M. Sc. Thesis

# Improvement of the Flood Early Warning System for Valkenburg along the Geul River

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HKV LIJN IN WATER

# Improvement of the Flood Early Warning System for Valkenburg along the Geul River

by

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# Preface

This report concludes the three-year journey of my Master's in Science in hydraulic engineering. I am grateful for everything I have learned during this part of my education and my life and I am looking forward to the start of my professional career. I consider this project to be the most fitting conclusion to my time at TU Delft. As an international master's student, I partipicated in the Introduction Programme (IP) Week in 2019, during which several international students and I were grouped together. Each group was named after a city in the Netherlands. Mine was named *Valkenburg*.

The thank you's:

One million to my parents and brother, whose love and support were the main reason that starting and completing this huge milestone was possible to begin with. One million more to my grandparents, uncles, and aunts who provided me with the love, support, and vaccinations that I needed to get through this tumultuous era (both the Master's and the pandemic).

To Barry Bunin, for the life-changing conversation that inspired me to move to the Netherlands in pursuit of my master's in the first place. I'm looking forward to our next lunch.

To my advisors Prof. Dr. Ir. S. N. Jonkman, Ir. J. R. Moll, Ir. W. ter Horst and Dr. Ir. M. M. Rutten for guiding me throughout this whole process and fostering my growth as a student, researcher, and person.

To the people of HKV lijn in water BV for the opportunity to work on this project and for helping making it a success, especially Bas Kolen, Joost Driebergen, Geerten Horn, and Nicole Jungermann. Thank you also to Helena Pavelkova at the Waterboard for all the insight into Valkenburg that I lacked before this project. Hartelijk dank ook voor de kans om mijn Nederlands te verbeteren.
And to the friends I've made here during what can be considered the most insane time in all of our lives, who have effectively become my chosen family.

Hurricane Sandy hit New York in 2012. The experience changed my life forever, inspiring me to pursue a career in flood risk and protection. This lead me to the adventure of a lifetime in the Netherlands. Six months after I got here, the pandemic began, driving us all into the "uncertain times" that we'll likely never forget. Throughout this uncertainty, I successfully completed my classes in and out of lockdown, in different countries and time zones. I consider this to be no small feat, and the events have changed me as a person and shaped my life and outlook for the future forever. I am fortunate to have been able to complete my master's thesis — the magnum opus — with the option of in-person study at the HKV office in Delft, the TU Campus, and in the company of friends. I am looking forward to a lifetime of studying solutions to uncertainty of flooding.

*G. B. Godlewski*
*Delft, August 2022*

# Abstract


The combination of climate change and increased urbanization has resulted in cities with no historic flooding experience suddenly vulnerable to extreme flood events. Climate change increases the frequency and intensity of rainfalls, whereas urbanization decreases the total porous surface area, resulting in pluvial (rainwater) flooding. One such affected city is Valkenburg, located in South Limburg in the Netherlands. Valkenburg flooded on 14 July 2021 after experiencing an unusually heavy rainfall that deposited 146 mm of rain into the Geul Catchment, causing up to €600 million in damage. In such communities, flood early warning systems (FEWS) are emerging as possible non-structural solutions to minimizing costs of damage and loss of life from flooding. These systems are people-centered, end-to-end networks that predict floods before they are meant to occur to warn people living in vulnerable areas so that they can protect their homes, businesses, and themselves.

The FEWS network for the Geul uses forecasted precipitation data to predict discharge and water level conditions for the Geul. In the event that the predictions result in an abnormally high water level, warnings can be communicated to the necessary parties and to the population to allow for ample preparation. At the time of the July 2021 flood, the system was offline, with experts familiar with the network believing that it would not have worked even if it was online. This project aimed to analyze the existing FEWS from data collection to communication of warnings to locate existing issues and potential sources of weakness, thereby improving the system to effectively warn for future floods.

Each step of the FEWS was tested to find and strengthen potential weaknesses. The data inputs were analyzed and compared to the recorded precipitation that occurred in July 2021. Then, this data was inputted into the FEWS prediction models to understand how the system would have calculated the discharge and water level for that event. Both the July 2021 flood event as well as four non-flooding scenarios (summer storm, winter storm, dry season, wet season) were tested. The models were then used to create a flood map, and this flood map was inputted into the Damage and Casualties Model (SSM2017) to estimate how much in damage costs could be saved for the case with FEWS and the case without FEWS. Communication and evacuation were not extensively tested in this research project due to these components being determined by social and political frameworks.

When inputting the precipitation data associated with the July 2021 flood, it was found that the 1D model overestimated the water level to be 76.5 m+NAP, 6.5 m greater than the expected water level. Implementing a 2D grid reduced this value to 70 m+NAP, which matched the expected water level. It was also found that both HBV and SOBEK produce simulation results that consistently do not align with recorded data, suggesting a need to recalibrate the models to better reflect the behavior of the Geul River. Analyzing the recorded discharge and precipitation data found that using forecasted precipitation data gives Valkenburg enough time to communicate warnings and evacuate if necessary. Cost-benefit analysis that compared the economic impact of warning versus not warning revealed that warning and evacuation is more cost-effective than not not warning and evacuating, even in the case of a false alarm. An evacuation in the event of a false alarm can cost 1/10 of the difference in damage costs with and without evacuation. However, false alarms must still be avoided, as they erode trust in the warning system, thereby reducing its effectiveness in possible cost and loss of life reduction. Analysis of the expected costs of damage with and without the warning system revealed that the inclusion of the warning system has the potential to reduce the total expected damage by more than 50%.

The insights found in this project can be used to improve the FEWS for the Geul. Future research can be done to create a 2D or quasi-2D model that can predict the discharge and water levels of the Geul in a timely manner (no more than one-two hours' simulation time). The 2D aspect is important to a warning system as the expected amount of water affects how the community prepares for the disaster. This project can contribute not only to the improvement of the FEWS for the Geul but also for the improvement or creation of FEWS for other river catchments in newly vulnerable cities.

# Contents

# List of Figures

# List of Tables

# 1 Introduction

Climate change has increased the threat of flooding in communities around the world [1] [2] [3] [4]. Rising water levels in both the oceans and rivers have resulted in more flooding in residential areas close to these bodies of water. The trend is also affecting communities that are nowhere near bodies of water and never had a history of flooding before due to extreme precipitation. Due to rising temperatures, more evaporation occurs, leading to more moisture in the atmosphere [2]. This increase in moisture as well as the convection of warmer air currents results in more frequent and intense precipitation as well as slower-moving rain clouds that deposit more precipitation in one area [2] [3].

Not only has climate change impacted the frequency of flooding, but the increased urbanization of cities has reduced the absorption of excess precipitation [5]. As cities continue to grow, more buildings and roads cover porous soil and increase impervious cover. These impervious areas cause water from excess precipitation to pool, sometimes in amounts great enough to cause damage to said cities [6] [5]. Pluvial floods, or flooding from precipitation, have occurred in communities all over the world: China, England, the United States, Ghana, Australia, and even in the Netherlands [6].

Globally, the Netherlands is renown for its innovative and effective hydraulic structures. As the saying goes, "God created the world but the Dutch created the Netherlands" [7]. Despite the majority of the country being below sea level, the country does not flood due to the intricate flood protection systems in place. Not only is the country protected against storm surge from the ocean with dike rings and the Delta Works, but the areas inland near rivers are protected from river flooding through a water management plan known as Room for the River [7] [8]. Of course, the flood protection systems were not formed overnight, and many of the systems were not built until after storms devastated certain regions. Unfortunately, this is often the case: it is not until after disaster strikes that the demand for flood protection is created. The Netherlands has effectively protected itself from lateral flooding forces, but what can we do if a new threat comes from above?

In July 2021, an extreme precipitation event rained down on Germany, Belgium, and the Netherlands. The overland flow from the precipitation entered several river catchments in the area, including the Rhine, the Meuse, and the Geul, resulting in the water from these rivers overflowing the river banks and causing millions of euros in damage. Not only did Germany and Belgium suffer damage to infrastructure but hundreds of lives were also lost as a result of the intensity of the event [9]. The flooding in the Netherlands occurred along the Geul River and damaged many cities within the river valley. Among these cities was Valkenburg aan de Geul (hereonafter referred to simply as Valkenburg). While the Netherlands claims €350-600 million in damages [10], the city of Valkenburg alone experienced an estimated €200-250 million in damages, approximately half of that resulting from direct damages to homes and businesses [9]. Despite the damage, the Netherlands did not experience any casualties [9].

