1000 | - | 100-250 | 5000-10000 |
| Deadly victims [number] | None | None | <10 | - | <10 | 100-250 |
| Harmed inhabitants [number] | 1000 | 1000-2500 | 5000-10000 | - | 1000-2500 | >50000 |
| Nature and ecology [x1000 ha] | 50-75 | 50-75 | 50-75 | - | <1 | 50-75 |
| Cultural heritage [number] | 250-500 | 250-500 | 500-1000 | - | 100-250 | 1000-2500 |
| Social disruption | Medium | Medium | Medium | - | Large | Large |
| | **Regional water system protected area (type C)** | | | **Regional water system unprotected area (type D)** | | |
| Flooding risk [1/year] | 1/10 | 1/100 | 1/1000 | 1/10 | 1/100 | 1/1000 |
| Economic damage [M€] | 10-40 | 40-400 | 400-750 | 5 | 10 | 50 |
| Deadly victims [number] | None | <10 | 50-100 | None | None | None |
| Harmed inhabitants [number] | Unknown | 2500 | 2500-5000 | 250 | 250-500 | 1000-2500 |
| Nature and ecology [x1000 ha] | Unknown | 25-50 | 25-50 | <10 | <10 | <10 |
| Cultural heritage [number] | - | 1000-2500 | 1000-2500 | 25-50 | 50-100 | 100-200 |
| Social disruption | Small | Medium | Large | Medium | Medium | Medium |

**Table 31 Overview amount of damage based on probability of flooding (1/10, 1/100 and 1/1000) for each type of water system in NL, adjusted from (Ministerie van infrastructuur en waterstaat, 2018).**

| Name | Administrator | Damage [M€] | Damage [M€] | Victims [number] | Cross borders |
|---|---|---|---|---|---|
| Flooding risk [1/year] | | 1/100 | 1/1000 | 1/100 | |
| River Roer | WS Limburg | 25-50 | 125-250 | 0 | Yes |
| River Gulp | WS Limburg | 10-25 | 50-125 | 1-5 | Yes |
| River Geul | WS Limburg | 25-50 | 125-250 | 1-5 | Yes |
| River Geleenbeek | WS Limburg | 10-25 | 50-125 | 0 | Yes |
| River Linge | WS Rivierenland | 50-100 | 250-500 | 0 | No |

**Table 32 Regional water systems in NL with large potential consequences for 1/100 situation, 4 out of 5 located in Limburg, adjusted from (Ministerie van infrastructuur en waterstaat, 2018). The 1/1000-year flooding damage is extrapolated based on the available data for both the 1/100- and 1/1000- year flooding (Type D) from Table 31 and the given damage of Table 32 for the 1/100-year flooding.**

# Appendix Chapter 5

## Appendix 5A

## Precipitation July 2021

| | Netherlands | Belgium | Germany | Luxemburg |
|---|---|---|---|---|
| **Precipitation in 48 hours** | > 150 mm (182 mm locally) | 170 - 190 mm | > 160 mm (224 mm in 24 h locally) | 105 mm (in 24 h) |

**Table 33 Overview precipitation amount for the Netherlands, Belgium, and Germany in 48 hours during 13th and 14th of July 2021, adjusted from (ENW, 2021).**

## Appendix 5B

## Precipitation duration lines

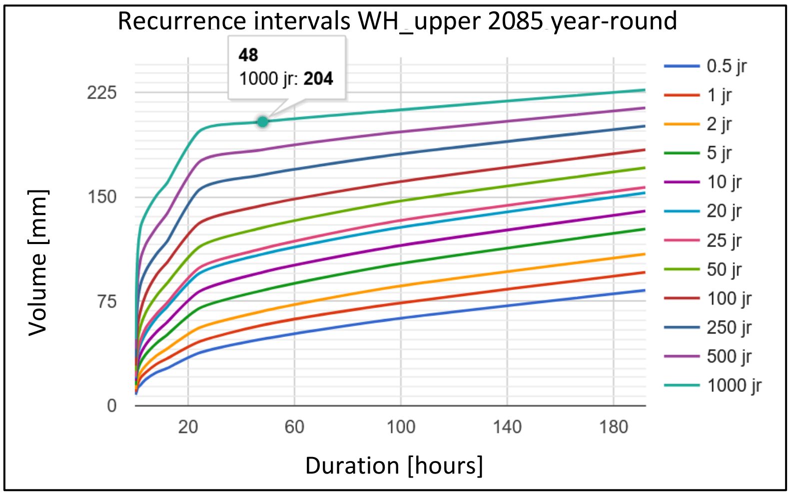


**Figure 64 Recurrence intervals 2085 year-round scenario WH_upper (Beersma et al., 2019).**

| Duration(hours) | 1/1000 per year |
|---|---|
| 1 | 111 |
| 2 | 128 |
| 3 | 133 |
| 4 | 138 |
| 8 | 151 |
| 12 | 160 |
| 24 | 197 |
| 48 | 204 |
| 96 | 212 |
| 192 | 227 |

**Table 34 1/1000 per year recurrence interval 2085 year-round scenario WH_upper (Beersma et al., 2019).**

# Appendix Chapter 6

## Appendix 6A
## The calibration of the SOBEK model

In the research from ENW (2021) the maximum measured water levels in the River Geul and tributaries are given. These measurements are coming from the measurement locations from waterboard Limburg. Table 35 shows the measured water levels. The output of the SOBEK model of the River Geul is compared with Table 35. The locations of each measurement location are visualized in Figure 65.

### Measured water levels and the climate scenario

Table 35 shows the accuracy of the WH_Center 2050 climate scenario in comparison with measurements of the maximum water level during the flooding of July 2021.

| nr | Meetstation in het Geuldal | Maximum gemeten waterstand (m+NAP) | Waterstand 1:100 WHCenter 2050 klimaat (m+NAP) | Waterstands-verschil (m) |
|---|---|---|---|---|
| | *Geul* | | | |
| 1 | Meerssen Maastrichterlaan | 46.16 | 46.83 | -0.67 |
| 2 | Rothemermolen | 50.43 | 50.82 | -0.39 |
| 3 | Grote Molen | 52.95 | 52.75 | +0.2 |
| 4 | Geulhemmermolen | 59.09 | 58.98 | +0.11 |
| 5 | Geulhem | 60.56 | 60.48 | +0.08 |
| 6 | Valkenburg Wiegert | 67.71 | 67.94 | -0.23 |
| 7 | Wijlre | 84.07 | 83.78 | +0.29 |
| 8 | Wijlre Brand bierbrouwerij | 85.94 | 86.38 | -0.44 |
| 9 | Samenvloeiing Geul Gulp Selzerbeek Eyserbeek | 89.59 | 89.4 | +0.19 |
| 10 | Mechelen | 101.31 | 100.93 | +0.38 |
| 11 | Commandeursmolen | 102.88 | 102.77 | +0.11 |
| 12 | Volmolen Hurpesch | 106.63 | 106.17 | +0.46 |
| 13 | Epenermolen | 113.37 | 113.26 | +0.11 |
| 14 | Cottessen | 122.04 | 121.79 | +0.25 |
| | | | | |
| | *Gulp* | | | |
| 1 | Gulpen Azijnfabriek | 91.93 | 93.5 | -1.57 |
| 2 | Euverem | 104.99 | 104.97 | +0.02 |
| 3 | Beutenaken | 124.05 | 123.76 | +0.29 |
| 4 | Instroom molentak Broekermolen | 137.23 | 137.53 | -0.3 |
| 5 | Slenaken | 138.24 | 137.81 | +0.43 |
| | | | | |
| | *Eyserbeek* | | | |
| 1 | Meetgoot Eys | 102.74 | 101.8 | +0.94 |
| 2 | Eys | 111.62 | 111.51 | +0.11 |
| 3 | Simpelveld Oude Molen | 131.35 | 131.6 | -0.25 |
| 4 | Simpelveld | 141.18 | 140.92 | +0.26 |

**Table 35 Maximum measured water levels and simulated water levels along the River Geul and tributaries for the fact finding of the flooding of July 2021 (ENW, 2021).**

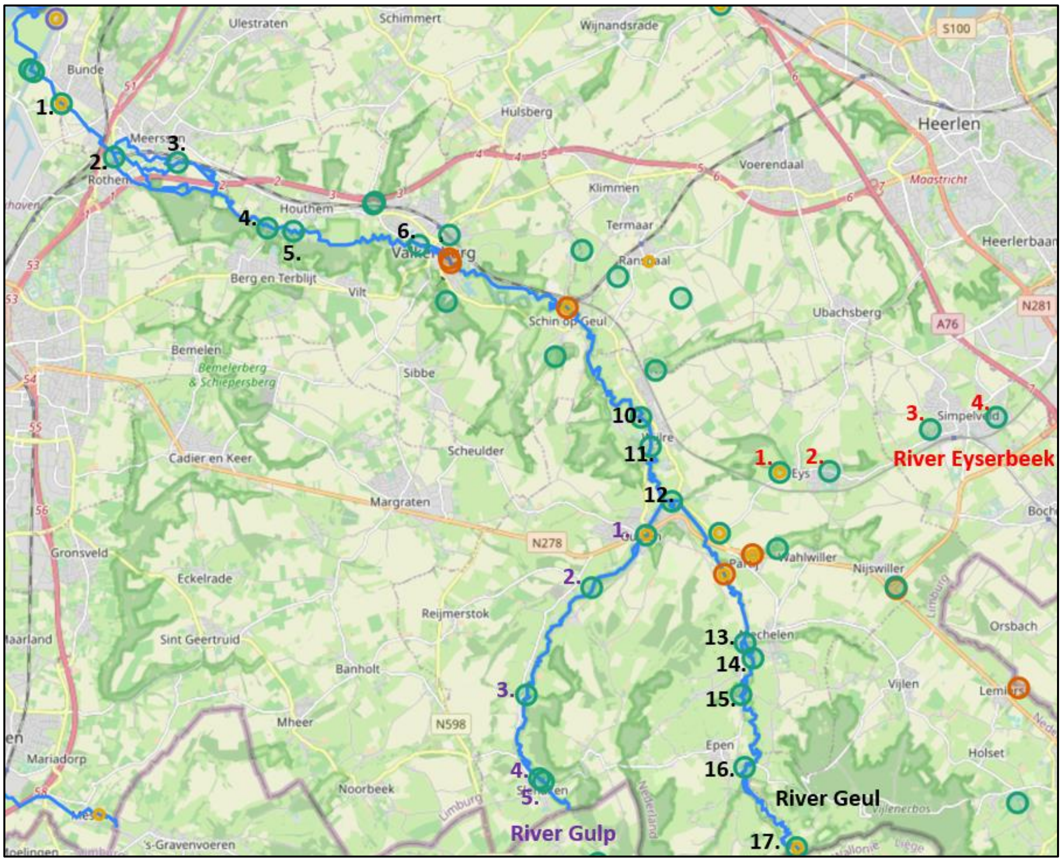


Figure 65 Measurement locations for the River Geul, River Gulp and River Eyserbeek as defined in Table 35 (https://hw2021.surge.sh/Alle_metingen.html).

## Overview input SOBEK model

The initial and boundary conditions are implemented as defined in section 6.2.1. Based on the water levels from the SOBEK model the boundary conditions are slightly changed. The water level at the mouth is not changed because these are measured values, but the discharge of the River Geul and the tributaries is unsure and are adapted to calibrate the SOBEK model to simulate the water levels more precise.

## Calibration

For each river, the average difference of the modelled and measured water level for several locations is calculated to define how accurate the model represents the water levels. A few iterations are necessary to find an optimum. Eventually, the following changes give the optimum:

1. The River Geul at the Dutch-Belgium border from 105 to 140 m³/s,
2. The River Gulp at the Dutch-Belgium border from 19.5 to 16 m³/s,
3. The River Eyserbeek at the source from 12.7 to 14 m³/s,

The measurement locations, as defined in Figure 65, are matched with the right locations in the SOBEK model. Some measurement locations were already defined in the SOBEK model. These locations start with 'MS', which stands for measurement station. All the other locations start with 'cp', these are calculation points in between reaches. This matching is necessary to make sure that the comparison of water levels happens for exactly the same location within the river system.

Table 36 shows the name of each location and the same numbering as Table 35 is maintained. The maximum measured water level is compared to a few different cases to eventually get a calibrated SOBEK model for the flooding of July 2021. The goal is to find the optimum for the difference between the maximum water levels of the SOBEK model and the measured maximum water levels. This holds for each river; the River Geul, the River Gulp, and the River Eyserbeek. This goal is reached for a discharge of 140 $m^3/s$ for the boundary condition of the River Geul, 16 $m^3/s$ for the boundary condition of the River Gulp and 14 $m^3/s$ for the boundary condition of the River Eyserbeek.

| River Geul | | | | | | | |
|---|---|---|---|---|---|---|---|
| Measurement location from Table 35 | Corresponding node in SOBEK | Measured water level [m] | 105 $m^3/s$ Δh [m] | 110 $m^3/s$ Δh [m] | 125 $m^3/s$ Δh [m] | 140 $m^3/s$ Δh [m] | 150 $m^3/s$ Δh [m] |
| 1 | cp_2652 | 46.16 | -0.04 | 0.13 | 0.16 | 0.23 | 0.28 |
| 2 | MS_Rothemermolen | 50.43 | -0.68 | -0.22 | -0.02 | 0.17 | 0.22 |
| 3 | cp_geul_304 | 52.95 | -0.15 | -0.09 | -0.08 | -0.03 | 0.02 |
| 4 | MS_Geulhemmermolen | 59.09 | -0.21 | -0.16 | -0.15 | -0.10 | -0.05 |
| 5 | cp_1059 | 60.56 | -0.51 | -0.35 | -0.28 | -0.15 | -0.10 |
| 6 | cp_geul_289 | 67.71 | -0.35 | -0.10 | 0.02 | 0.19 | 0.24 |
| 7 | cp_155 | 84.07 | -0.48 | -0.44 | -0.39 | -0.29 | -0.24 |
| 8 | cp_geul_46 | 85.59 | 0.18 | 0.20 | 0.23 | 0.29 | 0.34 |
| 9 | cp_2375 | 89.59 | -0.21 | -0.19 | -0.16 | -0.08 | -0.03 |
| 10 | cp_geul_599 | 101.31 | -0.39 | -0.36 | -0.29 | -0.17 | -0.12 |
| 11 | cp_geul_514 | 102.88 | -0.11 | -0.10 | -0.06 | 0.03 | 0.08 |
| 12 | cp_2486 | 106.63 | -0.35 | -0.34 | -0.30 | -0.20 | -0.15 |
| 13 | MS_Epermolen | 113.37 | -0.18 | -0.16 | -0.11 | -0.01 | 0.04 |
| 14 | cp_Geul_762 | 122.04 | -0.25 | -0.23 | -0.19 | -0.10 | -0.05 |
| | | **Average** | **-0.27** | **-0.17** | **-0.12** | **-0.02** | **0.03** |
| River Gulp | | | | | | | |
| | | Measured water level [m] | 19.5 $m^3/s$ Δh [m] | 19.5 $m^3/s$ Δh [m] | 16 $m^3/s$ Δh [m] | 16 $m^3/s$ Δh [m] | 17.5 $m^3/s$ Δh [m] |
| 1 | cp_geul_443 | 91.93 | 1.13 | 1.13 | 0.60 | 0.60 | 0.68 |
| 2 | cp_2284 | 104.99 | -0.10 | -0.10 | -0.17 | -0.17 | -0.09 |
| 3 | cp_2139 | 124.05 | -0.32 | -0.32 | -0.48 | -0.48 | -0.40 |
| 4 | cp_geul_139 | 137.23 | 0.30 | 0.30 | 0.27 | 0.27 | 0.35 |
| 5 | cp_geul_35 | 138.24 | -0.22 | -0.22 | -0.32 | -0.32 | -0.24 |
| | | **Average** | **0.16** | **0.16** | **-0.02** | **-0.02** | **0.06** |
| River Eyserbeek | | | | | | | |
| | | Measured water level [m] | 12.7 $m^3/s$ Δh [m] | 12.7 $m^3/s$ Δh [m] | 14 $m^3/s$ Δh [m] | 14 $m^3/s$ Δh [m] | 15 $m^3/s$ Δh [m] |
| 1 | cp_3075 | 102.74 | 0.12 | 0.12 | 0.17 | 0.17 | 0.20 |
| 2 | cp_geul_1022 | 111.62 | -0.23 | -0.23 | -0.15 | -0.15 | -0.12 |
| 3 | cp_geul_104 | 131.35 | 0.30 | 0.30 | 0.31 | 0.31 | 0.34 |
| 4 | cp_geul_385 | 141.18 | -0.39 | -0.39 | -0.37 | -0.37 | -0.34 |
| | | **Average** | **-0.05** | **-0.05** | **-0.01** | **-0.01** | **0.02** |

**Table 36 Calibration of the SOBEK model, based on water levels of the measurement locations and water levels in SOBEK. The discharge is adapted at the boundary conditions upstream to find the optimum condition.**

## Discharge boundary conditions after calibration

Based on this calibration the discharge boundary conditions for the July 2021 flooding, as defined in subsection 6.2.1, are be adapted. The method to calculate the discharge for the extreme event remains the same. Table 37 shows the new discharge boundary conditions.

| Boundary Condition | July 2021 before calibration [$m^3/s$ ] | July 2021 after calibration [$m^3/s$] |
|---|---|---|
| 1 The River Geul at the Dutch-Belgium border | 105 | 140 |
| 2 The River Gulp at the Dutch-Belgium border | 19.5 | 16 |
| 3 The River Selzerbeek at the Dutch-German border | 18.6 | 18.6 |
| 4 The River Eyserbeek at the source | 12.7 | 14 |

**Table 37 Discharge boundary conditions for July 2021, before and after calibration.**

# Appendix 6B
## Influence of the River Meuse on the River Geul

### Appendix 6B1
### Froude Number

The calculation of the Froude number during the flooding of July 2021 is done to find out if the flow is sub- or supercritical. When the Froude number is smaller than one the flow is subcritical, and use is made of the M-backwater curves. Figure 66 shows that the flow during flooding is subcritical.

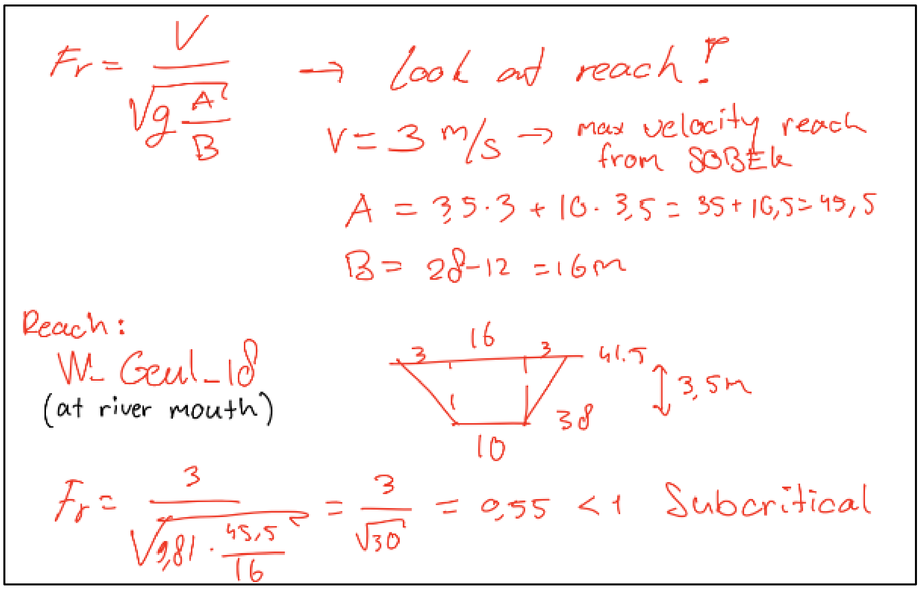


Figure 66 Hand calculation to estimate wether the flow is critical or subcritical.

### Appendix 6B2
### Scenario 1 versus 3 longitudinal cross-section

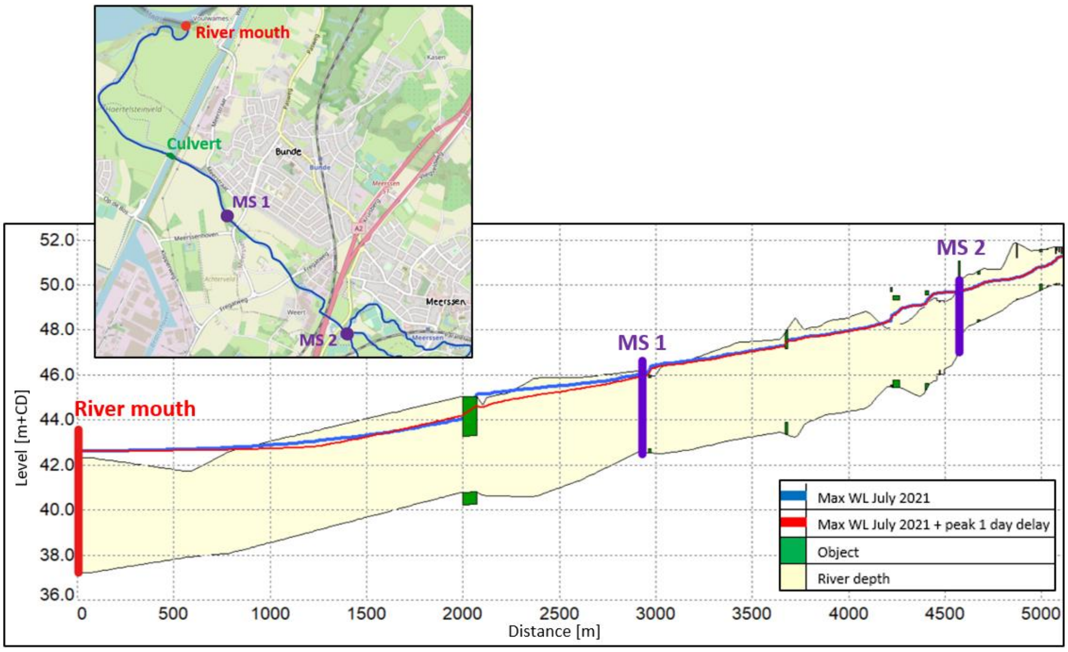


Figure 67 Side view scenario 1 and 3: 1. Both peaks arrive at the same time at the mouth and 2. 1 day delay in between the water level peaks.

## Appendix 6C
# Natura 2000 areas in the catchment area

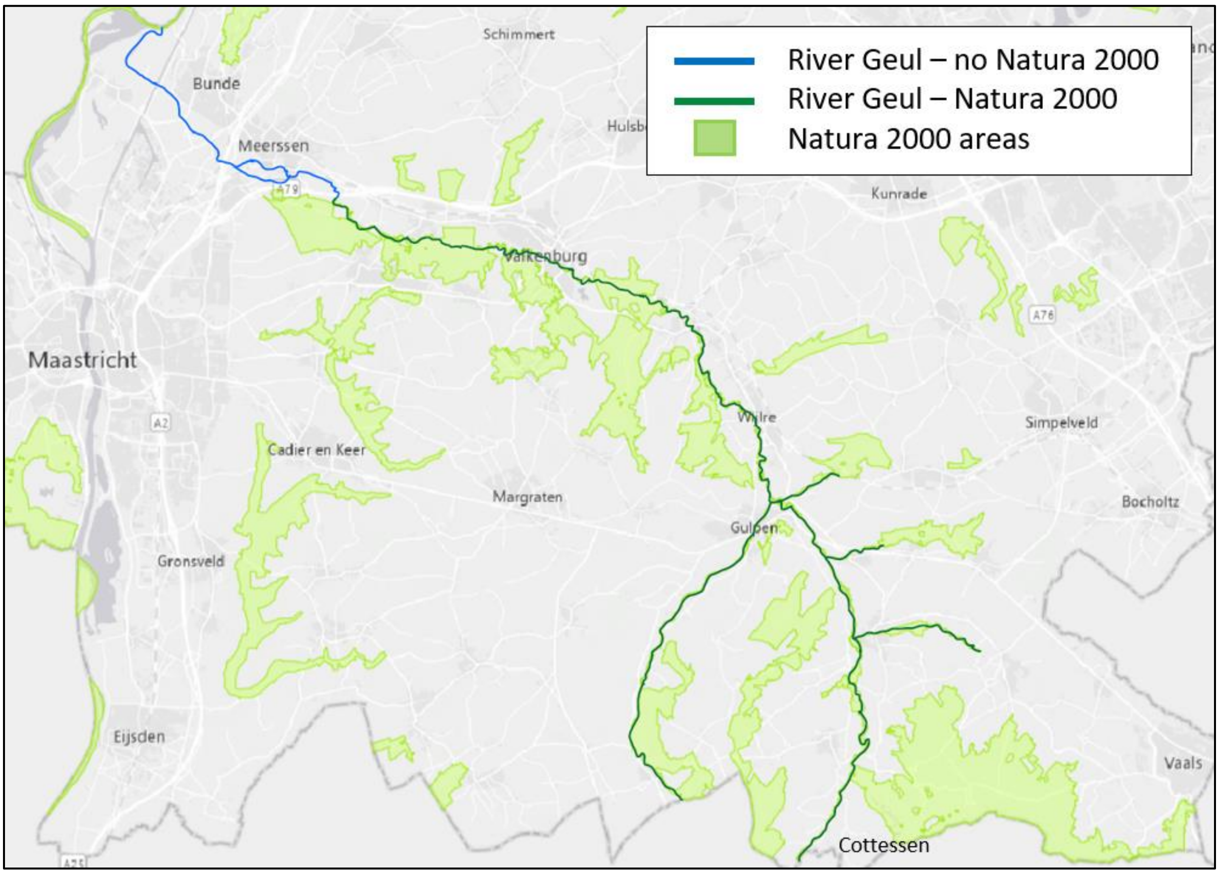


**Figure 68 Natura 2000 areas along the River Geul, adjusted from (Natura 2000-gebiedskaart, 2021).**

# Appendix Chapter 7

## Appendix 7A
## Selection of possible measures

### Appendix 7A1
### Bypass through Valkenburg

Figure 69 shows a vertical core sample profile of the soil in Valkenburg and it consist out of sand, clay, and marl. This proves the statement that the soil in Valkenburg can be unstable when deepening the River Geul in Valkenburg and constructing a tunnel.

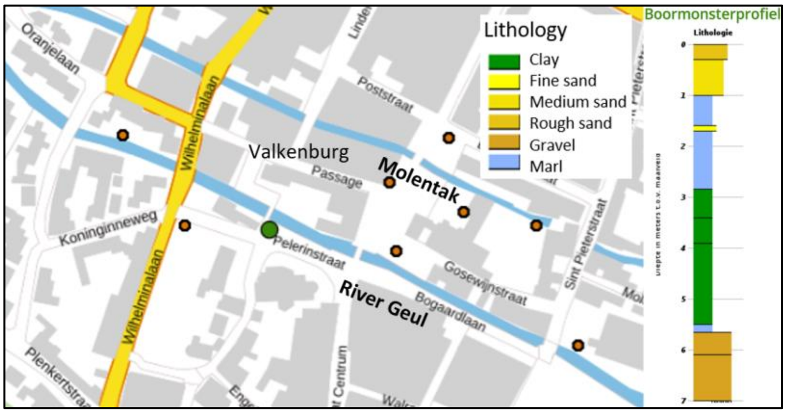


**Figure 69 Vertical core sample profile in Valkenburg, combined with a top view of the location of the sample shown with a green dot (*Ondergrondgegevens | DINOloket*, z.d.).**

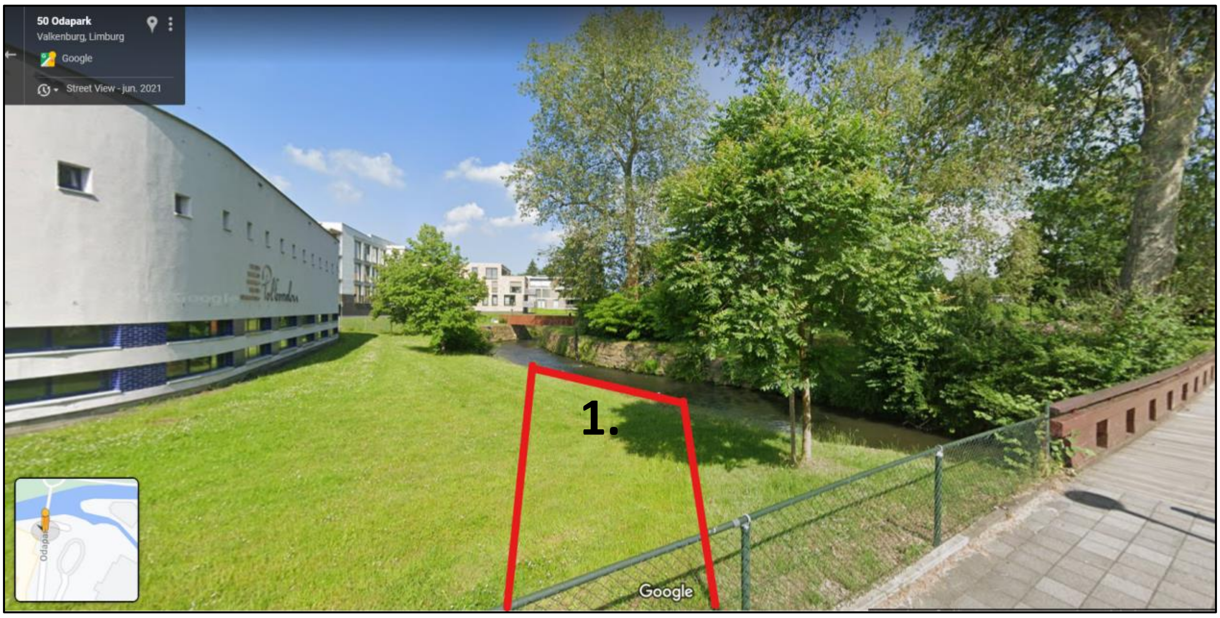


**Figure 70 Outlet location bypass Valkenburg, nr 1 in Figure 37 (Google, n.d.).**

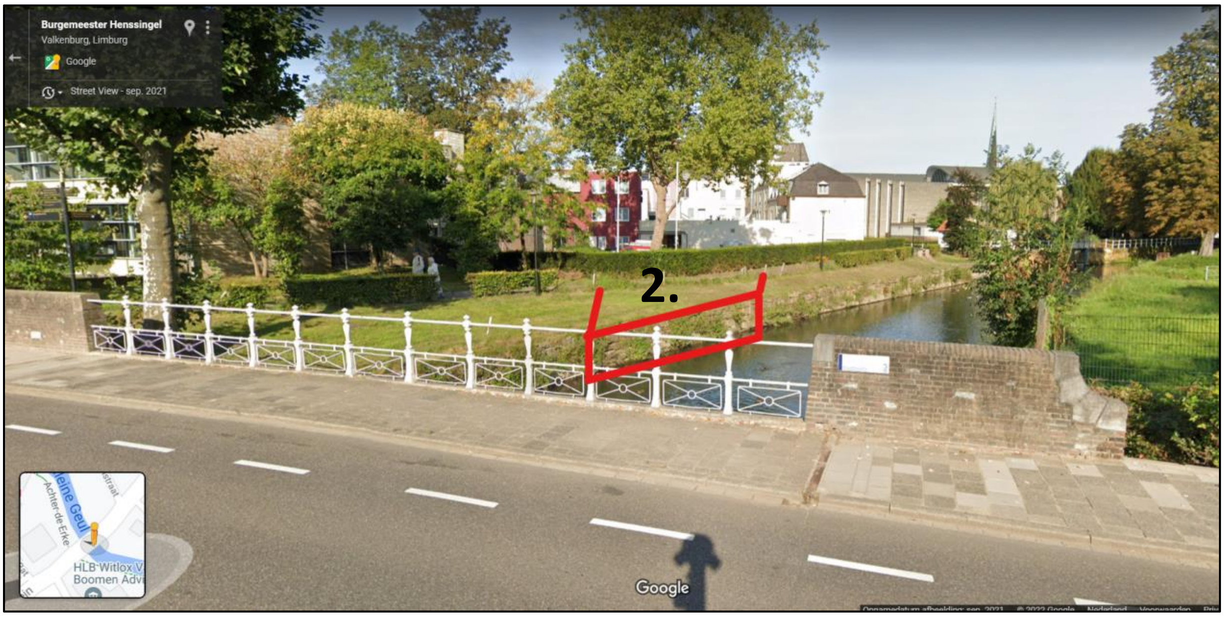


Figure 71 Inlet location bypass Valkenburg, nr 2 in Figure 37 (Google, n.d.).


Figure 72 Longitudinal cross-section of the River Geul, comparing the max water levels of July 2021 for the std case and the case with a bypass of 5 x 2.5 metres. Location = from downstream Valkenburg until upstream Valkenburg.

***Hand calculation discharge capacity bypass***

A quick hand calculation based on the estimated peak discharge upstream Valkenburg is performed. No precipitation in between Valkenburg and the upstream boundary conditions is taken into account. Figure 73 shows the calculation and Figure 74 shows the discharges in the River Geul for the calibrated model of July 2021. The discharge capacity is estimated at 141.6 $m^3/s$, based on the discharge above Valkenburg of 188.6 $m^3/s$. This discharge is a summation of the discharges from the four rivers as defined during the calibration of the SOBEK model in chapter 6. The research of Deuss et al. (2016) showed that the River Geul in Valkenburg is flooding at 47 $m^3/s$. This value is subtracted from the 188.6 $m^3/s$ to show the capacity of the bypass to prevent flooding of Valkenburg. Multiple SOBEK simulations show how effective this bypass really is.