Given that the Netherlands already has many ways of combating flooding in residential areas, it is very possible to design and build a structure that protects Valkenburg against flooding. However, the many existing structural methods to protect a community against flooding are not only expensive but also take a lot of time to design and build. Meanwhile, the city remains unprotected and vulnerable to other flooding events during the design and building process. Non-structural solutions can assist such a vulnerable city to potentially reduce the intensity and costs of damage. A non-structural method is defined as a method or technique other than a physical structure that can effectively reduce flood risk or damage [11]. Several non-structural methods to protect against flooding can be implemented in a community that is new to the threat of flooding. Non-structural mitigation methods include governmental regulation of land use, land acquisition, or relocation to designate certain areas as floodplains and reduce human risk [11]. Governmental policies have a strong influence on the preparedness of an area, but creating these policies involves the cooperation of many parties that may be hindered by local politics. Flood-proofing of private properties can be done independently by homeowners to waterproof the structures of their homes or create a passageway through which water can safely pass [11], but the flood-proofing of most properties is up to the owner of said property. Furthermore, such a project can be costly, and the homeowner usually bears the burden of the entire expense.

A flood early warning system, hereinafter referred to as *FEWS*, is a type of non-structural flood mitigation method that has the potential to decrease damage due to flooding through the detection of threat and dissemination of information. FEWS are networks that convert available data into forecasts to predict potential natural disasters that may occur for the purpose of informing a community and giving them enough time to take action. According to the United Nations, an effective FEWS is ”end-to-end”, or completely functional from beginning to end, and ”people-centered,” or customized to the needs of the local populace [12]. Such FEWS networks prioritize the following [12]:

1. Knowledge of risk based on the systemic and effective collection of data and disaster risk assessment
2. Detection of hazards in the form of monitoring, analysis, and/or forecasting of hazards and possible consequences.
3. Communication by an official authoritative source in a timely and accurate manner on likelihood and impact and dissemination of information of associated information and actionable tasks on.
4. Preparedness of all involved programs and parties to act in the event of warning.

A FEWS network has already been designed for the Geul and is designed to predict the discharge and water level of the Geul River using local precipitation data. The current system used by the Limburg Waterboard uses water level and discharge models provided by Deltares to detect potential high-water events at various points along the Geul and its tributaries. At the time of the July 2021 flood, the system was offline due to maintenance work. However, it is believed by experts familiar with the system that it would not have been able to accurately predict the flooding that occurred [9]. This presents several interesting questions worth exploring. Is the belief of the experts plausible? How would the FEWS have behaved had the system been online at the time of the July 2021 flooding event?

The current workflow of the Geul FEWS is illustrated in Figure 1.1. The conceptual model of the FEWS for the Geul outlines the various components that make up the FEWS, starting from collection of data inputs to citizen action in response to warnings. First, the FEWS collects meteorological data pertaining to the precipitation and temperature of the area. The meteorological data is provided by third parties such as the Royal Dutch Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut, or KNMI). This information is then inputted into two forecasting models, the Hydrologiska Byråns Vattenbalansavdelning (HBV) model and the SOBEK model, which are calibrated to the geographic and topographic features of the Geul catchment. These models produce discharge and water level predictions, respectively, from the meteorological inputs. Not only can they be used to predict the flood risk of the area from a specific precipitation event, but they are also useful in understanding which areas in Valkenburg are more prone to flooding. If an extreme flooding event is detected, then an expert hydrologist at the Limburg Waterboard analyzes the data to determine whether the citizens should be warned. Having received a warning, citizens of Valkenburg can then take a course of action to protect themselves and their properties, potentially saving damage costs as well as their own lives.

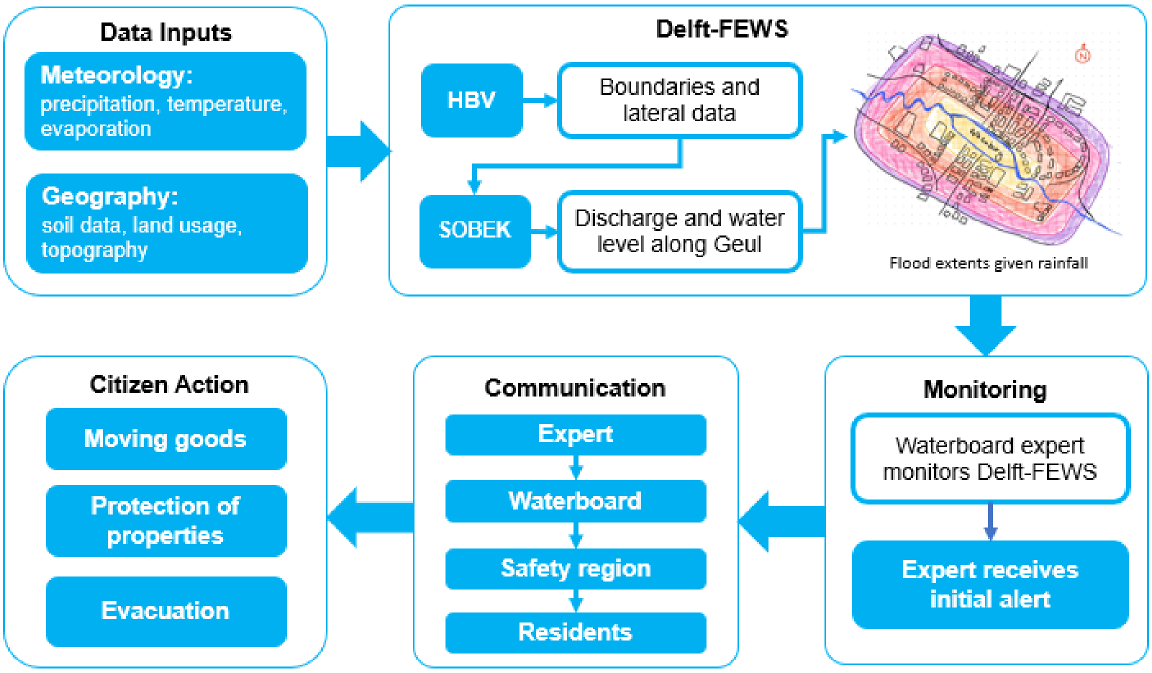



**Figure 1.1:** Conceptual model showing the workflow of the different components (data inputs, Delft-FEWS, monitoring, communication, citizen action) that make up the existing flood early warning system for the Geul River

## 1.1. Objective and Research Questions

The goal of this project is to investigate the potential of the existing FEWS system meant to assist the citizens of Valkenburg against damages from flooding. This is done through the analysis of each section of the Geul FEWS illustrated in Figure **??** with the intention of understanding how each of the individual sections are designed to work, where potential weaknesses may lie, and how the system can be improved to effectively warn the citizens of Valkenburg about potentially deadly high-water events.

The main research question is:

**How can the flood early warning system (FEWS) designed for the Geul River be assessed and improved based on the UNDRR criteria for an effective warning system?**

The sub-questions to support the answering of the main research question are listed below.

1. What data inputs and boundary conditions are needed to recreate the events of the July 2021 flood in Valkenburg?
2. How does the FEWS react to the following rainfall test cases: summer storm, winter storm, rain after a dry season, and rain after a wet season?
3. What information is necessary for a monitor to trigger a warning to give residents in Valkenburg enough time to evacuate?
4. Under which circumstances is warning and evacuation cost-effective?

## 1.2. Research Methods

The research for this project was conducted by going through the existing FEWS illustrated in Figure 1.1 and analyzing the five different components: data inputs, Delft-FEWS, monitoring, communication, and citizen action. Each component of the FEWS involves different research parameters, limitations, and goals, prompting different research methods to be used to answer each research question. The method and limitations for each of the listed research subquestions are discussed in this section. This section elaborates upon how each research question will be answered and within which chapters the methodology and results for each question can be found.

***What data inputs and boundary conditions are needed to recreate the events of the July 2021 flood in Valkenburg?***

In Chapter 3, the modelling components of the FEWS will be run to simulate the July 2021 event and adjustments will be made to correct any errors in the results. First, precipitation data pertaining to the July 2021 event will be compared to the recorded precipitation data to ensure that the data inputs accurately reflected the July 2021 precipitation event. This data will then be inputted into the existing HBV and SOBEK models within the Delft-FEWS to simulate the July 2021 event. The results of the simulations will be compared to the observed discharge and water level data recorded after the event. Adjustments will be made to the system where necessary to return data that more accurately reflected the recorded discharge and water level data from the event [9] [13]. The data inputs as well as any adjustments made to the system are the answer to research question 1. The methodology, results, and discussion are detailed in Chapter 3.