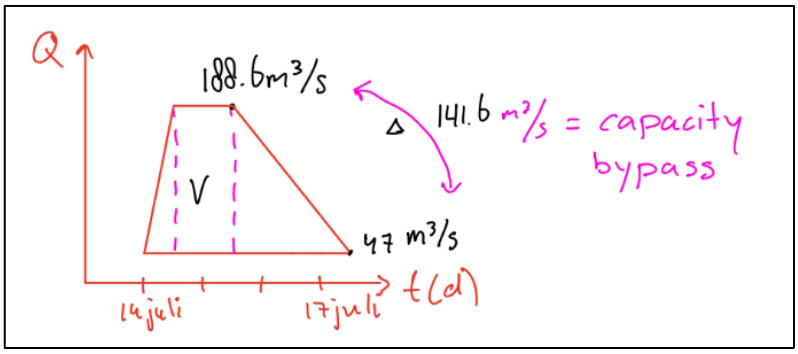


**Figure 73 Calculation required capacity bypass to prevent flooding of Valkenburg.**

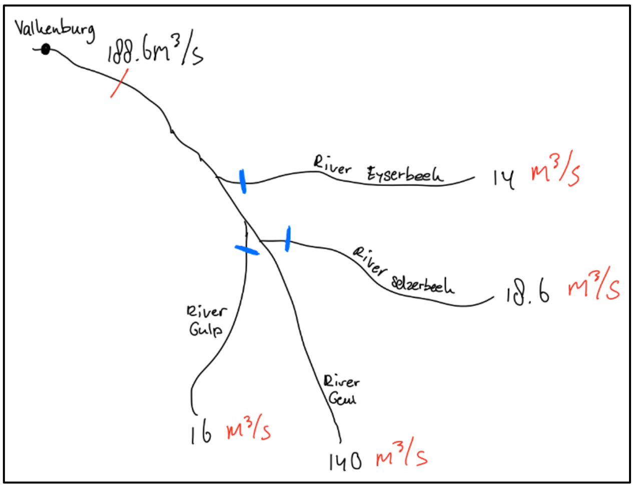


**Figure 74 Discharges as defined during calibration in Section 6.2.2, which is used for the calculation in Figure 73.**

## Appendix 7A2

## Weirs before the three tributaries reach the River Geul

Figure 75 shows the calculation of the volumes of each tributary that temporarily has to be stored upstream the weir. The discharges are defined during the calibration in chapter 6. For these simple hand calculations, the precipitation on the catchment area is not taken into account. The duration of the discharge peak is estimated from the water level graphs from the 12th until the 15th of July 2021 (https://hw2021.surge.sh/Alle_metingen.html).

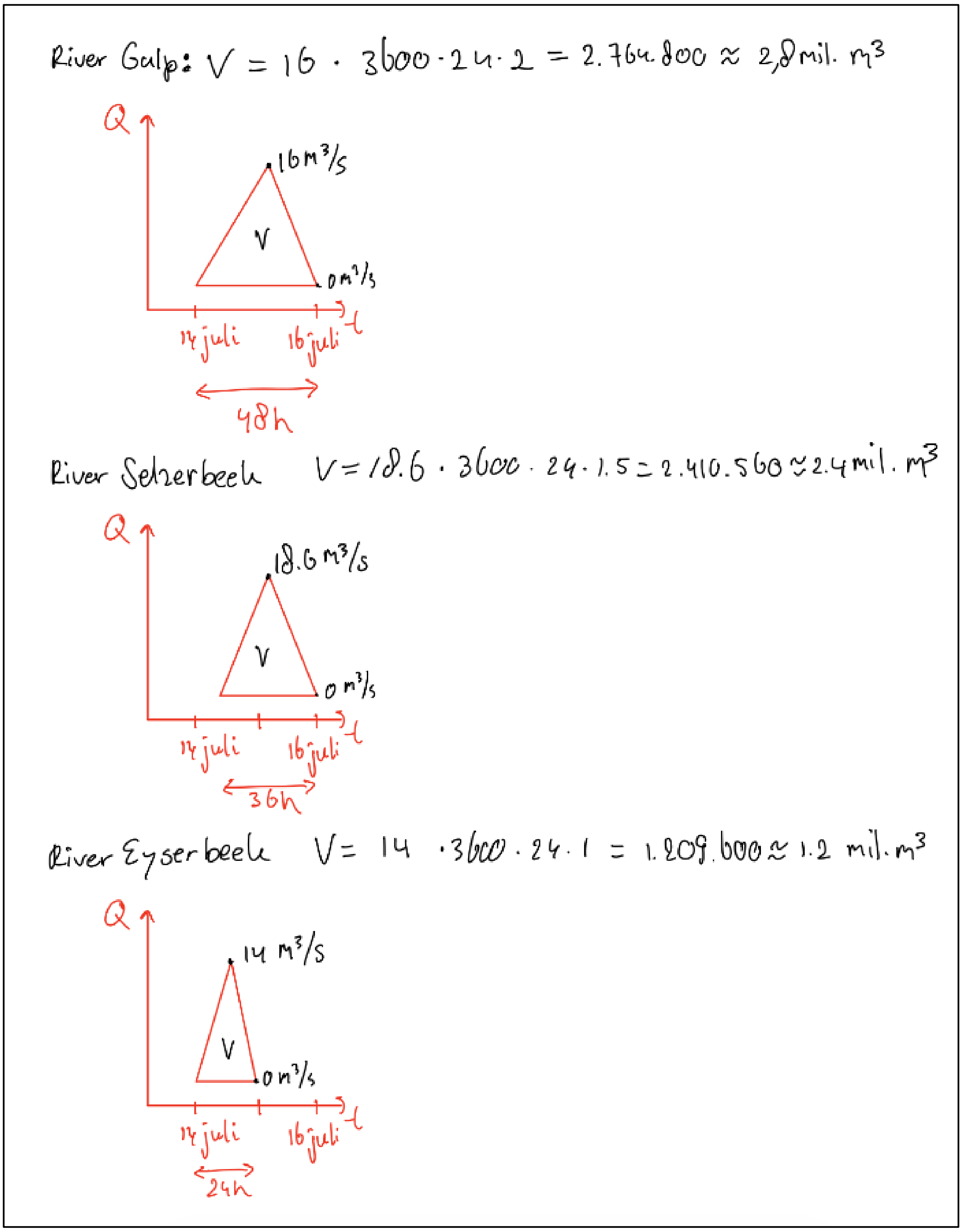


**Figure 75 Calculation of the volumes to be stored behind upstream the weirs in the tributaries.**

# Appendix 7B
## SOBEK output evaluation of ineffective measures

# Appendix 7B1
## Enlarge the culvert underneath the Julianakanaal

According to Table 38, for July 2021 the differences in flooding depths are smaller than for the stress test. These differences are only visible at MS 1. Further upstream no influence of the different culvert cross-sections is visible. For both scenarios, the 7.5 by 2.5-metre culvert performs the worst and leads to the highest flooding depths. However, there is no major difference between the 12.5 by 2.5 metre and 15 by 2.5-metre culvert. Largening the current culvert of 12.5 by 2.5-metre sounds therefore unnecessary but making sure that no openings of the culverts are blocked during flooding and the culvert does not become a 7.5 by 2.5-metre culvert is particularly important. For all the different cross-sections no major changes in maximum velocities are visible (Appendix 7C1).

| Difference in flooding depth [m] for different culvert cross-sections and conditions | | | | | | | |
|---|---|---|---|---|---|---|---|
| Location MS | MS River Geul | July 2021 (140 m³/s) | | | Stress test (224 m³/s) | | |
| River mouth | | D [m] for 12.5x2.5 m | Δh [m] for 7.5x2.5 m | Δh [m] for 15x2.5 m | D [m] for 12.5x2.5 m | Δh [m] for 7.5x2.5 m | Δh [m] for 15x2.5 m |
| 1 Bunde | MS 1 | 0.33 | 0.03 | -0.01 | 0.53 | 0.24 | -0.02 |
| 2 Meerssen downstr. | MS 2 | 0.40 | 0.00 | 0.00 | 1.08 | 0.00 | 0.00 |
| 3 Meerssen upstr. | MS 3 | 0.00 | 0.00 | 0.00 | 0.08 | 0.00 | 0.00 |

**Table 38 Flooding depths relative to the 12.5x2.5m culvert flooding depths for July 2021 and the stress test. Red cell = flooding depth increase and green cell = flooding depth decrease.**

Figure 76 shows the longitudinal cross-sections of the culvert for the flooding of July 2021 to show the differences between the different culvert cross-sections. These differences are very locally and mainly the culvert of 7.5 by 2.5 metres shows a large peak upstream the culvert, which seems like the culvert is not large enough to discharge all the water during the wave peak.

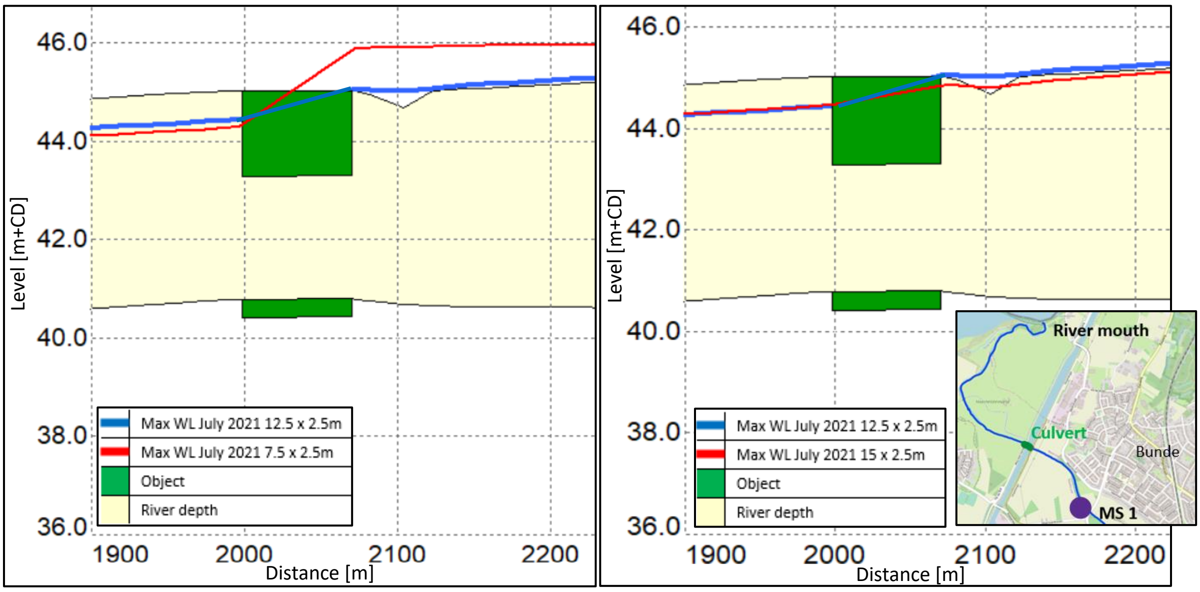


**Figure 76 Longitudinal cross-section of the River Geul comparing the 12.5 by 2.5-metre culvert with the 7.5 by 2.5 and 15 by 2.5-metre culvert for July 2021. Location = in between the river mouth and MS1.**

### Conclusion
Do not enlarge the culvert, but make sure the culvert cannot be blocked during flooding of the River Geul.

## Appendix 7B2
## Remove channelization in Valkenburg

Removing the channelization in Valkenburg leads to no significant flooding depth and flow velocity differences for July 2021 and the stress test (max - 0.05 m and + 0.1 m/s at MS 7). Appendix 7C3 shows these minor changes in flooding depth and flow velocity. This is in line with the expectations, because the capacity of the River Geul becomes only slightly larger, while the discharge remains the same. Therefore, the flooding depths decrease slightly, and the flow velocity rises. Furthermore, upstream Valkenburg the flooding depths are already much higher and the River Geul is flooding according to Figure 77 (Appendix 7C3, Figure 83 shows the flood inundation map). This means that, even if you remove the channelization in Valkenburg, the water still flows outside the riverbanks directly to the urban areas in Valkenburg. It is also confirmed by waterboard Limburg that the exact same situation occurred during the flooding of July 2021 (H. Pavelkova, personal communications, January 14, 2022).

Figure 77 shows the longitudinal cross-section along Valkenburg with the maximum water level during July 2021 with and without channelization. Locally, in between MS 6 and MS 7 the differences are also barely visible (and in the order of - 0.05m), which means that this measure is ineffective.

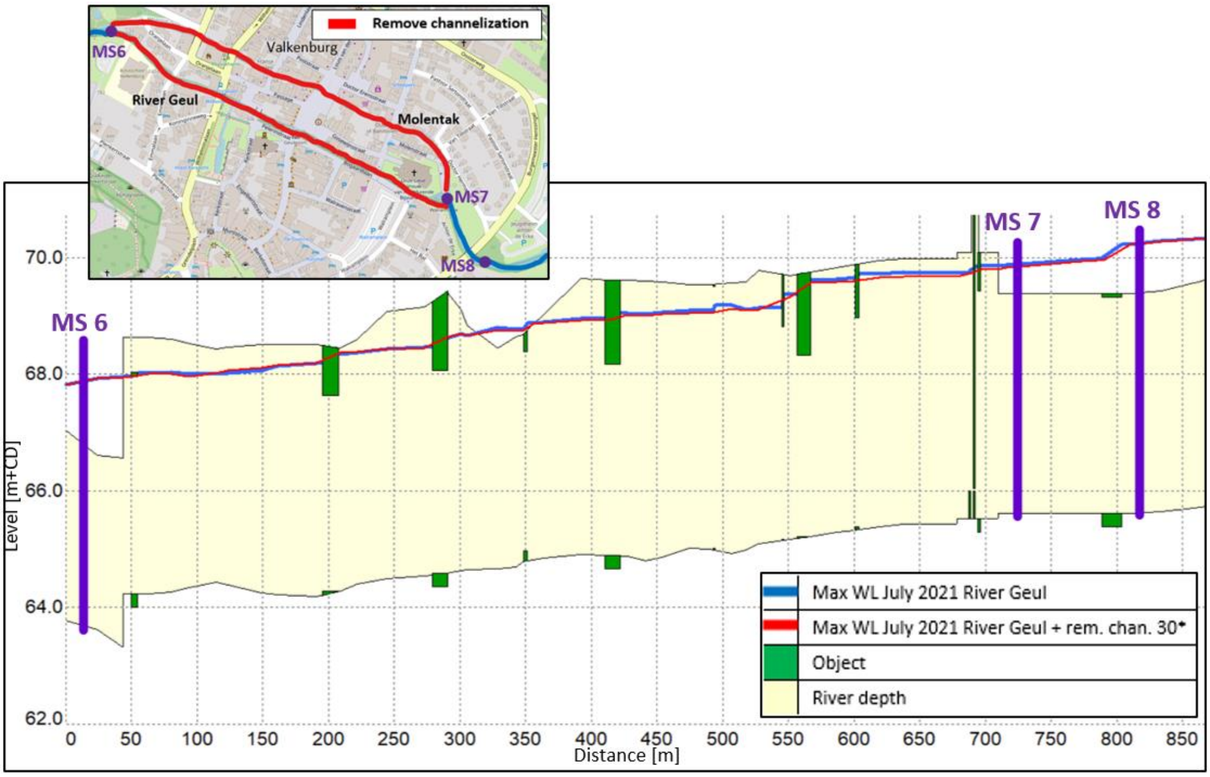


**Figure 77 Longitudinal cross-section of the River Geul comparing the std river with the removement of channelization (30 degrees) for July 2021. Location = along Valkenburg.**

## Conclusion

The measure is not easy to implement due to the dense urban area and the many buildings along the River Geul in Valkenburg. Regarding the minor effect of the measure, the measure is not considered for further research.

## Appendix 7B3
# Raise dikes in Valkenburg

Raising the dikes with either 0.5 or 1.0m has almost no influence (max - 0.07m at MS 7) on the flooding depths in Valkenburg for both July 2021 and the stress test. Figure 78 shows the longitudinal cross-section of the River Geul for July 2021. Locally, in between MS 6 and MS 7 the differences are barely visible. Close to MS 7 the water level after raising the dikes goes down with 0.05 m (600 – 750 m in Figure 78) and more downstream in Valkenburg the water level after raising dikes goes up with maximum 0.1 m (150 – 450 m in Figure 78). It makes sense that the water level goes up over a longer reach because the dikes are higher and locally increase the discharge capacity of the river. Appendix 7C5 (Table 50 and Table 51) shows the minor decrease in flooding depth and flow velocity at the measurement stations. The measurement stations show however a different result as the longitudinal cross-section.

The reason why raising dikes is not effective has the same reason as described in Appendix 7B2 for removing the channelization in Valkenburg. Raising the dikes also increases the discharge capacity of the river but again, the River Geul is already flooding upstream Valkenburg.

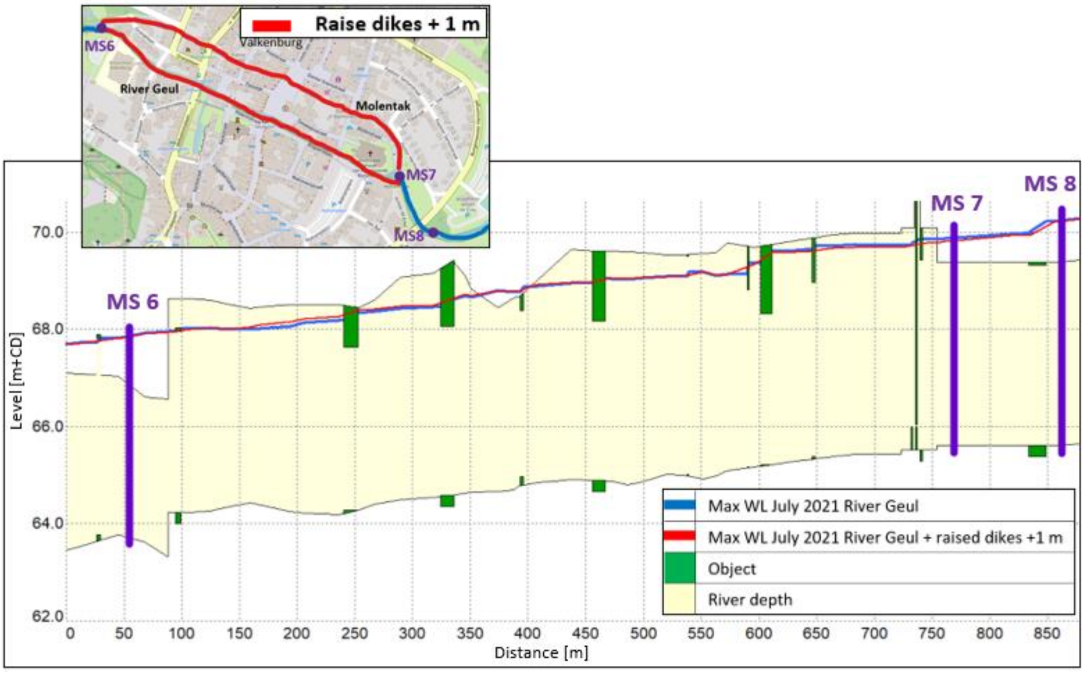


**Figure 78 Longitudinal cross-section of the River Geul comparing the std river with raising dikes with 1 m for July 2021. Location = along Valkenburg.**

## Conclusion

Do not raise the dikes in Valkenburg, because the measure is not effective during flooding of the River Geul. Besides, it blocks the view in Valkenburg.

## Appendix 7B4
# Thresholds upstream Valkenburg

No differences in flooding depths occurred after implementing the thresholds, also locally no differences in flooding depths are visible (Figure 79). This happens because the thresholds do not have any function during flood conditions, which was already expected before the simulation. The water depths during floods are significantly larger than the threshold heights of 0.5, 1.0 and 1.5 m. Furthermore, the additional storage capacity upstream of the thresholds is already full before the wave peak arrives. Appendix 7B shows some significant differences in flow velocities in the order of - 0.5 until + 1.5 m/s. However, these are local differences and do not influence the water level.

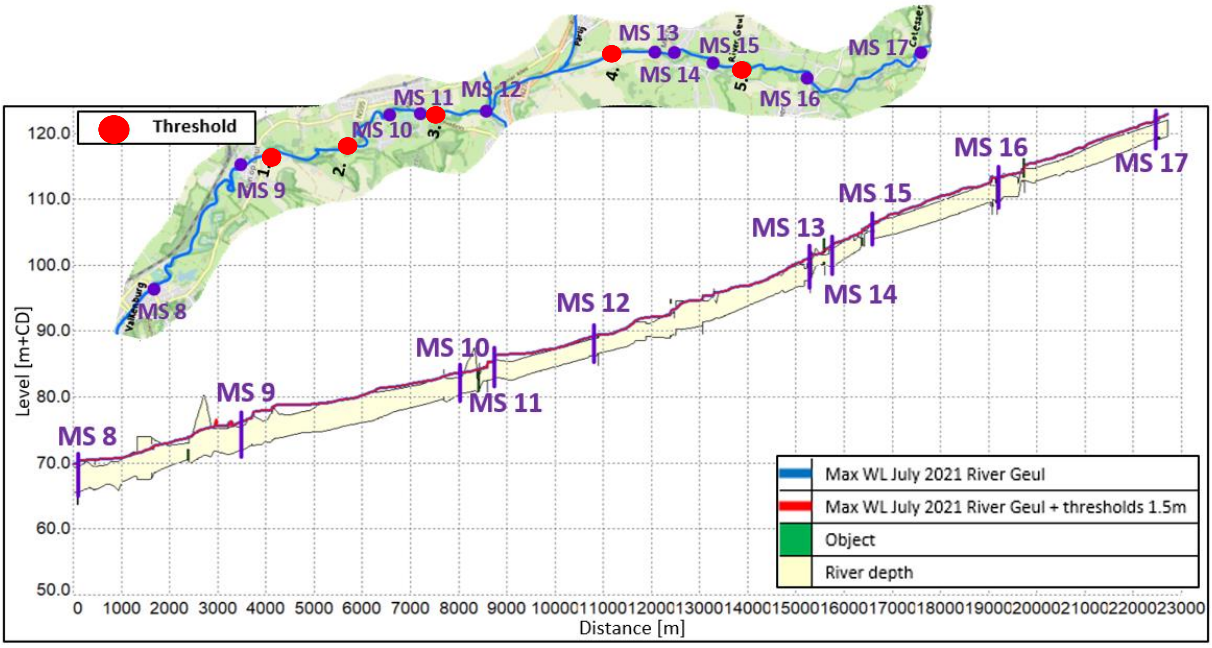


**Figure 79 Longitudinal cross-section of the River Geul, comparing the max water levels for July 2021 for the std case and the case with 1.5m thresholds. Location = upstream Valkenburg until Cottessen.**

### Conclusion

Thresholds upstream Valkenburg are not effective during flood conditions which makes this a useless measure to decrease the impact of flooding of the River Geul.

## Appendix 7B5

# Weirs before the three tributaries reach the River Geul

The longitudinal cross-section, as shown in Figure 79, also holds for this measure. After simulating the weirs, no differences in flooding depths occur, because eventually the water flows around the weirs over land. Also, the contribution from the tributaries is small compared to the discharge of the River Geul; only 25 percent (48.6 / 188.6 * 100 %, see Table 7) of the total River Geul discharge that reaches Valkenburg comes from the three tributaries.

Some minor differences in flow velocities are visible in Table 39 because of the difference in closed weir duration but this is only locally upstream the weirs. After 12 or 48 hours the weirs open and the flow velocities slightly rise. This holds for both July 2021 and the stress test.

| **Difference in flow velocity [m/s] for different weir durations and conditions** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Location MS | MS River Geul | July 2021 (140 m³/s) | | | Stress test (224 m³/s) | | |
| | | v [m/s] for std | Δv [m/s] for 12 h | Δv [m/s] for 48 h | v [m/s] for std | Δv [m/s] for 12 h | Δv [m/s] for 48 h |
| 11 – Wÿlre | MS 11 | 3.33 | 0.00 | 0.00 | 3.61 | 0.00 | 0.00 |
| 12 – Connection 3 tributaries | MS 12 | 1.41 | 0.09 | 0.14 | 1.50 | 0.00 | 0.05 |
| 13 – Mechelen | MS 13 | 3.16 | 0.43 | -0.08 | 3.13 | 0.31 | -0.05 |
| 14 – Mechelen upstr. | MS 14 | 2.14 | 0.00 | 0.00 | 2.41 | 0.00 | 0.00 |
| 15 – Hurpesch | MS 15 | 2.09 | -0.14 | 0.00 | 2.10 | 0.00 | 0.18 |
| 16 – Epen | MS 16 | 0.85 | 0.00 | 0.00 | 0.85 | 0.00 | 0.00 |

**Table 39 Flow velocities for different weir durations relative to the std case for July 2021 and the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

### Conclusion

The weirs raise the flow velocity locally and do not decrease the flooding depths, which is opposite to the goal the weirs have to fulfil. The SOBEK model shows no positive results compared to other measures.

## Appendix 7B6

# Add vegetation upstream Valkenburg

After adding vegetation, the flooding depths go up slightly (max +0.18 m) but most of the flooding depths go up locally where the vegetation was added. Figure 80 and Figure 81 show these local water level increases. This is the result of lower flow velocities, which is visible in Table 40. The lower flow velocities can be effective to slow down and spread the wave peak to lower the flooding depths in Valkenburg. This was not the result, and the flooding depths only went up where the vegetation was added. This holds for both July 2021 and the stress test.

The flooding depths for the different cases are available in Appendix 7C9.

| **Difference in flow velocity [m/s] for different amounts of vegetation and conditions** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Location MS | MS River Geul | July 2021 (140 $m^3/s$) | | | Stress test (224 $m^3/s$) | | |
| | | v [m/s] for std | Δv [m/s] for $c_f$ = 0.075 | Δv [m/s] for $c_f$ = 0.1 | v [m/s] for std | Δv [m/s] for $c_f$ = 0.075 | Δv [m/s] for $c_f$ = 0.1 |
| 9 – Schin op Geul | MS 9 | 2.30 | -0.46 | -0.84 | 2.54 | -0.67 | -1.07 |
| 10 – Wijlre downstr. | MS 10 | 2.10 | -0.44 | -0.67 | 2.16 | -0.43 | -0.67 |
| 11 – Wijlre | MS 11 | 3.33 | -0.42 | -0.77 | 3.61 | -0.51 | -0.93 |
| 12 – Connection 3 tributaries | MS 12 | 1.41 | -0.02 | -0.02 | 1.50 | -0.01 | -0.02 |
| 13 – Mechelen | MS 13 | 3.16 | -0.92 | -0.47 | 3.13 | 0.37 | 0.17 |
| 14 – Mechelen upstr. | MS 14 | 2.14 | 0.00 | 0.00 | 2.41 | 0.00 | 0.00 |
| 15 – Hurpesch | MS 15 | 2.09 | -0.51 | -0.79 | 2.10 | 0.84 | 0.26 |
| 16 – Epen | MS 16 | 0.85 | -0.02 | -0.09 | 0.85 | -0.03 | -0.09 |

**Table 40 Flow velocities for adding vegetation relative to the std case for July 2021 and the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

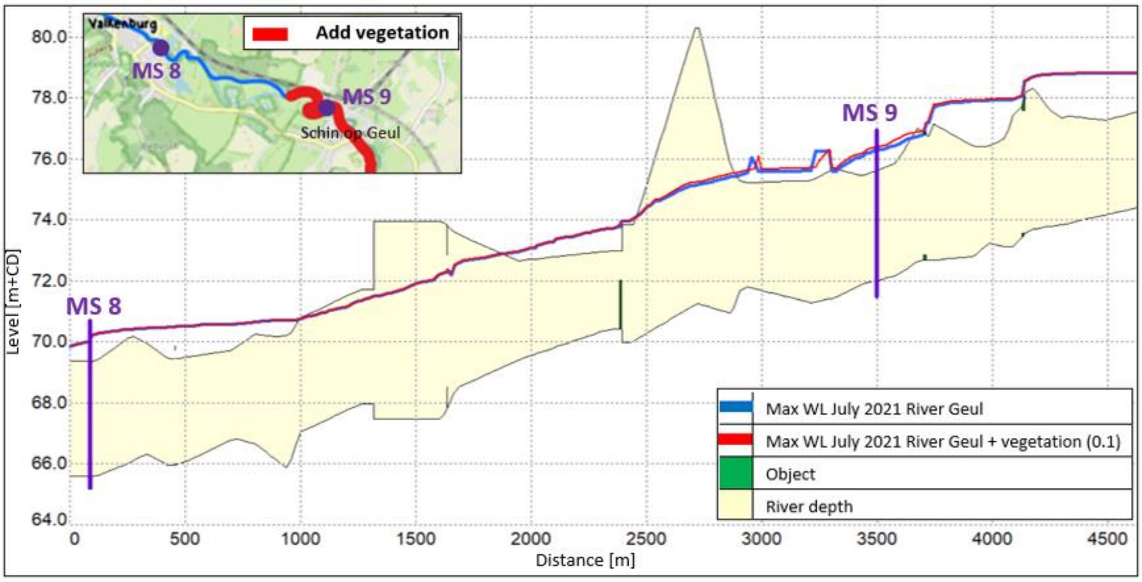


**Figure 80 Longitudinal cross-section of the River Geul, comparing the max water levels for July 2021 for the std case and the case with added vegetation (manning 0.1). Location = upstream Valkenburg until Schin op Geul.**

## Conclusion

Adding vegetation shows effective decreases of flow velocities upstream Valkenburg. However, the decrease of the flow velocity did not show any positive effects for spreading out the peak and decreasing the flooding depths downstream the measure. Therefore, the measure is not effective.

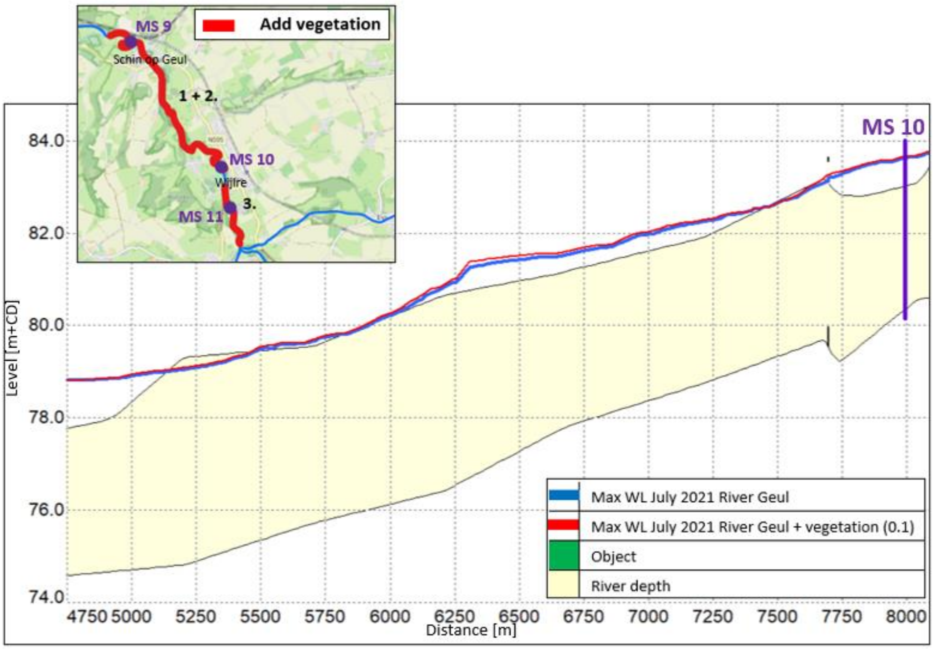


**Figure 81 Longitudinal cross-section of the River Geul, comparing the max water levels for July 2021 for the std case and the case with added vegetation (manning 0.1). Location = Schin op Geul until connection tributaries.**

## Appendix 7B7
## Raise riverbed upstream Valkenburg

The results of raising the riverbed should, in a way, be similar to the results of adding vegetation. Also, for this measure the flooding depths are not changed that much for all the different riverbed raises (+0.01-0.02m, see Appendix 7B10). The longitudinal cross-section, as shown in Figure 79, also holds for this measure. The flow velocities are lower for a few locations (Table 41), but the decrease is slightly lower compared to adding vegetation. Also, in the case of raising the riverbed the decrease of the velocity and increase of the water level is over a shorter length compared to adding vegetation. This is the result of the way the measure is simulated. The vegetation is added over a longer distance compared to the riverbed raise, as a consequence of model limitations.

| Difference in flow velocity [m/s] for different riverbed raises and conditions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | | | Stress test (224 m³/s) | | | |
| | v [m/s] for std case | Δv [m/s] for +0.5 m | Δv [m/s] for +1 m | Δv [m/s] for +1.5 m | v [m/s] for std case | Δv [m/s] for +0.5 m | Δv [m/s] for +1 m | Δv [m/s] for +1.5 m |
| MS 12 | 1.41 | 0.00 | 0.00 | 0.00 | 1.50 | 0.00 | 0.00 | 0.00 |
| MS 13 | 3.16 | -0.48 | -0.04 | -0.30 | 3.13 | -0.33 | 0.58 | -0.32 |
| MS 14 | 2.14 | 0.00 | 0.00 | 0.00 | 2.41 | 0.00 | 0.00 | 0.00 |
| MS 15 | 2.09 | -0.12 | -0.18 | -0.87 | 2.10 | -0.13 | -0.19 | -0.94 |
| MS 16 | 0.85 | 0.00 | 0.00 | 0.01 | 0.85 | 0.00 | 0.00 | 0.01 |

**Table 41 Flow velocities for riverbed raises relative to the std case for July 2021 and the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

### Conclusion

Raising the riverbed shows minor decrease of flow velocities upstream Valkenburg. Furthermore, the decrease of the flow velocity did not show any positive effects on spreading out the peak and decreasing the flooding depths downstream the measure. Therefore, the measure is not effective.