***How does the FEWS react to the following rainfall test cases: summer storm, winter storm, rain after a dry season, and rain after a wet season?***

The models with Delft-FEWS are again tested, this time under non-flooding circumstances, to analyze how accurately the FEWS models the behavior of the Geul. Four precipitation events will be chosen to study the effect of soil moisture and the effect of temperature and evaporation on the results. The effect of soil moisture will be tested by comparing the discharge and water level results between a simulation using high-frequency precipitation data and a simulation of a precipitation event after a dry season. The effect of temperature and evaporation will be tested through the comparison of the results for a precipitation event during the winter, when temperature and evaporation are low, and the summer, when temperature and evaporation are high. The results will then be compared to recorded data wherever the recorded data is available, and recommendations will be made to improve the models as necessary. The methodology, results, and discussion can be found in Chapter 4.

***What information is necessary for a monitor to trigger a warning to give residents in Valkenburg enough time to evacuate?***

To answer research question 3, two different data sources that can possibly be used for a river FEWS will be analyzed to determine which source can provide information in a timely manner to deliver a warning and allow for safe evacuation before a flood occurs in Valkenburg. The two data sources are discharge and precipitation. Historic real-time data available within the Delft-FEWS for both discharge and precipitation will be analyzed to determine the lead time between the start of the high precipitation and discharge events and the time when the flood wave reaches Valkenburg. This time difference will then be compared to the lead time necessary for safe evacuation in Valkenburg, which is determined to be 1.5 - 2.5 days. This comparison determines which of the two data sources is more suitable for monitoring to safely warn the people of Valkenburg. If neither of these options are suitable, then forecasting options are explored. The methodology, results, and discussion is found in Chapter 5.

***Under which circumstances is warning and evacuation cost-effective?***

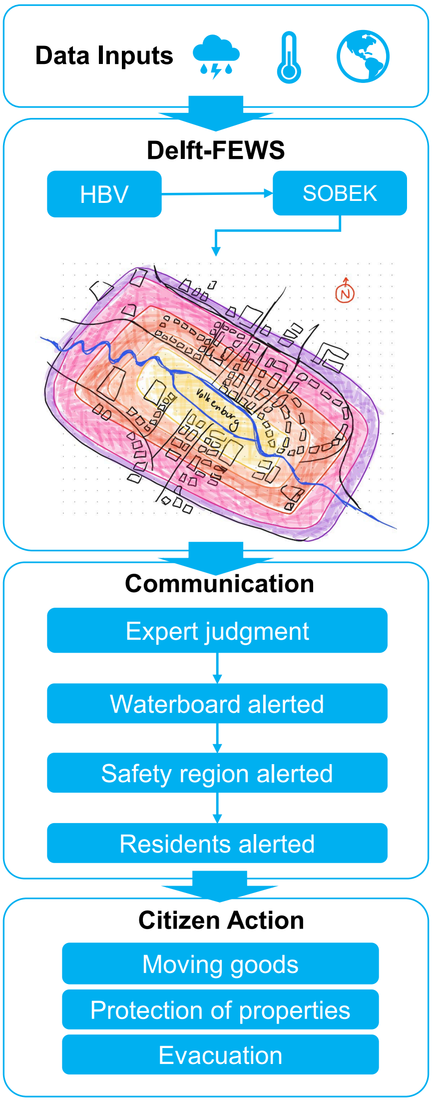
To answer this question, two cost-benefit analyses will be conducted. The first cost-benefit analysis will be conducted for a hypothetical flood warning scenario that represents a situation where an extreme event has a small probability of occurring. The cost-benefit analysis determines whether warning the population under uncertain circumstances is economically justifiable. A second cost-benefit analysis will compare the overall cost of the investments into the warning system and evacuation to the possible reduction in damage costs over the operational lifetime of the FEWS. For both cost-benefit analyses, seven flood-causing precipitation scenarios of varying intensity will be modelled using the HBV and SOBEK programs tested from Chapters 3 to 5. These seven scenarios are based on statistics for four-day precipitation events, and the following scenarios will be simulated: one-year, five-year, ten-year, twenty-five-year, fifty-year, hundred-year, and thousand-year precipitation events. Seven precipitation data files will be created to represent each scenario and each will be inputted into the monitoring models to simulate corresponding floods. The results will be compiled to create a flood risk map for Valkenburg. The modelling of the seven flood scenarios and final risk map as well as a discussion can be found in Chapter 6. Costs of damage with and without FEWS will be calculated for each of the seven scenarios using the Schade Slachtoffer Model (SSM2017). The costs of evacuation and investment into FEWS, which will be estimated through discussion with experts and through literature, will also be calculated for each of the scenarios. The damage costs with and without FEWS will be inputted into both cost-benefit analyses to draw conclusions about the economic benefit of having a working FEWS. The cost-benefit analyses, results, and discussions can be found in Chapter 7.

## 1.3. Limitations

The precipitation and discharge data used in this research project is limited to the available forecasted and recorded precipitation and discharge data already available within Delft-FEWS. Historic precipitation data is available from a date range from 2019 - 2021, limiting all simulations involving precipitation to this time frame. Historic water level data was also used in the comparison of simulated water level data, ranging approximately over the same time frame. However, there are many gaps in the water level data. All historic data is limited to data collected within the Netherlands. Germany and Belgium collect precipitation and discharge data, but this data is not immediately available within the Delft-FEWS interface. Although this data may be accessible through other sources, the main purpose of this research is to examine the capabilities of the FEWS as it currently exists, so using German and Belgian data is outside the scope of this research.

While there are many different programs that are capable of modelling discharge and water level, only HBV and SOBEK are tested in this research. The programs are already available within Delft-FEWS and programmed to receive precipitation data and communicate information from one program to another. Programs such as wflow and D-HYDRO are potential modelling alternatives for discharge. However, the scope of this project is improving what is already available in the system. The limits on data collection and programming affect the methodology and results for research questions 1, 2, and 3.

The calculation of the cost-benefit analysis in research question 4 for warning of a singular potential extreme event is limited to deterministic cost calculations. The cost-benefit analyses use cost calculations based on seven precise precipitation and flooding scenarios, while real-life flooding situations are likely to deviate from the exact precipitation amounts and flood extents reflected in the simulations. The scenarios that are examined in the cost-benefit analysis also assume a fixed cost without evacuation and with evacuation, while costs in practice are more variable as they are dependent on numerous factors. The cost-benefit analyses used in this study also assume precise probabilities for each extreme event scenario, which is also not realistic in warning system monitoring. For both damage costs, the values are based around the results of the SSM2017 model and adjusted based on indirect damage costs, the costs of moveable goods, and the economic valuation of loss of life. The calculated costs of damage likely exclude certain costs that are considered in actual flooding situations. The costs of damage with FEWS and evacuation are also very optimistic, calculating a scenario where every moveable good is moved and every person safely and successfully evacuates.




Start

1 Chapter 1 contains the problem definition and framework of the research.

2 Chapter 2 provides the background information for why this research is needed.

3 Chapter 3 describes the data inputs needed to successfully create a simulation in Delft-FEWS and describes the step-by-step process of simulating the July 2021 flooding event, answering the first research question. Recommendations are made for the improvements of the models where necessary.

4 Chapter 4 describes more simulations conducted to model the reaction of the Geul catchment to different meteorological conditions, answering the second research question. Recommendations are made for the improvement of the models where necessary.

5 Chapter 5 analyzes the different possible data inputs that could be used to see which allow for optimum time for communication and, if necessary, evacuation. The third research question is answered. Recommendations are made for the chain of communication as well as what to consider regarding the issuing of a warning.

6 Chapter 6 shows the usage of HBV and SOBEK simulations to create a flood extent map for Valkenburg to better understand flooding patterns and potential scenarios in the area to answer research question 4. Recommendations are made for future research to optimize the accuracy of the flood map.

7 Chapter 7 contains a cost-benefit analysis done to assess the potential economic impact of FEWS and evacuation on Valkenburg. Both a case study of an uncertain warning with a chance at a huge flood and the comparison of the costs and benefits of investment in the FEWS are explored, answering the fourth research question.

8 Chapter 8 contains conclusions of the report and answers to the research questions.

End

# 2 Background

This chapter contains the background information of the research, contextualizing why this research is needed. This background information includes the effect of climate change on pluvial flooding, the circumstances that lead to the July 2021 flooding event, the aftermath of the flood, and current flood early warning systems including the system for the Geul. The monitoring technology, communication systems, and evacuation methods related to this warning system are explained, setting up the background of the components of the warning system that are studied in this project.