# Appendix 7C
## Additional SOBEK output graphs and tables

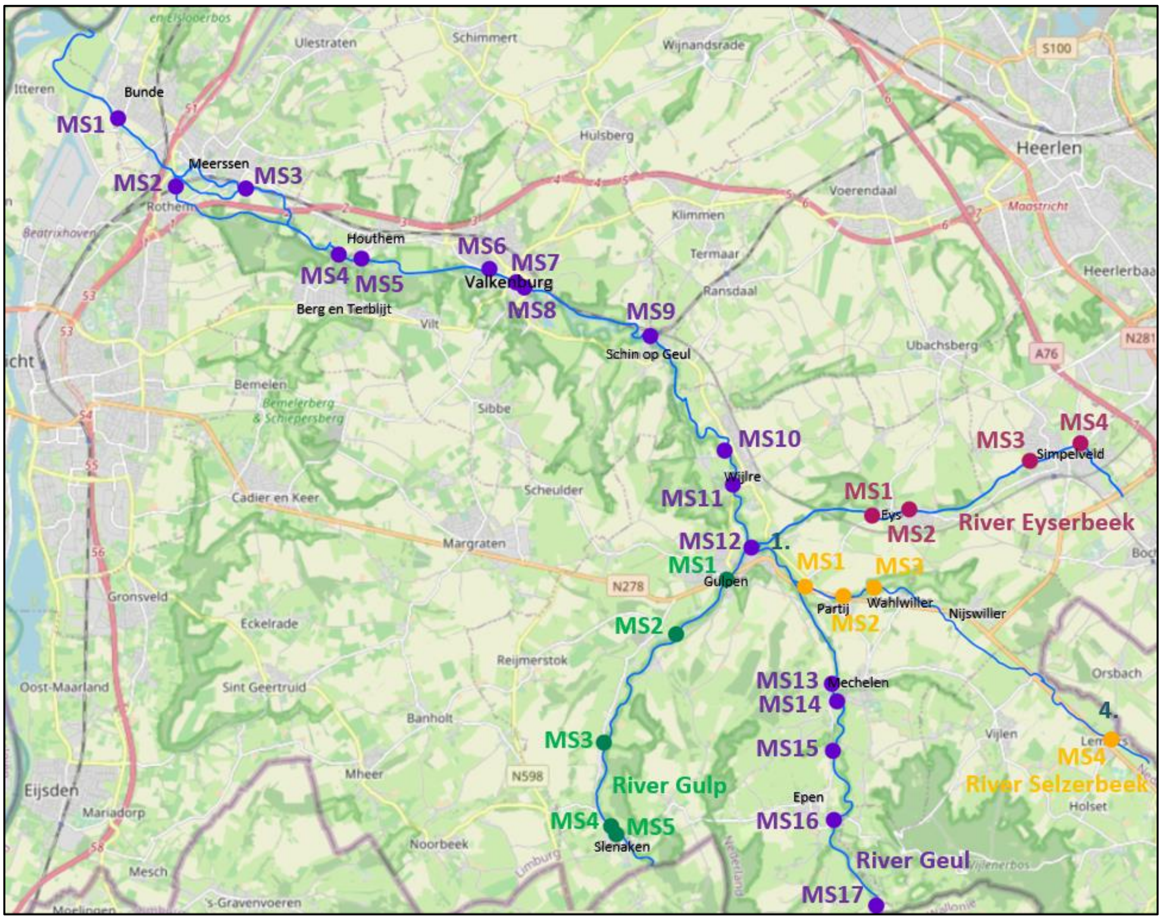


**Figure 82 Measurement locations in the catchment area of the River Geul and tributaries, as defined by waterboard Limburg (https://hw2021.surge.sh/Alle_metingen.html).**

### Appendix 7C1
## Enlarging culvert Julianakanaal

| Difference in flow velocity [m/s] for different culvert cross-sections and conditions | | | | | | | |
|---|---|---|---|---|---|---|---|
| Location | MS | July 2021 (140 m³/s) | | | Stress test (224 m³/s) | | |
| River mouth | River Geul | v [m/s] for 12.5 x 2.5 m | Δv [m/s] for 7.5 x 2.5 m | Δv [m/s] for 15 x 2.5 m | v [m/s] for 12.5 x 2.5 m | Δv [m/s] for 7.5 x 2.5 m | Δv [m/s] for 15 x 2.5 m |
| 1 Bunde | 1 | 1.61 | 0.00 | 0.00 | 1.63 | -0.07 | 0.01 |
| 2 Meerssen downstr. | 2 | 1.50 | 0.00 | 0.00 | 1.50 | 0.00 | 0.00 |
| 3 Meerssen upstr. | 3 | 1.83 | 0.00 | 0.00 | 1.87 | 0.00 | 0.00 |

**Table 42 Flow velocities relative to the 12.5x2.5m culvert flooding depths for July 2021 and the stress test. Red cell = flooding depth increase and green cell = flooding depth decrease.**

## Appendix 7C2

# Widen the river downstream

| Difference in flooding depth [m] for different river widenings and conditions | | | | | | |
|---|---|---|---|---|---|---|
| Location | MS River Geul | Stress test (224 m³/s) | | | | |
| River mouth | | D [m] for std case | Δh [m] for +5 m | Δh [m] for +10 m | Δh [m] for +20 m | Δh [m] for +20 m Opt |
| 1 - Bunde | 1 | 0.53 | -0.14 | -0.23 | -0.33 | -0.32 |
| 2 - Meerssen downstr. | 2 | 1.08 | -0.05 | -0.07 | -0.08 | -0.04 |
| 3 - Meerssen upstr. | 3 | 0.08 | 0.00 | 0.00 | -0.01 | -0.01 |
| 4 - Geulhem | 4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 5 - Houthem | 5 | 0.60 | -0.01 | -0.01 | -0.02 | -0.02 |
| 6 - Valkenburg downstr. | 6 | 1.12 | -0.01 | -0.02 | -0.03 | -0.03 |

**Table 43 Flooding depths for different river widenings relative to the std case for the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

| Difference in flow velocity [m/s] for different river widenings and conditions | | | | | | |
|---|---|---|---|---|---|---|
| Location | MS River Geul | July 2021 (140 m³/s) | | | | |
| River mouth | | v [m/s] for std case | Δv [m/s] for +5 m | Δv [m/s] for +10 m | Δv [m/s] for +20 m | Δv [m/s] for +20 m Opt |
| 1 - Bunde | 1 | 1.61 | -0.06 | -0.18 | -0.43 | -0.42 |
| 2 - Meerssen downstr. | 2 | 1.50 | 0.01 | 0.01 | 0.02 | 0.02 |
| 3 - Meerssen upstr. | 3 | 1.83 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4 - Geulhem | 4 | 1.20 | 0.04 | 0.04 | 0.04 | 0.04 |
| 5 - Houthem | 5 | 1.80 | 0.06 | 0.08 | 0.09 | 0.07 |
| 6 - Valkenburg downstr. | 6 | 1.55 | 0.06 | 0.12 | 0.20 | 0.20 |

**Table 44 Flow velocities for different river widenings relative to the std case for July 2021. Red cell = flow velocity increase and green cell = flow velocity decrease.**

| Difference in flow velocity [m/s] for different river widenings and conditions | | | | | | |
|---|---|---|---|---|---|---|
| Location | MS River Geul | Stress test (224 m³/s) | | | | |
| River mouth | | v [m/s] for std case | Δv [m/s] for +5 m | Δv [m/s] for +10 m | Δv [m/s] for +20 m | Δv [m/s] for +20 m Opt |
| 1 - Bunde | 1 | 1.63 | -0.08 | -0.16 | -0.37 | -0.37 |
| 2 - Meerssen downstr. | 2 | 1.50 | 0.01 | 0.01 | 0.02 | 0.02 |
| 3 - Meerssen upstr. | 3 | 1.87 | 0.00 | 0.00 | -0.01 | -0.01 |
| 4 - Geulhem | 4 | 1.21 | 0.03 | 0.03 | 0.03 | 0.03 |
| 5 - Houthem | 5 | 1.94 | 0.06 | 0.08 | 0.09 | 0.05 |
| 6 - Valkenburg downstr. | 6 | 1.57 | 0.06 | 0.12 | 0.19 | 0.19 |

**Table 45 Flow velocities for different river widenings relative to the std case for the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

Appendix 7C3

## Remove channelization in Valkenburg

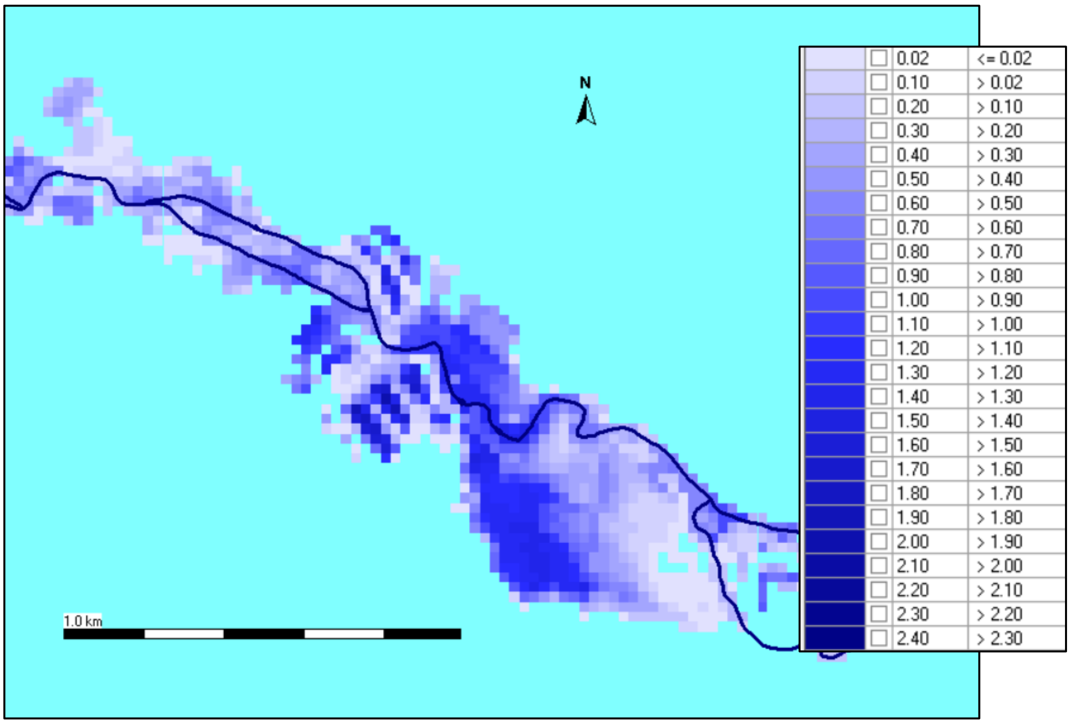


**Figure 83 Flood inundation map Valkenburg and upstream Valkenburg during wave peak**

| Difference in flooding depth [m] for different riverbank angles and conditions | | | | | | |
|---|---|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | | Stress test (224 m³/s) | | |
| | D [m] for std case | Δh [m] for 45* bank | Δh [m] for 30* bank | D [m] for std case | Δh [m] for 45* bank | Δh [m] for 30* bank |
| 5 | 0.29 | 0.00 | 0.00 | 0.60 | 0.00 | 0.00 |
| 6 | 0.79 | -0.01 | -0.01 | 1.12 | -0.01 | 0.00 |
| 7 | 0.49 | -0.03 | -0.05 | 0.77 | -0.03 | -0.04 |
| 8 | 0.85 | -0.01 | -0.02 | 1.11 | -0.01 | -0.01 |
| 9 | 0.60 | 0.00 | 0.00 | 0.86 | 0.00 | 0.00 |

**Table 46 Flooding depths for different bank angles relative to the std case for July 2021 and the stress test. Red cell = flooding depth increase and green cell = flooding depth decrease.**

| Difference in flow velocity [m/s] for different riverbank angles and conditions | | | | | | |
|---|---|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | | Stress test (224 m³/s) | | |
| | v [m/s] for std case | Δv [m/s] for 45* banks | Δv [m/s] for 30* banks | v [m/s] for case | Δv [m/s] for 45* banks | Δv [m/s] for 30* banks |
| 5 | 1.80 | 0.00 | 0.00 | 1.94 | 0.00 | 0.00 |
| 6 | 1.55 | 0.00 | -0.01 | 1.57 | -0.01 | -0.01 |
| 7 | 1.60 | 0.08 | 0.11 | 1.79 | 0.07 | 0.09 |
| 8 | 2.30 | 0.05 | 0.07 | 2.38 | 0.04 | 0.05 |
| 9 | 2.30 | 0.00 | 0.00 | 2.54 | 0.00 | 0.00 |

**Table 47 Flow velocities for different bank angles relative to the std case for July 2021 and the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

## Appendix 7C4

# Bypass: tunnel or additional channel

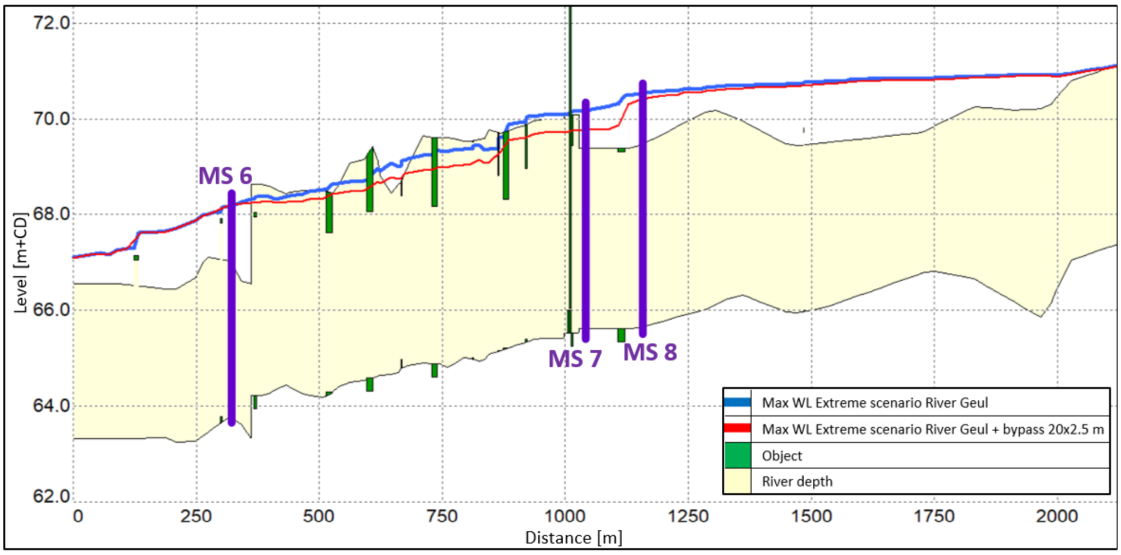


**Figure 84 Longitudinal cross-section of the River Geul, comparing the max water levels for the stress test (extreme scenario) for the std case and the case with a bypass of 20 x 2.5 metres. Location = along Valkenburg.**

| Difference in flow velocity [m/s] for different bypasses and conditions | | | | | | | |
|---|---|---|---|---|---|---|---|
| MS | 140 m³/s | | | | | | |
| River Geul | v [m/s] for std width | Δv [m/s] for channel 2 m | Δv [m/s] for channel 5 m | Δv [m/s] for channel 10 m | Δv [m/s] for culvert 10 m | Δv [m/s] for culvert 15 m | Δv [m/s] for culvert 20 m |
| 6 | 1.55 | 0.34 | 0.42 | 0.48 | -0.10 | 0.02 | 0.01 |
| 7 | 1.60 | -0.15 | -0.30 | -0.37 | 0.64 | 1.30 | -0.54 |
| 8 | 2.30 | 0.91 | 1.19 | 1.35 | 0.33 | 9.02 | 1.26 |

**Table 48 Flow velocities for different bypasses relative to the std case for July 2021. Red cell = flow velocity increase and green cell = flow velocity decrease.**

| Difference in flow velocity [m/s] for different bypasses and conditions | | | | | | | |
|---|---|---|---|---|---|---|---|
| MS | 224 m³/s | | | | | | |
| River Geul | v [m/s] for std width | Δv [m/s] for channel 2 m | Δv [m/s] for channel 5 m | Δv [m/s] for channel 10 m | Δv [m/s] for culvert 10 m | Δv [m/s] for culvert 15 m | Δv [m/s] for culvert 20 m |
| 6 | 1.57 | 0.61 | 0.78 | 0.97 | 0.08 | 0.16 | 0.22 |
| 7 | 1.79 | -0.08 | -0.27 | -0.51 | 0.61 | -0.44 | -0.60 |
| 8 | 2.38 | 0.87 | 1.13 | 10.42 | 0.73 | 1.03 | 1.27 |

**Table 49 Flow velocities for different bypasses relative to the std case for the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

***Numerical errors***

Table 18 and Table 19 show two striking values with more than 1 metre flooding depth increase at MS8. Also, the flow velocities, shown in Table 48 and Table 49, show a large increase for the same measurement station and bypass types. To explain and understand what happens, a longitudinal cross-section for this specific situation is shown in Figure 85. For both the 15 m culvert (140m³/s) and the 10 m channel (224m³/s ) the same wave peak around MS8, as shown in Figure 85, is visible. This is exactly at the location where the bypass begins. Apparently, a numerical mistake occurs at this location in the SOBEK model. This is no part of the scope of this research and is therefore not further investigated.