## 2.1. Valkenburg and the Geul Catchment

The Geul catchment is located within South Limburg and spans an area of approximately 380 km$^2$. The Geul River flows for approximately 58 km starting in Belgium and ending at the Meuse River north of Maastricht (see map in Figure 2.1). Approximately 25 km of the river is located in the Netherlands. The three main tributaries that flow into the Geul are the Gulp, Selzerbeek, and Eyserbeek.

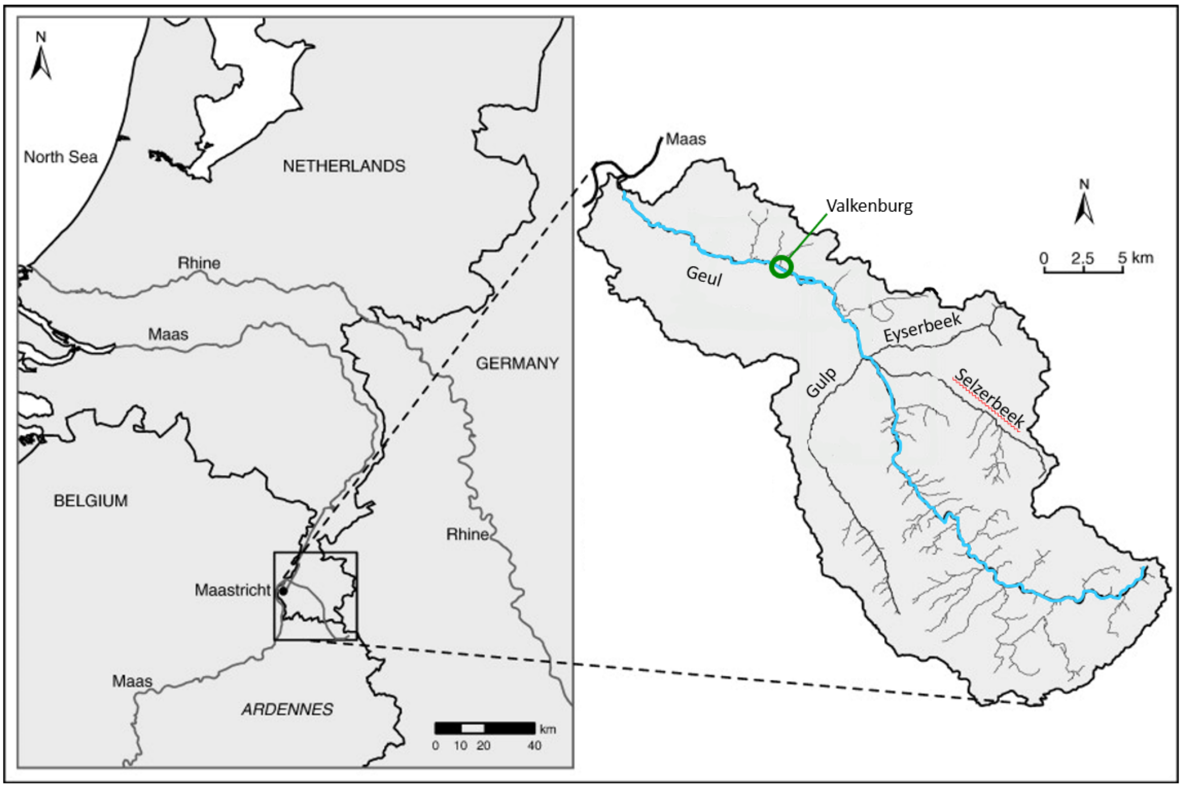



**Figure 2.1:** Map of the Geul catchment in the Netherlands and Belgium [4]

The city of Valkenburg is located in South Limburg within the Geul Valley approximately 10 km from the Meuse (see Figure 2.1). The part of the city known as Old Valkenburg that has many historic buildings and central shops is built right on the banks of the Geul River. When Valkenburg was built around the 14th century, the city was not built to prevent flooding as it was not an issue at the time [9]. Now with increased threats due to climate change, the location right next to the river within a valley is not ideal given that the local topography increases the likelihood for rainfall runoff pooling in the city, as evident in Figure 2.2 [14]. The current city planning of Valkenburg makes adapting the city to the Room for the River program a particular challenge. Many buildings along the Geul are built right at the edge of the riverbank, presenting two problems. The first is that these buildings are very old and cannot be moved away from the riverbank, preventing the floodplains from being increased. Furthermore, many of those buildings are historic landmarks, such as the Geulpoort, which was a medieval city gate and is currently a major tourist attraction. The preservation of these buildings is a priority for Valkenburg as tourism is one of the most lucrative industries of the area. Secondly, given that these buildings are built right along the river, there is little room for dike walls to be built without presenting an inconvenience to property owners.

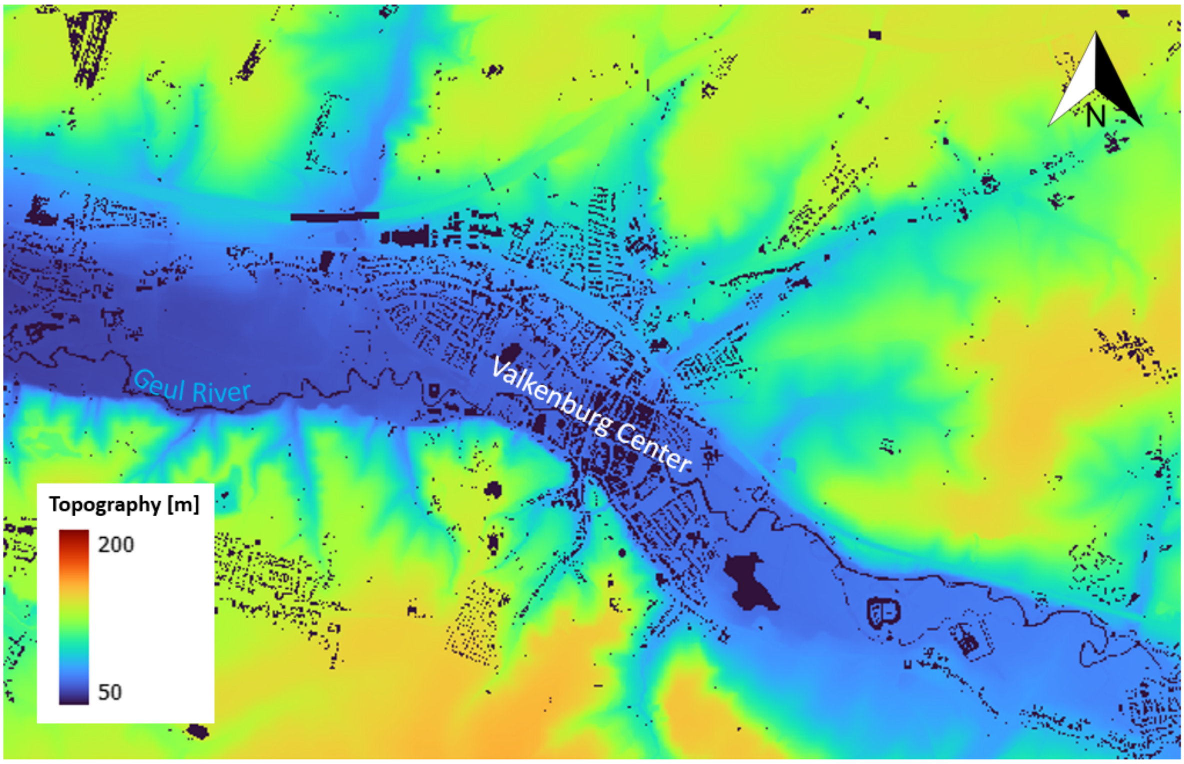



**Figure 2.2:** Topographic map showing the elevation of Valkenburg within the Geul Valley

The soil found in the Geul Valley consists predominantly of loess (or *löss*). Loess is a type of loosely-compacted soil consisting mostly of silt-like particles [15]. This soil experiences different levels of infiltration depending on the soil saturation. One experiment determining the rain infiltration of loess samples discovered infiltration rates of around 40 mm/h for unsaturated soil, which was reduced to 5 mm/h when the soil was saturated [16]. However, loess often experiences a crusting phenomenon that results in lowered rain infiltration during higher rainfall intensities [16].

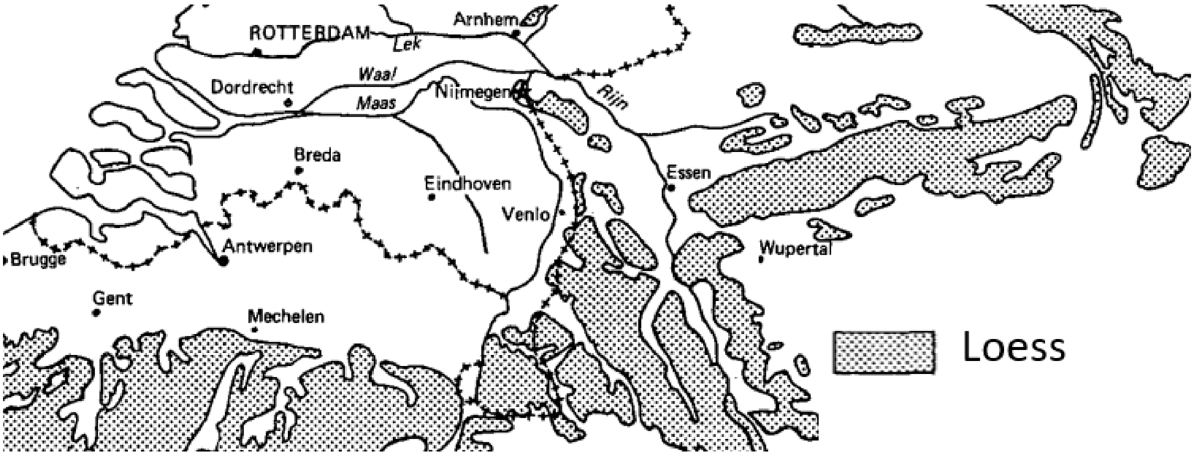



**Figure 2.3:** Loess distribution along the south of the Netherlands as well as through Belgium and Germany [17]. The Loess deposits cover most of the area of Limburg, including the area around the Geul River

## 2.2. Flooding in the Netherlands and Room for the River

The Netherlands is renown for its defenses against both coastal and fluvial (river) flooding. For most of its history, the Netherlands experienced devastating floods due to the activity of the North Sea and the low elevation of the country. Over the centuries, dikes against sea flooding were built to protect the country against these floods. Following the Great Flood of 1953, the Deltaworks were built, consisting of three locks, five storm-surge barriers, and six dams were built. This large-scale hydraulic engineering protect continues to protect the Netherlands from coastal flooding to this day [18].

Locations more inland in the Netherlands away from the coast also experience flood as a result of the proximity to the rivers. Many rivers and canals flow throughout the Netherlands, with some examples of major rivers including the Waal, Meuse, Rhine, and Geul. Two major flooding events in the winters of 1993 and 1995 occurred after exceptionally large amounts of discharge entered the Meuse, where no dikes were present [19]. The frequency and intensity of river flooding in the Netherlands is expected to increase due to a decrease of floodplains and an increase in the effects of climate change. Floodplains in the Netherlands are decreasing for two main reasons. The first comes as a result of river flooding. When a river floods, it deposits sediment before retreating back into the river banks. Over time, this deposited sediment reduces the floodplain area [14]. Climate change is also an influencing factor, as rising temperatures contribute to more moisture in the air, and therefore contributes to precipitation events with a higher intensity and amount of rainfall [20], [21], [22]. Increased urbanization and higher amounts of rainfall contribute to the problem together. When there is more water entering the system from precipitation and more impervious surface area from paved roads and buildings, more runoff flows into rivers, contributing to more frequent and intense river flooding [14].

The Room for the River project in the Netherlands is a hydraulic engineering and water management project focused on reducing the water levels in rivers by means of increasing floodplains and building more dikes along the river [14]. Increasing the floodplains can be done by reducing the surface elevation of the floodplains or removing any obstacles in the area that prevent river flow. The river flow can also be manipulated through the construction of higher dikes, water reservoirs, or bypasses. These measures can be schematized in Figure 2.4. Physical construction projects are effective at physically preventing water from entering an area, therefore preventing physical damage from floods. However, these construction projects take a long time to design, approve, and build, and during these phases the area continues to be vulnerable. It is possible to protect such areas through non-structural flood mitigation techniques while physical structures are being built. The non-structural techniques can be used separately or in tandem with the physical structures. These techniques are created through policy and management techniques, include land acquisition, land use regulations, flood emergency preparedness plans, and flood early warning systems [11].

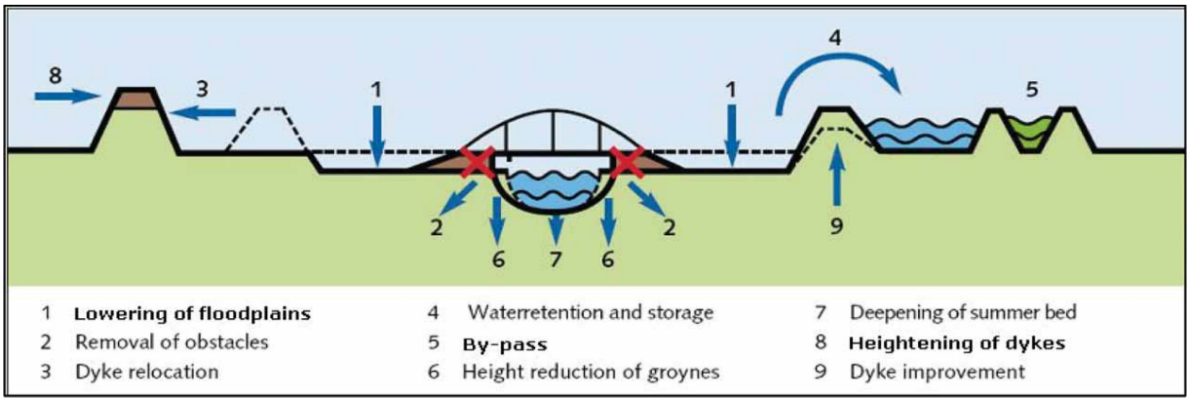



**Figure 2.4:** Various structural methods currently in use to protect riverside communities in the Room for the River Program [14]

## 2.3. The July 2021 Event in Valkenburg

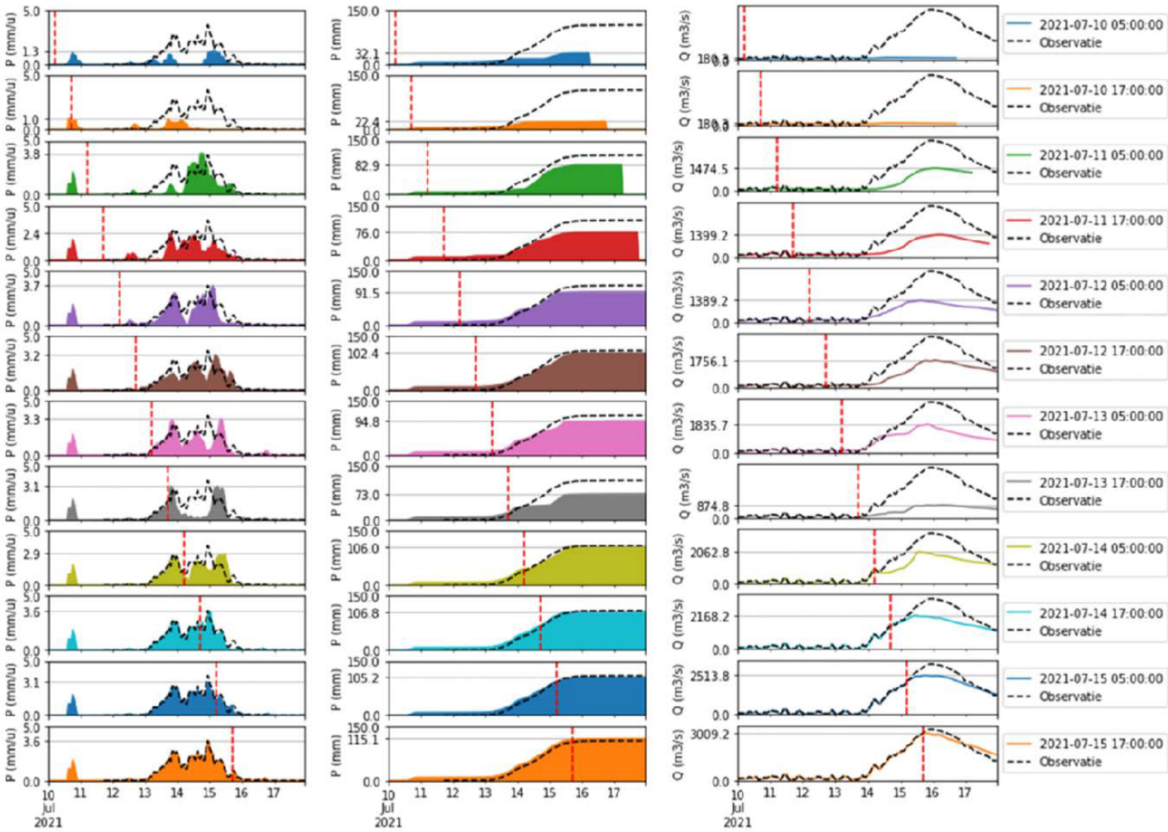



**Figure 2.5:** Precipitation and forecast predictions for the Meuse Catchment for each hour staring on 10 July 2021, three days before precipitation began. Left: Precipitation forecast in mm/hr. Middle: Precipitation forecast in cumulative mm. Right: Discharge forecast at the Meuse River. The precipitation forecasts were made using RWSoS and COSMO-EU forecasting systems and the discharge predictions were made using Delft-FEWS [9]