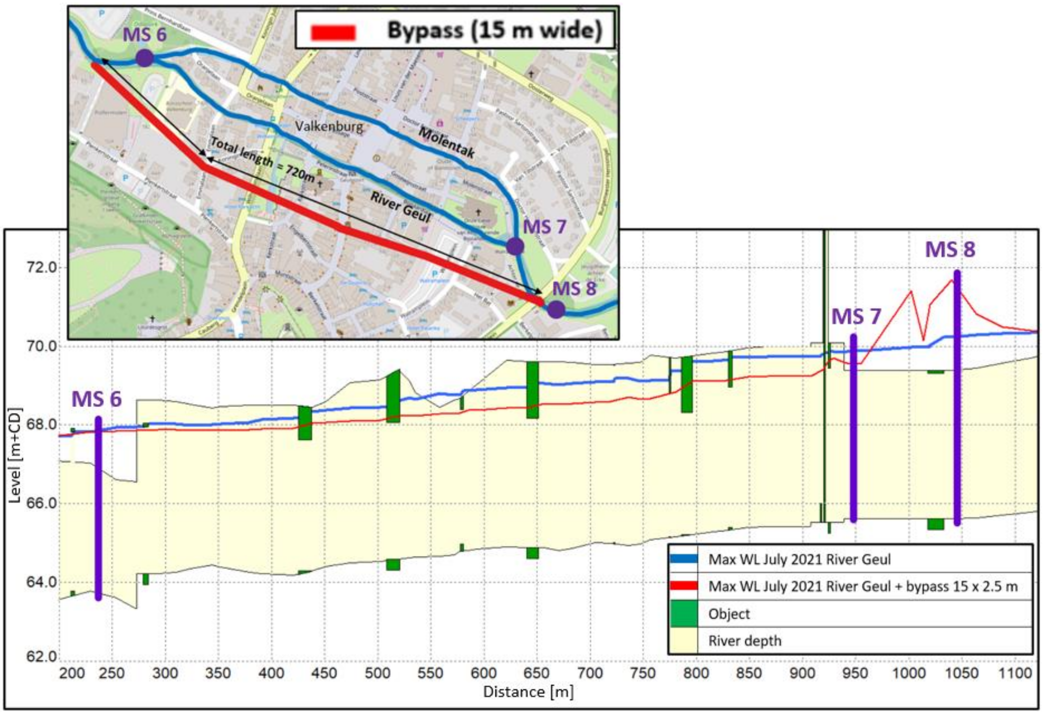


**Figure 85 Longitudinal cross-section of the River Geul, comparing the max water levels of July 2021 for the std case and the case with a bypass of 15 x 2.5 metres. Location = along Valkenburg.**

## Appendix 7C5

# Raise dikes in Valkenburg

| Difference in flooding depth [m] for different dike raises and conditions | | | | | | |
|---|---|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | | Stress test (224 m³/s) | | |
| | D [m] for std case | Δh [m] for +0.5 m | Δh [m] for +1 m | D [m] for std case | Δh [m] for +0.5 m | Δh [m] for +1 m |
| 5 | 0.29 | 0.00 | 0.00 | 0.60 | 0.00 | 0.00 |
| 6 | 0.79 | -0.01 | -0.01 | 1.12 | -0.01 | -0.01 |
| 7 | 0.49 | -0.07 | -0.07 | 0.77 | -0.05 | -0.05 |
| 8 | 0.85 | -0.02 | -0.02 | 1.11 | -0.01 | -0.01 |
| 9 | 0.60 | 0.00 | 0.00 | 0.86 | 0.00 | 0.00 |

**Table 50 Flooding depths for dike raises relative to the std case for July 2021. Red cell = flooding depth increase and green cell = flooding depth decrease.**

| Difference in flow velocity [m/s] for different dike raises and conditions | | | | | | |
|---|---|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | | Stress test (224 m³/s) | | |
| | v [m/s] for std | Δv [m/s] for +0.5 m | Δv [m/s] for +1 m | v [m/s] for std | Δv [m/s] for +0.5 m | Δv [m/s] for +1 m |
| 5 | 1.80 | 0.00 | 0.00 | 1.94 | 0.00 | 0.00 |
| 6 | 1.55 | -0.01 | 0.00 | 1.57 | -0.01 | -0.01 |
| 7 | 1.60 | 0.11 | 0.08 | 1.79 | 0.09 | 0.07 |
| 8 | 2.30 | 0.07 | 0.05 | 2.38 | 0.05 | 0.04 |
| 9 | 2.30 | 0.00 | 0.00 | 2.54 | 0.00 | 0.00 |

**Table 51 Flow velocities for different dike raises relative to the std case for July 2021 and the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

## Appendix 7C6
# Remove obstacles in the River Geul

| Difference in flow velocity [m/s] for removing obstacles and different conditions | | | | |
|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | Stress test (224 m³/s) | |
| | v [m/s] for std case | Δv [m/s] no obstacles | v [m/s] for std case | Δv [m/s] no obstacles |
| 6 | 1.55 | 0.44 | 1.57 | 0.55 |
| 7 | 1.60 | 0.23 | 1.79 | 0.18 |
| 8 | 2.30 | 0.14 | 2.38 | 0.10 |

**Table 52 Flow velocities for removing obstacles relative to the std case for July 2021 and the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

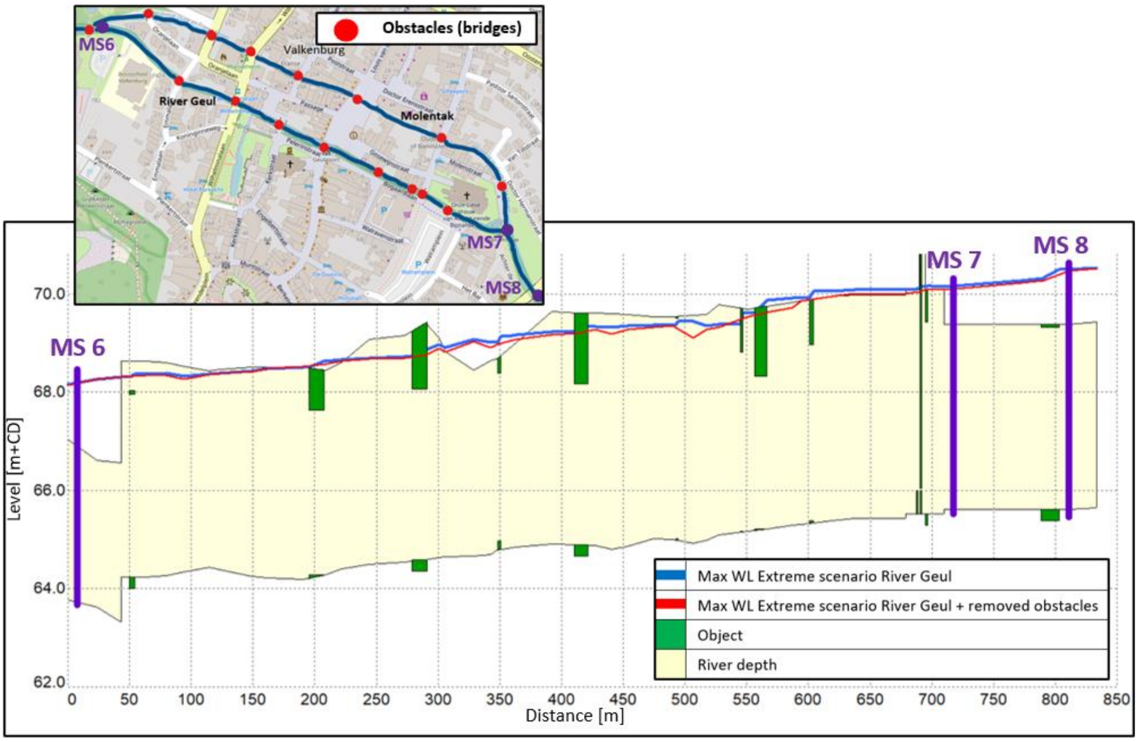


**Figure 86 Longitudinal cross-section of the River Geul, comparing the max water levels during the stress test (extreme scenario) for the std case and the obstacles removed. Location = along Valkenburg.**

## Appendix 7C7
# Thresholds upstream Valkenburg

| Difference in flow velocity [m/s] for different threshold heights and conditions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | | | Stress test (224 m³/s) | | | |
| | v [m/s] for std case | Δv [m/s] for +0.5 m | Δv [m/s] for +1 m | Δv [m/s] for +1.5 m | v [m/s] for std case | Δv [m/s] for +0.5 m | Δv [m/s] +1 m | Δv [m/s] +1.5 m |
| 12 | 1.41 | 0.00 | 0.00 | 0.00 | 1.50 | 0.00 | 0.00 | 0.00 |
| 13 | 3.16 | 0.69 | 0.42 | 0.02 | 3.13 | -0.55 | -0.54 | 0.13 |
| 14 | 2.14 | 0.00 | 0.00 | 0.00 | 2.41 | 0.00 | 0.00 | 0.00 |
| 15 | 2.09 | 0.03 | -0.01 | -0.19 | 2.10 | 1.84 | 0.00 | 0.35 |
| 16 | 0.85 | 0.00 | 0.00 | 0.00 | 0.85 | 0.00 | 0.00 | 0.00 |

**Table 53 Flow velocities for thresholds upstream Valkenburg relative to the std case for July 2021 and the stress test. Red cell = flow velocity increase and green cell = flow velocity decrease.**

## Appendix 7C8
## Weirs before the 3 tributaries reach the River Geul

## Appendix 7C9
## Add vegetation upstream Valkenburg

| Difference in flooding depth [m] for different amounts of vegetation and conditions | | | | | | |
|---|---|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | | Stress test (224 m³/s) | | |
| | D [m] for std case | Δh [m] for $c_f$ = 0.075 | Δh [m] for $c_f$ = 0.1 | D [m] for std case | Δh [m] for $c_f$ = 0.075 | Δh [m] for $c_f$ = 0.1 |
| 8 | 0.85 | 0.00 | 0.00 | 1.11 | 0.00 | 0.00 |
| 9 | 0.60 | 0.13 | 0.18 | 0.86 | 0.09 | 0.12 |
| 10 | 0.27 | 0.02 | 0.04 | 0.46 | 0.02 | 0.03 |
| 11 | 0.39 | -0.03 | 0.00 | 0.51 | -0.03 | -0.06 |
| 12 | 0.43 | 0.00 | 0.00 | 0.56 | 0.00 | 0.01 |
| 13 | 0.53 | 0.05 | 0.08 | 0.76 | 0.05 | 0.08 |
| 14 | 0.51 | 0.00 | 0.00 | 0.73 | 0.00 | 0.00 |
| 15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.01 |

**Table 54 Flooding depths for adding vegetation relative to the std case for July 2021 and the stress test. Red cell = flooding depth increase and green cell = flooding depth decrease**

## Appendix 7C10
## Raise riverbed

## Appendix 7C11
## Enlarge current basins

| Difference in flow velocity [m/s] for different river basin sizes and conditions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MS River Geul | July 2021 (140 m³/s) | | | | Stress test (224 m³/s) | | | |
| | v [m/s] for std case | Δv [m/s] for x1.5 | Δv [m/s] for x3 | Δv [m/s] for x5 | v [m/s] for std case | Δv [m/s] for x1.5 | Δv [m/s] for x3 | Δv [m/s] for x5 |
| 12 | 1.41 | 0.00 | 0.00 | 0.00 | 1.50 | 0.00 | 0.00 | 0.00 |
| 13 | 3.16 | -0.16 | 0.49 | -0.21 | 3.13 | 0.36 | 0.44 | -0.14 |
| 14 | 2.14 | 0.00 | 0.00 | 0.00 | 2.41 | 0.00 | 0.00 | 0.00 |
| 15 | 2.09 | -0.03 | -0.05 | -0.08 | 2.10 | 0.01 | 0.20 | 0.00 |
| 16 | 0.85 | 0.01 | 0.00 | 0.01 | 0.85 | 0.01 | 0.00 | 0.00 |

**Table 55 Flow velocities for different basin sizes relative to the std case for July 2021 and the stress test in the River Geul. Red cell = flow velocity increase and green cell = flow velocity decrease**

| Difference in flow velocity [m/s] for different river basin sizes and conditions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MS River Selzerbeek | July 2021 (140 m³/s) | | | | Stress test (224 m³/s) | | | |
| | v [m/s] for std case | Δv [m/s] for x1.5 | Δv [m/s] for x3 | Δv [m/s] for x5 | v [m/s] for std case | Δv [m/s] for x1.5 | Δv [m/s] for x3 | Δv [m/s] for x5 |
| 1 | 2.52 | 0.00 | 0.00 | 0.00 | 2.52 | 0.00 | 0.00 | 0.00 |
| 2 | 1.23 | -0.01 | -0.22 | -0.49 | 1.25 | 0.02 | 0.06 | -0.05 |
| 3 | 1.27 | 0.05 | 0.18 | 0.16 | 1.27 | 0.05 | 0.72 | 1.52 |
| 4 | 2.66 | 0.00 | 0.00 | 0.01 | 2.66 | 0.00 | 0.00 | 0.00 |

**Table 56 Flow velocities for different basin sizes relative to the std case for July 2021 and the stress test in the River Selzerbeek. Red cell = flow velocity increase and green cell = flow velocity decrease**

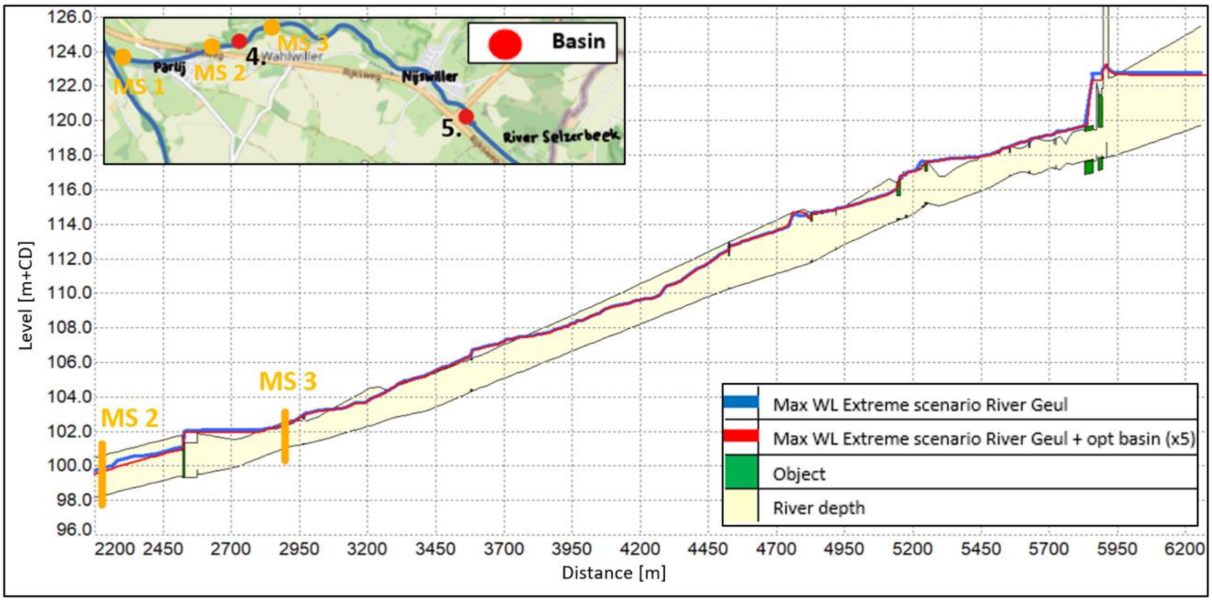


**Figure 87 Longitudinal cross-section of the River Selzerbeek, comparing the max water levels for the stress test (extreme scenario) for the std case and the case with enlarged basins (x5). Location = downstream Partij until upstream Nijswiller.**

# Appendix 7D
SSM2017 & cost estimates

## Appendix 7D1
**Explanation flood inundation maps for SSM2017**

SSM2017 requires flooding depths as minimum input to calculate the damage for a certain area. The necessary format of these flooding depths is a grid that contains flooding depths of the 2D overland flow module, which SOBEK automatically stores in a file after running a case. In the previous evaluation of measures only the decrease in flooding depth and water level in the River Geul itself is taken into account. This method shows local decreases more precise, but the flooding overland is not taken into account.