On 13 July 2021, a rainfall began that continued for more than three days. A majority of the precipitation was deposited over Belgium and Germany. In the Netherlands, the most precipitation fell over Eyserbeek in the southeast part of Limburg (see Figure 2.6). This area experienced a total of approximately 158 mm of precipitation [9]. As a result of this extreme precipitation, a flood in Valkenburg occurred at approximately 23:00 on 14 July 2021, less than two days after the rainfall began. The flood reached an extent shown in Figure 2.7 and caused an estimated €350-600 million in damage [9]. Half of this amount is estimated to be due to indirect damages of business closure and residential displacement

[23]. Evacuation occurred in the Netherlands during the July 2021 event, but not along the Geul River or in Valkenburg. People along the Rhine and the Meuse were given notice to evacuate a few days in advance. The only people in Valkenburg to evacuate were 193 residents within senior homes who did so voluntarily upon witnessing the rising water [9]

Predictive technology was available at the time of the July 2021 flood. Rainfall was first detected on 10 July using other predictive technology programs including RWsOS and COSMO-EU [24]. However, it wasn't until 11 July when the system detected a possible extreme rainfall event. This changed when a potentially extreme rainfall was detected on July 11, two days in advance of the actual rainfall and three days in advance of the flood in Valkenburg [9]. The amount of simulated rainfall continued to vary in intensity until 13 July, when the precipitation actually fell. Although a rainfall was detected, a high discharge was also simulated using the existing Delft-FEWS program, but the initial simulated discharge was only half that of the actual discharge that flowed through the river. The discharge simulation did not predict a high discharge result until the precipitation began, one day before the flood water reached Valkenburg [9]. The forecasted precipitation and discharge of the Geul River is shown in Figure 2.5.

Although the forecasting programs successfully predicted a potential extreme rainfall scenario, observation data did not. At the time of the rainfall, the real-time precipitation recording missed the storm entirely, and the early reanalysis underestimated the total rainfall by a factor of three [9]. This is attributed to the lack of sufficient precipitation radar stations in the area. Given this issue, experts at KNMI are currently working to improve the detection technology of the radar stations to more accurately record precipitation conditions in the area.

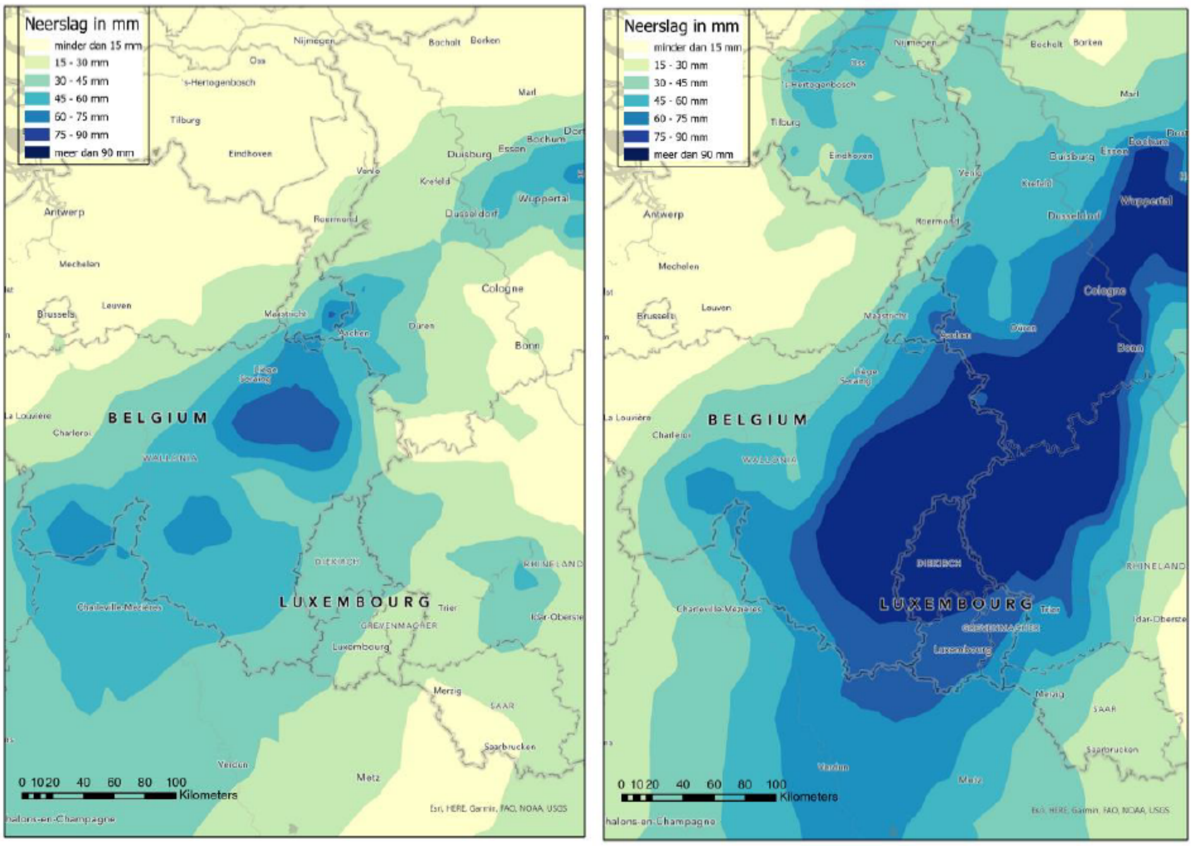



**Figure 2.6:** Precipitation event in Netherlands, Belgium, and Germany for 13 and 14 July [9].

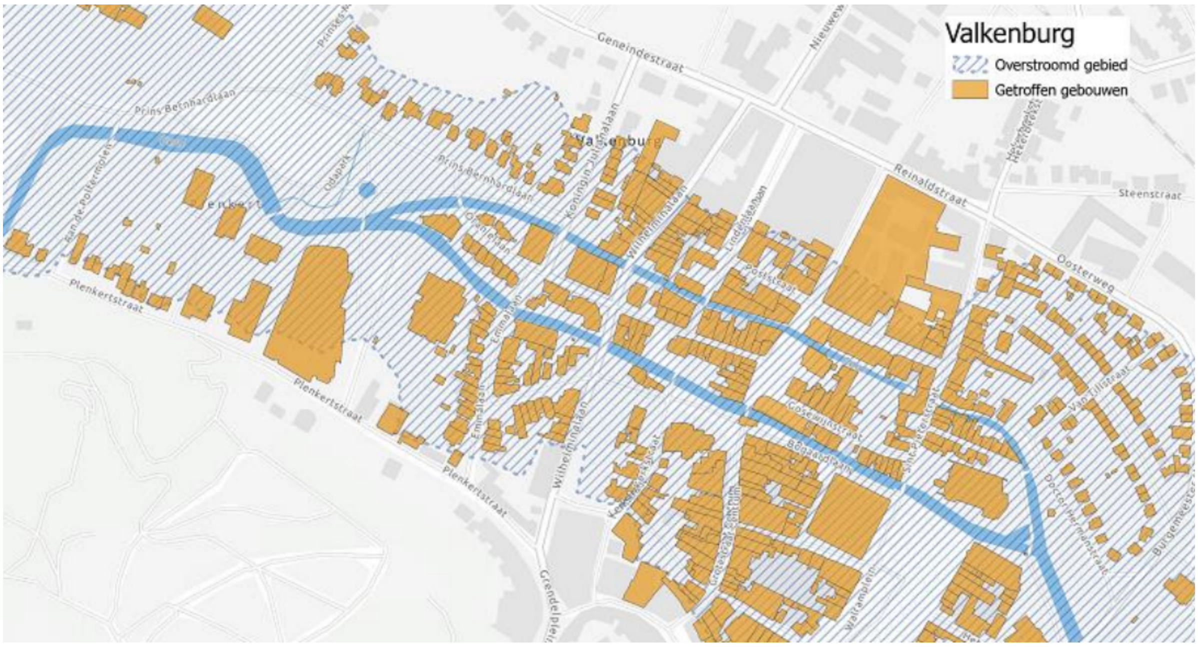


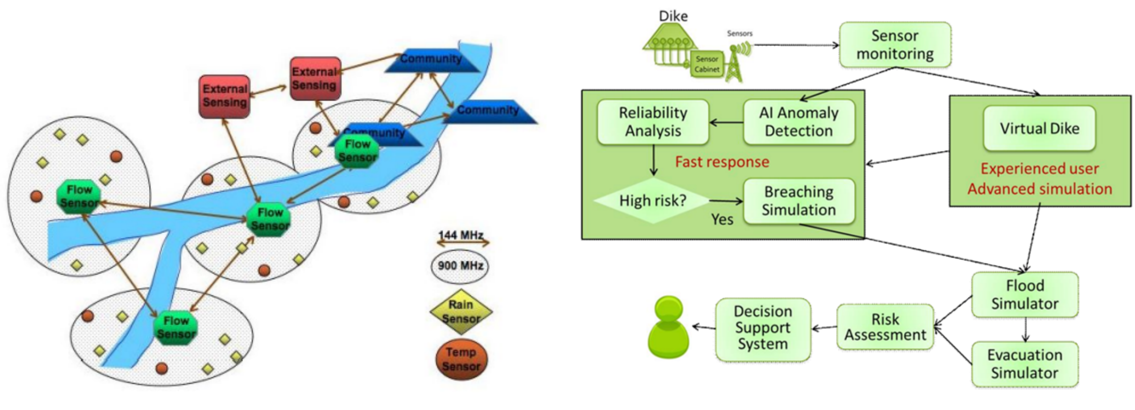

**Figure 2.7:** Observed flood extents during the July 2021 flood in Valkenburg. The buildings affected by the flood are highlighted in orange. [9]

## 2.4. Existing Flood Early Warning Systems

The UNDRR (United Nations Office for Disaster Risk Reduction) has defined an early warning system as a system that integrates hazard monitoring, forecasting and prediction of relevant conditions, risk assessment using the forecasts, and communication of results. A working early warning system would enable various stakeholders — local residents, communities, businesses, governments — to take timely action in the event of a potential natural disaster [25].

In order to classify an effective warning system, the UNDRR has defined four ”interrelated key elements” necessary for effective end-to-end and people-centered warning systems: knowledge, monitoring, communication, and preparedness [25] **UNDRR2017UNISDR2016-2021**. Knowledge refers to the collection of data necessary to quantify the disaster risk assessment. Monitoring refers to the process of detecting, analyzing, and forecasting the hazards and possible consequences. Communication refers to the dissemination of the information resulting from the monitoring process, usually from an authoritative figure. This communication must be timely, accurate, and actionable, and the consequences must be clearly communicated. Finally, preparedness refers to the response ability of every part of the system, from the accuracy of the data collection to the willingness of the stakeholders being warned to respond to the advice [25].

Early warning systems (EWS) exist throughout the world and can be designed to protect communities against different types of natural disasters. Warning systems made specifically for floods are known as flood early warning systems (hereonafter referred to as *FEWS*). Several FEWS exist throughout the world, and each is designed specific to the area, including unique features such as: the type of data that is available, the kind of flood threat that puts the area at risk (coastal, fluvial, pluvial), and the needs of the local stakeholders. One such FEWS that illustrates the framework for knowledge collection, monitoring, and communication is located in Honduras by a river that experiences floods due to heavy rainfall from hurricanes [26]. This FEWS uses local rainwater and temperature sensors to collect knowledge and monitors the flow that would theoretically result from the meteorological conditions. These sensors transfer data to local monitoring stations, where experts determine whether the conditions are extreme enough to warn local communities [26].




**(a)** Honduras FEWS

**(b)** UrbanFlood FEWS in England

**Figure 2.8:** Conceptual models of FEWS examples in Honduras and England

Of the examples presented in this report, the most complex FEWS is known as UrbanFlood, which is implemented in the Netherlands and the United Kingdom. UrbanFlood is designed for areas that are within dike rings and is a good example of how a FEWS can work to protect communities in tandem with structural interventions. This system uses a computational module that simulated a virtual dike for its monitoring component. [21]. Precipitation data is collected from meteorological sensors and converts them into load combinations that act on a virtual AI dike to monitor the risk. If the AI dike collapses (breaching simulation), then a flood in the area is simulated along with an evacuation route. The risk is then assessed and potential hazards are communicated to the relevant stakeholders [21]. The conceptual models for both the FEWS examples is seen in Figure 2.8.

## 2.5. The Flood Early Warning System for the Geul River

### 2.5.1. The Delft-FEWS Interface

The Delft-FEWS interface (hereonafter referred to as *Delft-FEWS*, which refers to the modelling interface rather than the entire flood early warning system *FEWS*) was developed in 2002/2003 by Deltares as a way to create a framework system that offers flexibility in terms of what data inputs and models are used. This flexibility allows unique FEWS networks to be created in different locations and be customized to the location based on the available data, programs, and needs of the area [27] [28].

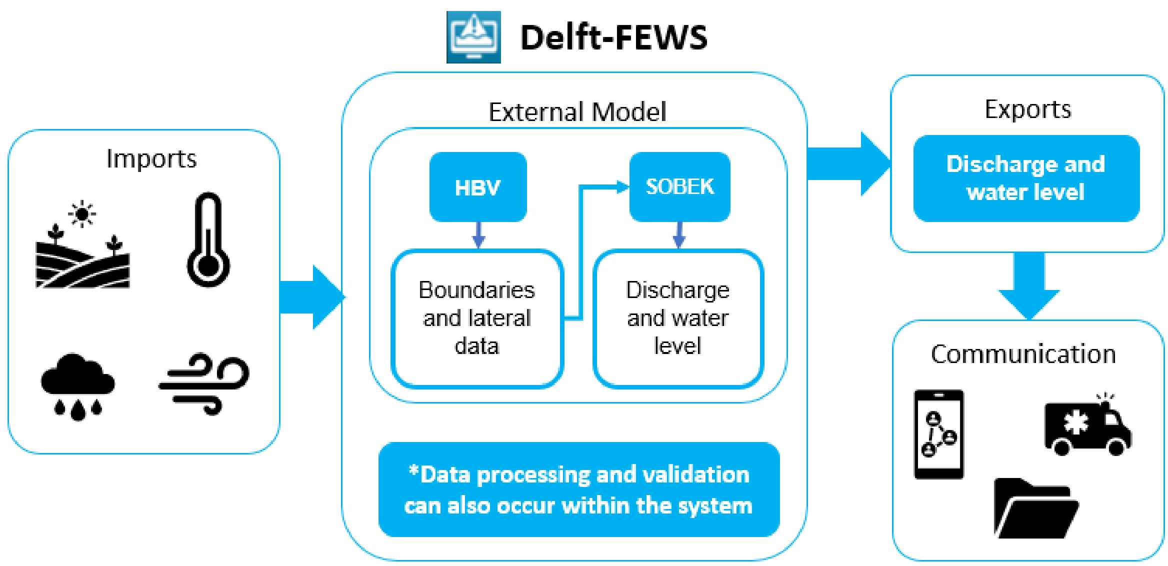



**Figure 2.9:** The conceptual model of Delft-FEWS for the Geul [27] [28].

In the complete FEWS network for the Geul, Delft-FEWS functions as part of the knowledge, monitoring, and communications components (see Figure 1.1) **UNDRR2017UNISDR2016-2021**. The interface receives knowledge from available forecasting technology and processes this data in the best-suited program used for modelling. The programs are chosen based on which models are available and which program best suits the needs of the area, such as HEC-RAS, D-HYDRO, HBV, and SOBEK [27]. The results of the programs are then disseminated using a method determined by the user. Individuals, whether experts or civilians, can get alerts based on results and parameters set by the programmer of the FEWS. The conceptual model of Delft-FEWS for the Geul is shown in Figure 2.9.

The current FEWS for the Geul River uses the Delft-FEWS system as a way to process the gathered meteorological data and to host the models used to predict the behavior of the Geul River. Meteorological data (knowledge) comes from several sources. Real-time and historical meteorological data - including precipitation, temperature, and evaporation - is collected by Weather Information Water Management (WIWB) radar stations [27]. The Ensemble Prediction System (EPS) Harmonie component developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) uses historical and real-time meteorological data to predict the conditions two days in advance. LMW-Matroos, developed by KNMI, predicts meteorological conditions two weeks in advance. Both historical and forecasted rain data occurs independently of the Delft-FEWS and is downloaded into the system to be used in forecasting [27].