To explain why the damages for the stress test do not go down an example is given using the bypass tunnel of 20x2.5 m. What the flood inundation maps of Valkenburg in Figure 88 show is that the flooding depths decrease drastically after implementing the bypass for July 2021, while for the stress test the flooding depths barely lower after implementing the bypass. The longitudinal cross-sections already showed this major difference, but the flood inundation maps show that overall, the measures for the stress test barely have any influence on the flooding depths. Therefore, the decrease in damages calculated by SSM2017 is equal to zero (expect for bypass channel where a decrease of 9% is realized).

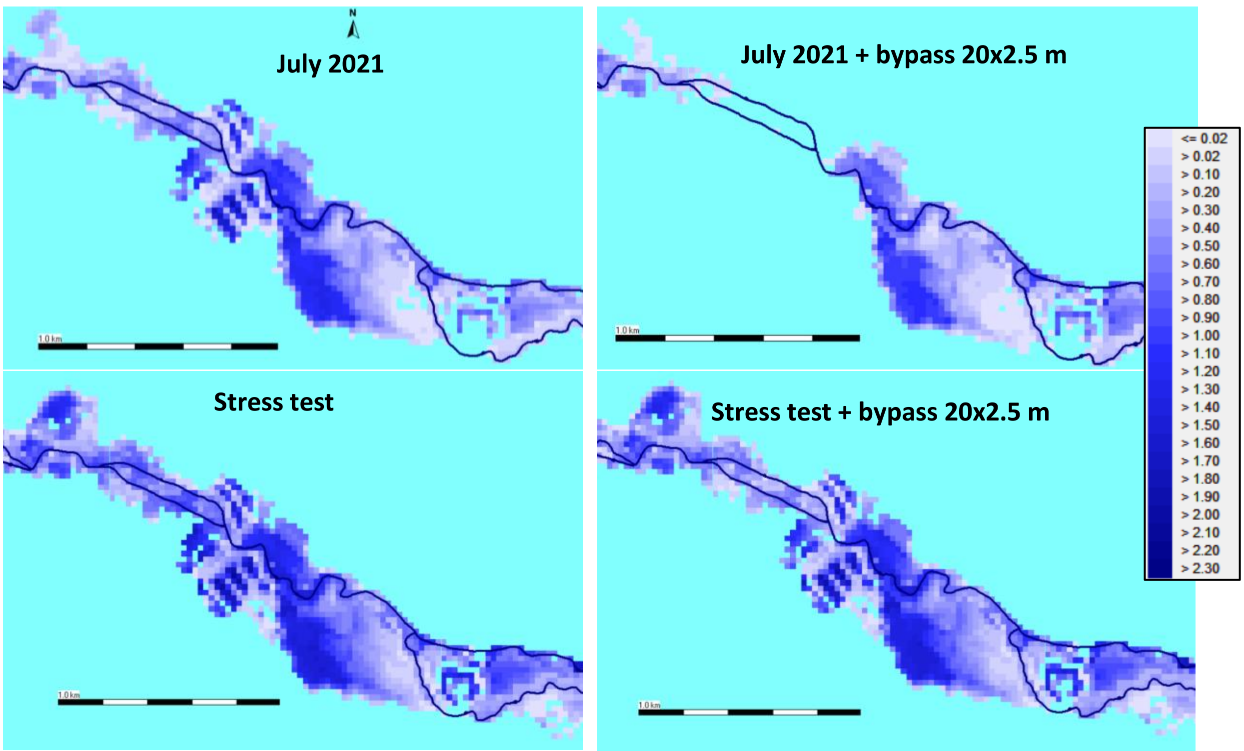


**Figure 88 Flood maps Valkenburg and upstream Valkenburg, maximum water levels for July 2021 and the stress test with and without bypass 20x2.5 m.**

# Appendix 7D2

## Results SSM2017

| method: SSM2017 Regional | July 2021 | Widening | Bypass tunnel | Bypass channel | Rem. Obstacles | Enl. basin |
|---|---|---|---|---|---|---|
| Category name | **Damage [€(x1000)]** | **Damage [€(x1000)]** | **Damage [€(x1000)]** | **Damage [€(x1000)]** | **Damage [€(x1000)]** | **Damage [€(x1000)]** |
| Companies: Meeting | 1700 | 1700 | 320 | 300 | 1500 | 1700 |
| Companies: Healthcare | 380 | 380 | 120 | 120 | 350 | 360 |
| Companies: Industry | 6200 | 5300 | 5400 | 5300 | 5900 | 6000 |
| Companies: Office | 2000 | 1800 | 580 | 550 | 1800 | 1900 |
| Companies: Education | 700 | 610 | 730 | 730 | 700 | 690 |
| Companies: Sports | 45 | 45 | 37 | 37 | 41 | 45 |
| Companies: Store | 5700 | 5600 | 880 | 870 | 4700 | 5600 |
| Infrastructure: Motorways | 170 | 170 | 170 | 170 | 170 | 150 |
| Infrastructure: Other roads | 1100 | 990 | 1100 | 1100 | 1100 | 1100 |
| Infrastructure: National Highways | 62 | 52 | 62 | 63 | 61 | 61 |
| Infrastructure: Railways (electric) | 150 | 19 | 180 | 180 | 150 | 140 |
| Other: Extensive recreation | 3700 | 3600 | 3700 | 3700 | 3700 | 3700 |
| Other: Intensive recreation | 770 | 730 | 680 | 680 | 760 | 770 |
| Other: Agriculture | 4700 | 4300 | 4800 | 4800 | 4700 | 4600 |
| Other: Urban area | 6400 | 6200 | 3900 | 3700 | 6000 | 6300 |
| Other: Means of transport | 2600 | 2500 | 1400 | 990 | 2400 | 2500 |
| Other: Treatment plants | 4600 | 4600 | 4600 | 4600 | 4600 | 4600 |
| Homes: Ground floor apartments (furniture) | 2800 | 2800 | 1100 | 700 | 2500 | 2700 |
| Homes: Ground floor apartments (building) | 3500 | 3400 | 1500 | 1000 | 3100 | 3300 |
| Homes: Single-family homes (furniture) | 12000 | 11000 | 8500 | 8100 | 12000 | 12000 |
| Homes: Single-family homes (building) | 2100 | 2000 | 1300 | 1200 | 2000 | 2000 |
| Total | **62000** | **58000** | **41000** | **39000** | **58000** | **60000** |

**Table 57 Damage subdivided in categories for scenario July 2021.**

| method: SSM2017 Regional | Stress test | Widening | Bypass tunel | Bypass channel | Rem. obst | Enl. basin |
|---|---|---|---|---|---|---|
| Category name | **Damage [€(x1000)]** | **Damage [€(x1000)]** | **Damage [€(x1000)]** | **Damage [€(x1000)]** | **Damage [€(x1000)]** | **Damage [€(x1000)]** |
| Companies: Meeting | 2800 | 2800 | 2200 | 1800 | 2700 | 2800 |
| Companies: Healthcare | 1000 | 1000 | 960 | 940 | 1000 | 1100 |
| Companies: Industry | 11000 | 10000 | 15000 | 14000 | 14000 | 11000 |
| Companies: Office | 3800 | 3400 | 3500 | 3200 | 3700 | 3700 |
| Companies: Education | 1400 | 1400 | 1400 | 1300 | 1400 | 1400 |
| Companies: Sports | 71 | 70 | 63 | 58 | 70 | 71 |
| Companies: Store | 10000 | 10000 | 7700 | 6100 | 9500 | 10000 |
| Infrastructure: Motorways | 370 | 370 | 380 | 370 | 370 | 300 |
| Infrastructure: Other roads | 2500 | 2400 | 2500 | 2500 | 2500 | 2500 |
| Infrastructure: National Highways | 220 | 200 | 230 | 220 | 220 | 210 |
| Infrastructure: Railways (electric) | 1000 | 940 | 1100 | 1000 | 1000 | 990 |
| Other: Extensive recreation | 5500 | 5300 | 5500 | 5500 | 5500 | 5500 |
| Other: Intensive recreation | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| Other: Agriculture | 6900 | 6600 | 7000 | 6900 | 6900 | 6900 |
| Other: Urban area | 13000 | 12000 | 12000 | 12000 | 13000 | 13000 |
| Other: Means of transport | 5100 | 4900 | 4300 | 4000 | 4900 | 5100 |
| Other: Treatment plants | 5200 | 5200 | 5200 | 5200 | 5200 | 5200 |
| Homes: Ground floor apartments (furniture) | 5100 | 5100 | 4100 | 3600 | 4900 | 5100 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Homes: Ground floor apartments (building) | 6200 | 6200 | 5000 | 4400 | 5900 | 6100 |
| Homes: Single-family homes (furniture) | 26000 | 23000 | 25000 | 24000 | 25000 | 25000 |
| Homes: Single-family homes (building) | 4600 | 4300 | 4300 | 4000 | 4500 | 4600 |
| Total | **110000** | **110000** | **110000** | **100000** | **110000** | **110000** |

**Table 58 Damage subdivided in categories for the stress test.**

Appendix 7D3
## Calculation estimate costs

Figure 89 shows several calculated amounts which are necessary for the cost estimates in Table 59 until Table 64.

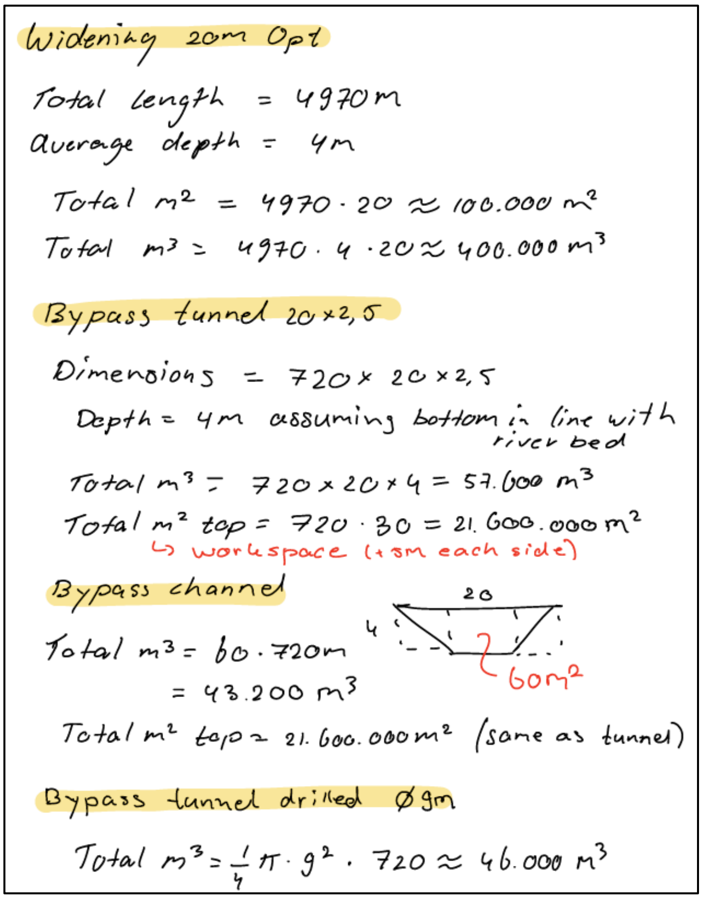


**Figure 89 Hand calculations necessary amounts cost estimation for different measures.**

For all the effective measures (river widening, remove obstacles, bypass, enlarge basin) a cost estimate is made. The method is called SSK which stands for 'Standaardsystematiek voor Kostenraming'. The tables below show the applied SSK-format for the different measures. The values in these tables are predefined by I. de Jong and E. Schulten from Witteveen+Bos.

| | | | | | |
|---|---|---|---|---|---|
| Client: | | Price level: | 2022 | Date: | 14-2-2022 |
| Project: | Widen River Geul | Version: | 01 | Project code: | |
| Sub-item: | | Status: | In progress | Author: | Yvo van Dijk |
| | | | | | |
| **code** | **description** | **quantity** | **unit** | **unit rate** | **total** |
| 1 | | | | | |
| | | | | | |
| | | | | | |
| | **INVESTMENT COSTS** | | | | |
| 10 | **River widening** | | | | |
| 100110 | Excavate soil for widening river | 400 000.00 | m³ | € 5.00 | € 2 000 000 |
| 100120 | Transport soil surplus, till 15 km (one-way) | 400 000.00 | m³ | € 15.00 | € 6 000 000 |

| | | | | | |
|---|---|---|---|---|---|
| | **Direct costs** | | | | **€ 8 000 000** |
| NTD011 | Additional items | 15.0% | | € 8 000 000 | € 1 200 000 |
| | **Direct costs incl. allowance** | | | | **€ 9 200 000** |
| | | | | | |
| IK016 | Non-reoccurring costs (eg. mob/demob) | 2.0% | | € 9 200 000 | € 184 000 |
| IK017 | Site facilities | 1.0% | | € 9 200 000 | € 92 000 |
| IK019 | Site organisation | 12.0% | | € 9 200 000 | € 1 104 000 |
| IK0110 | General costs | 8.0% | | € 10 580 000 | € 846 400 |
| IK0111 | Profit | 3.0% | | € 11 426 400 | € 342 792 |
| IK0112 | Risk | 2.0% | | € 11 426 400 | € 228 528 |
| | **Indirect costs ('contractors overhead')** | 30% | | | **€ 2 797 720** |
| | | | | | |
| **VZBK** | **Costs foreseen** | | | | **€ 11 997 720** |
| | | | | | |
| RBK013 | Contingency | 15.0% | | € 11 997 720 | € 1 799 658 |
| **RBK** | **Contingency** | 15% | | | **€ 1 799 658** |
| | | | | | |
| **BK01** | **Construction costs** | | | | **€ 13 797 378** |
| | | | | | |
| VK011 | Land plot acquisition, agricultural | 20 000.00 | m² | € 10.00 | € 200 000 |
| VK012 | Land plot acquisition, urban | - | m² | € 50.00 | € - |
| VK013 | Demolishing buildings | - | pcs | € 500 000.00 | € - |
| **VK01** | **Real estate** | | | | **€ 200 000** |
| | | | | | |
| **EK01** | **Engineering** | 22% | | | **€ 2 639 498** |
| | | | | | |
| OK011 | Import duties, taxes | 0.0% | | € 11 997 720 | € - |
| OK012 | Insurances | 0.5% | | € 11 997 720 | € 59 989 |
| OK013 | Underground facilities | 2.0% | | € 11 997 720 | € 239 954 |
| **OBK01** | **Remaining costs** | 3% | | | **€ 299 943** |
| | | | | | |
| **INV01** | **Total investment costs excl. taxes** | | | | **€ 16 936 819** |
| | Band width for communication | | | Lower bound | Upper bound |
| | | | | € 12 000 000 | € 23 000 000 |

**Table 59 Cost estimate river widening with the SSK-format.**

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| Client: | | Price level: | 2022 | Date: | 14-2-2022 |
| Project: | Remove obstacles Valkenburg | Version: | 01 | Project code: | |
| Sub-item: | | Status: | In progress | Author: | Yvo van Dijk |
| | | | | | |
| **code** | **description** | **quantity** | **unit** | **unit rate** | **total** |
| 1 | | | | | |
| | | | | | |
| | | | | | |
| | **INVESTMENT COSTS** | | | | |
| 10 | **Remove obstacles** | | | | |
| 100150 | Infrastructure | 1 200.00 | m² | € 50.00 | € 60 000 |
| 100160 | New fixed bridges | 1 000.00 | m² | € 1 500.00 | € 1 500 000 |

| | | | | | |
|---|---|---|---|---|---|
| 100170 | New movable bridges | 200.00 | m² | € 5 000.00 | € 1 000 000 |
| | **Direct costs** | | | | **€ 2 560 000** |
| | | | | | |
| NTD011 | Additional items | 15.0% | | € 2 560 000 | € 384 000 |
| | **Direct costs incl. allowance** | | | | **€ 2 944 000** |
| | | | | | |
| IK016 | Non-reoccurring costs (eg. mob/demob) | 2.0% | | € 2 944 000 | € 58 880 |
| IK017 | Site facilities | 1.0% | | € 2 944 000 | € 29 440 |
| IK019 | Site organisation | 12.0% | | € 2 944 000 | € 353 280 |
| IK0110 | General costs | 8.0% | | € 3 385 600 | € 270 848 |
| IK0111 | Profit | 3.0% | | € 3 656 448 | € 109 693 |
| IK0112 | Risk | 2.0% | | € 3 656 448 | € 73 129 |
| | **Indirect costs ('contractors overhead')** | 30% | | | **€ 895 270** |
| | | | | | |
| **VZBK** | **Costs foreseen** | | | | **€ 3 839 270** |
| | | | | | |
| RBK013 | Contingency | 15.0% | | € 3 839 270 | € 575 891 |
| **RBK** | **Contingency** | 15% | | | **€ 575 891** |
| | | | | | |
| **BK01** | **Construction costs** | | | | **€ 4 415 161** |
| | | | | | |
| VK011 | Land plot acquisition, agricultural | | m² | € 10.00 | € - |
| VK012 | Land plot acquisition, urban | - | m² | € 50.00 | € - |
| VK013 | Demolishing buildings | - | pcs | € 500 000.00 | € - |
| **VK01** | **Real estate** | | | | **€ -** |
| | | | | | |
| **EK01** | **Engineering** | 22% | | | **€ 844 639** |
| | | | | | |
| OK011 | Import duties, taxes | 0.0% | | € 3 839 270 | € - |
| OK012 | Insurances | 0.5% | | € 3 839 270 | € 19 196 |
| OK013 | Underground facilities | 2.0% | | € 3 839 270 | € 76 785 |
| **OBK01** | **Remaining costs** | 3% | | | **€ 95 982** |
| | | | | | |
| **INV01** | **Total investment costs excl. taxes** | | | | **€ 5 355 782** |
| | Band width for communication | | | Lower bound | Upper bound |
| | | | | € 4 000 000 | € 7 000 000 |

**Table 60 Cost estimate removing obstacles in Valkenburg with the SSK-format.**

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| Client: | | Price level: | 2022 | Date: | 14-2-2022 |
| Project: | Bypass Channel 10-20 m | Version: | 01 | Project code: | |
| Sub-item: | | Status: | In progress | Author: | Yvo van Dijk |
| | | | | | |
| **code** | **description** | **quantity** | **unit** | **unit rate** | **total** |
| 1 | | | | | |
| | | | | | |
| | | | | | |
| | **INVESTMENT COSTS** | | | | |
| | | | | | |
| 10 | **Bypass - channel (10m-18m)** | | | | |
| 100110 | Excavate soil | 43 200.00 | m³ | € 5.00 | € 216 000 |

| | | | | | |
|---|---|---|---|---|---|
| 100120 | Transport soil surplus, till 15 km (one-way) | 43 200.00 | m³ | € 15.00 | € 648 000 |
| 100130 | Clear terrain | 21 600.00 | m² | € 5.00 | € 108 000 |
| 100140 | | - | - | € - | € - |
| 100150 | River bed protection | 14 400.00 | m² | € 75.00 | € 1 080 000 |
| 100160 | Vertical walls | 3 600.00 | m² | € 350.00 | € 1 260 000 |
| 100170 | Maintenance paths/ public space | 8 640.00 | m² | € 200.00 | € 1 728 000 |
| 100180 | Crossings (brdiges) every 50 m | 14.00 | st | € 500 000.00 | € 7 000 000 |
| 100190 | Crossings (K&L) | 14.00 | st | € 100 000.00 | € 1 400 000 |
| | **Direct costs** | | | | **€ 13 440 000** |
| | | | | | |
| NTD011 | Additional items | 20.0% | | € 13 440 000 | € 2 688 000 |
| | **Direct costs incl. allowance** | | | | **€ 16 128 000** |
| | | | | | |
| IK016 | Non-reoccurring costs (eg. Mob/demob) | 2.0% | | € 16 128 000 | € 322 560 |
| IK017 | Site facilities | 1.0% | | € 16 128 000 | € 161 280 |
| IK019 | Site organisation | 12.0% | | € 16 128 000 | € 1 935 360 |
| IK0110 | General costs | 8.0% | | € 18 547 200 | € 1 483 776 |
| IK0111 | Profit | 3.0% | | € 20 030 976 | € 600 929 |
| IK0112 | Risk | 2.0% | | € 20 030 976 | € 400 620 |
| | **Indirect costs ('contractors overhead')** | 30% | | | **€ 4 904 525** |
| | | | | | |
| **VZBK** | **Costs foreseen** | | | | **€ 21 032 525** |
| | | | | | |
| RBK013 | Contingency | 25.0% | | € 21 032 525 | € 5 258 131 |
| **RBK** | **Contingency** | 25% | | | **€ 5 258 131** |
| | | | | | |
| **BK01** | **Construction costs** | | | | **€ 26 290 656** |
| | | | | | |
| VK013 | Demolishing buildings | 25.00 | pcs | € 1 000 000.00 | € 25 000 000 |
| VK013 | Additional costs | 0.10 | | € 25 000 000.00 | € 2 500 000 |
| **VK01** | **Real estate** | | | | **€ 27 500 000** |
| | | | | | |
| **EK01** | **Engineering** | 22% | | | **€ 4 627 155** |
| | | | | | |
| OK011 | Import duties, taxes | 0.0% | | € 21 032 525 | € - |
| OK012 | Insurances | 0.5% | | € 21 032 525 | € 105 163 |
| OK013 | Underground facilities | 2.0% | | € 21 032 525 | € 420 650 |
| **OBK01** | **Remaining costs** | 3% | | | **€ 525 813** |
| | | | | | |
| **INV01** | **Total investment costs excl. taxes** | | | | **€ 58 943 625** |
| | Band width for communication | | | Lower bound | Upper bound |
| | | | | € 42 000 000 | € 77 000 000 |

**Table 61 Cost estimate bypass channel with the SSK-format.**

| | | | | | |
|---|---|---|---|---|---|
| Client: | | Price level: | 2022 | Date: | 14-2-2022 |
| Project: | Bypass Tunnel in-situ 20 x 2.5 m | Version: | 01 | Project code: | |
| Sub-item: | | Status: | In progress | Author: | Yvo van Dijk |
| | | | | | |
| **code** | **description** | **quantity** | **unit** | **unit rate** | **total** |
| 1 | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| | **INVESTMENT COSTS** | | | | |
| | | | | | |
| 10 | **Bypass – tunnel (20 x 2.5 m)** | | | | |
| 100110 | Excavate soil | 57 600.00 | m³ | € 5.00 | € 288 000 |
| 100120 | Transport soil surplus, till 15 km (one-way) | 57 600.00 | m³ | € 15.00 | € 864 000 |
| 100130 | Clear terrain | 21 600.00 | m² | € 5.00 | € 108 000 |
| 100140 | | - | - | € - | € - |
| 100150 | Furnish area above tunnel | 21 600.00 | m² | € 100.00 | € 2 160 000 |
| 100160 | Building pit | 720.00 | m | € 3 900.00 | € 2 808 000 |
| 100170 | Foundation tunnel | 14 400.00 | m² | € 150.00 | € 2 160 000 |
| 100180 | Concrete in walls, floors and top (0.75 m) | 24 840.00 | m³ | € 750.00 | € 18 630 000 |
| 100190 | Crossings (K&L) | 14.00 | st | € 100 000.00 | € 1 400 000 |
| | **Direct costs** | | | | **€ 28 418 000** |
| | | | | | |
| NTD011 | Additional items | 15.0% | | € 28 418 000 | € 4 262 700 |
| | **Direct costs incl. allowance** | | | | **€ 32 680 700** |
| | | | | | |
| IK016 | Non-reoccurring costs (eg. Mob/demob) | 2.0% | | € 32 680 700 | € 653 614 |
| IK017 | Site facilities | 1.0% | | € 32 680 700 | € 326 807 |
| IK019 | Site organisation | 17.0% | | € 32 680 700 | € 5 555 719 |
| IK0110 | General costs | 8.0% | | € 39 216 840 | € 3 137 347 |
| IK0111 | Profit | 3.0% | | € 42 354 187 | € 1 270 626 |
| IK0112 | Risk | 2.0% | | € 42 354 187 | € 847 084 |
| | **Indirect costs ('contractors overhead')** | 36% | | | **€ 11 791 197** |
| | | | | | |
| **VZBK** | **Costs foreseen** | | | | **€ 44 471 897** |
| | | | | | |
| RBK013 | Contingency | 30.0% | | € 44 471 897 | € 13 341 569 |
| **RBK** | **Contingency** | 30% | | | **€ 13 341 569** |
| | | | | | |
| **BK01** | **Construction costs** | | | | **€ 57 813 466** |
| | | | | | |
| VK013 | Demolishing buildings | 25.00 | pcs | € 1 000 000.00 | € 25 000 000 |
| VK013 | Additional costs | 0.10 | | € 25 000 000.00 | € 2 500 000 |
| **VK01** | **Real estate** | | | | **€ 27 500 000** |
| | | | | | |
| **EK01** | **Engineering** | 22% | | | **€ 9 783 817** |
| | | | | | |
| OK011 | Import duties, taxes | 0.0% | | € 44 471 897 | € - |
| OK012 | Insurances | 0.5% | | € 44 471 897 | € 222 359 |
| OK013 | Underground facilities | 2.0% | | € 44 471 897 | € 889 438 |
| **OBK01** | **Remaining costs** | 3% | | | **€ 1 111 797** |
| | | | | | |
| **INV01** | **Total investment costs excl. taxes** | | | | **€ 96 209 080** |
| | Band width for communication | | | Lower bound | Upper bound |
| | | | | € 68 000 000 | € 126 000 000 |

**Table 62 Cost estimate bypass tunnel in-situ 20x2.5 m with the SSK-format.**

| | | | | | |
|---|---|---|---|---|---|
| Client: | | Price level: | 2022 | Date: | 14-2-2022 |
| Project: | Bypass Tunnel drilled (D = 9 m) | Version: | 01 | Project code: | |
| Sub-item: | | Status: | In progress | Author: | Yvo van Dijk |
| | | | | | |
| **code** | **description** | **quantity** | **unit** | **unit rate** | **total** |
| 1 | | | | | |
| | | | | | |
| | | | | | |
| | **INVESTMENT COSTS** | | | | |
| | | | | | |
| 10 | **Bypass - drilled (D = 9 m)** | | | | |
| 100110 | Costs drill and shafts | 50 000 000.00 | EUR | € 1.00 | € 50 000 000 |
| 100130 | Clear terrain | 21 600.00 | m² | € 5.00 | € 108 000 |
| 100140 | | - | - | € - | € - |
| 100150 | Drill tunnel and facilities | 792.00 | m | € 30 000.00 | € 23 760 000 |
| | **Direct costs** | | | | **€ 73 868 000** |
| | | | | | |
| NTD011 | Additional items | 10.0% | | € 73 868 000 | € 7 386 800 |
| | **Direct costs incl. allowance** | | | | **€ 81 254 800** |
| | | | | | |
| IK016 | Non-reoccurring costs (eg. mob/demob) | 2.0% | | € 81 254 800 | € 1 625 096 |
| IK017 | Site facilities | 1.0% | | € 81 254 800 | € 812 548 |
| IK019 | Site organisation | 12.0% | | € 81 254 800 | € 9 750 576 |
| IK0110 | General costs | 8.0% | | € 93 443 020 | € 7 475 442 |
| IK0111 | Profit | 3.0% | | € 100 918 462 | € 3 027 554 |
| IK0112 | Risk | 2.0% | | € 100 918 462 | € 2 018 369 |
| | **Indirect costs ('contractors overhead')** | 30% | | | **€ 24 709 585** |
| | | | | | |
| **VZBK** | **Costs foreseen** | | | | **€ 105 964 385** |
| | | | | | |
| RBK013 | Contingency | 20.0% | | € 105 964 385 | € 21 192 877 |
| **RBK** | **Contingency** | 20% | | | **€ 21 192 877** |
| | | | | | |
| **BK01** | **Construction costs** | | | | **€ 127 157 262** |
| | | | | | |
| VK013 | Demolishing buildings | 5.00 | pcs | € 1 000 000.00 | € 5 000 000 |
| VK013 | Additional costs | 0.10 | | € 5 000 000.00 | € 500 000 |
| **VK01** | **Real estate** | | | | **€ 5 500 000** |
| | | | | | |
| **EK01** | **Engineering** | 22% | | | **€ 23 312 165** |
| | | | | | |
| OK011 | Import duties, taxes | 0.0% | | € 105 964 385 | € - |
| OK012 | Insurances | 0.5% | | € 105 964 385 | € 529 822 |
| OK013 | Underground facilities | 2.0% | | € 105 964 385 | € 2 119 288 |
| **OBK01** | **Remaining costs** | 3% | | | **€ 2 649 110** |
| | | | | | |
| **INV01** | **Total investment costs excl. taxes** | | | | **€ 158 618 536** |
| | Band width for communication | | | Lower bound | Upper bound |
| | | | | € 112 000 000 | € 207 000 000 |

**Table 63 Cost estimate bypass tunnel drilled (D = 9 m) with the SSK-format.**

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| Client: | | Price level: | 2022 | Date: | 14-2-2022 |
| Project: | Optimize basin | Version: | 01 | Project code: | |
| Sub-item: | | Status: | In progress | Author: | Yvo van Dijk |
| | | | | | |
| **code** | **description** | **quantity** | **unit** | **unit rate** | **total** |
| 1 | | | | | |
| | | | | | |
| | | | | | |
| | **INVESTMENT COSTS** | | | | |
| 10 | **Enlarge basin** | | | | |
| 100110 | Excavate soil for widening river | 7 900 000.00 | m³ | € 5.00 | € 39 500 000 |
| 100120 | Transport soil surplus, till 15 km (one-way) | 7 900 000.00 | m³ | € 15.00 | € 118 500 000 |
| | **Direct costs** | | | | **€ 158 000 000** |
| NTD011 | Additional items | 15.0% | | € 158 000 000 | € 23 700 000 |
| | **Direct costs incl. allowance** | | | | **€ 181 700 000** |
| | | | | | |
| IK016 | Non-reoccurring costs (eg. mob/demob) | 2.0% | | € 181 700 000 | € 3 634 000 |
| IK017 | Site facilities | 1.0% | | € 181 700 000 | € 1 817 000 |
| IK019 | Site organisation | 12.0% | | € 181 700 000 | € 21 804 000 |
| IK0110 | General costs | 8.0% | | € 208 955 000 | € 16 716 400 |
| IK0111 | Profit | 3.0% | | € 225 671 400 | € 6 770 142 |
| IK0112 | Risk | 2.0% | | € 225 671 400 | € 4 513 428 |
| | **Indirect costs ('contractors overhead')** | 30% | | | **€ 55 254 970** |
| | | | | | |
| **VZBK** | **Costs foreseen** | | | | **€ 236 954 970** |
| | | | | | |
| RBK013 | Contingency | 15.0% | | € 236 954 970 | € 35 543 246 |
| **RBK** | **Contingency** | 15% | | | **€ 35 543 246** |
| | | | | | |
| **BK01** | **Construction costs** | | | | **€ 272 498 216** |
| | | | | | |
| VK011 | Land plot acquisition, agricultural | 1 580 000.00 | m² | € 10.00 | € 15 800 000 |
| VK012 | Land plot acquisition, urban | - | m² | € 50.00 | € - |
| VK013 | Demolishing buildings | - | pcs | € 500 000.00 | € - |
| **VK01** | **Real estate** | | | | **€ 15 800 000** |
| | | | | | |
| **EK01** | **Engineering** | 22% | | | **€ 52 130 093** |
| | | | | | |
| OK011 | Import duties, taxes | 0.0% | | € 236 954 970 | € - |
| OK012 | Insurances | 0.5% | | € 236 954 970 | € 1 184 775 |
| OK013 | Underground facilities | 2.0% | | € 236 954 970 | € 4 739 099 |
| **OBK01** | **Remaining costs** | 3% | | | **€ 5 923 874** |
| | | | | | |
| **INV01** | **Total investment costs excl. taxes** | | | | **€ 346 352 183** |
| | Band width for communication | | | Lower bound | Upper bound |
| | | | | € 243 000 000 | € 451 000 000 |

**Table 64 Cost estimate enlarge current basins (x5) with the SSK-format.**