The downloaded data is then inputted into HBV, which calculates the total discharge in the river system through individual lateral points. The HBV results are inputted into SOBEK-Rural, which calculates the discharge at one location over time as well as the water level. Delft-FEWS also has the potential to directly warn residents and emergency services. For the Geul FEWS, a hydrologist monitors the system and decides whether or not to trigger communications with the rest of the Waterboard, which then warns the appropriate emergency services. The data recorded by Delft-FEWS is saved as historic data to continue to improve the system [27].

### 2.5.2. Meteorological Data Products for Delft-FEWS

The Geul Catchment experiences increased discharge and flooding of the system when a large amount of precipitation falls into the area [4]. The validity of the discharge and water level predictions depends on the validity of the meteorological data. The Delft-FEWS system gets rainfall data from KNMI pluviographs that are located across the Netherlands. The stations located in Limburg and collect rainwater data that can be used to predict events for Valkenburg include Stein, Schimmert-Spaubeek, Kaffeberg, Ransdaal, Maastricht, Noorbeek and Vaals. These pluviographs, shown in Figure 2.10, collect the approximate precipitation at that point and serve as an indirect way to measure the rainfall entering the area.

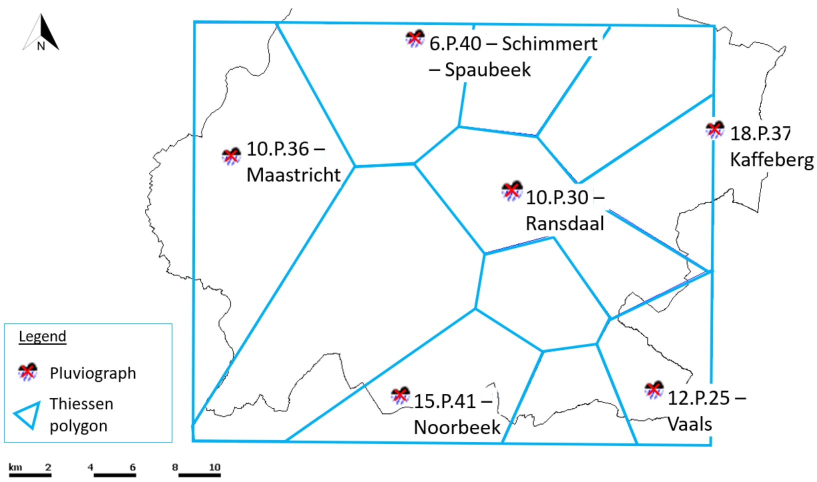



**Figure 2.10:** KNMI pluviographs in Limburg with Thiessen polygons shown in blue

Precipitation data is mercurial, meaning that even the slightest changes in the atmosphere can result in different behavior of the precipitation [29]. The recorded precipitation data often undergoes reanalysis conducted by KNMI via the International Radar Composite (IRC) product. The IRC provides near-realtime, early reanalysis, and final reanalysis precipitation data, which the Delft-FEWS interface can download via the WIWB [27]. The use of each product presents a trade-off between timeliness and accuracy, both of which are valuable in the design of a warning system. While real-time data is effectively available immediately, it is not always accurate. Better accuracy is present in the early and final reanalyses, both of which are available and viewable within the Delft-FEWS interface. The rain data available in Delft-FEWS through the real-time rain station collection shows several small rainfalls (0.1 - 1 mm per time step) for a duration of 5 minutes each. The final reanalysis for the same day shows an increase in the rainfall duration - up to one hour [27]. More accurate information is usually not available immediately, presenting a trade-off between timeliness and accuracy. The early reanalysis can be provided within 24-48 hours after the event, while the final reanalysis may take up to thirty days before the data is available [27].

Delft-FEWS calculates hindcasts, or discharge and water level projections of past scenarios in the Geul River using observed historical data confirmed through final reanalyses. Using different predictive programs, Delft-FEWS also predicts potential precipitation scenarios and create discharge and water level projections from this predicted data. The program has the option to take data from a wide variety of different rain data networks that use their own data processing technology. Using the available historical data, the LMW-Matroos and EUMETSAT polar system (EPS) programs create predictions up to two weeks in advance [27]. The Matroos program inputs data from the Landelijk Meetnet Water (LMW) data collection and creates meteorological forecasts up to two days in advance. Meanwhile, the EUMETSAT polar system (EPS) uses historical data to create forecasts from 10 to 15 days in advance [27]. The Delft-FEWS program created for the Geul catchment uses available historical data, LMW-Matroos, and Harmonie to create rainfall predictions. Temperature and evaporation conditions are also predicted through data collected from the EPS and Meteobase [27]. The water level where the Geul meets the Meuse also has a boundary condition, which is the recorded water level of the Meuse river at that point. The meteorological data sources and boundary conditions are summarized in Table 2.1.

| Data | Type | Source |
|---|---|---|
| Historic precipitation data | Measurement | Weather Information Water Management (WIWB) Database |
| Real-time precipitation | Measurement | KNMI radar meteo stations |
| Early reanalysis precipitation data | Measurement | KNMI international radar composite |
| Final reanalysis precipitation data | Measurement | KNMI international radar composite |
| Temperature | Forecast | EURMETSAT Polar System (EPS) |
| Evaporation | Forecast | KNMI radar meteo stations |
| Maas water level | Boundary condition | Water level stations |

**Table 2.1:** Meteorological data sources and boundary conditions inputted into HBV

### 2.5.3. The HBV Model

The Hydrologiska Byråns Vattenbalansavdelning (HBV) model is a hydrological transport model developed by the Swedish Meteorological and Hydrological Institute to measure the river discharge and pollution in river systems in Scandinavia. Within the Geul FEWS, it functions as the model that converts rainfall to runoff discharge. The first runoff calculation for this model was completed in 1973. Since then, the model has been applied to various catchments around the world for different purposes. The model has three main subroutine components: snow accumulation and melt, soil moisture accounting, and response and river routing [30]. Calibration of the model using soil and evapotranspiration data is necessary for the program to be used for a specific area [30].

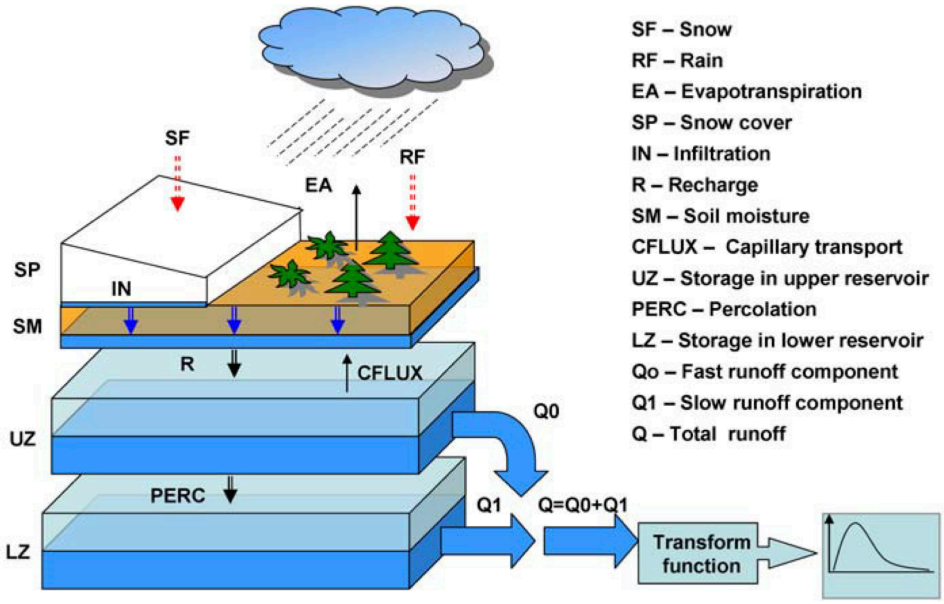



**Figure 2.11:** The conceptual model of HBV in Delft-FEWS showing the sources of the discharge that are used to compute the final discharge of the river [31].

HBV conducts its subroutine calculations using meteorological data inputted into the system. HBV sorts the inputted precipitation data into catchments inputted into the system using the method of Thiessen polygons. This method assigns areal significance to point rainfall values through polygons denoting a specific area. For the Geul FEWS, the point rainfalls are measured at the KNMI pluviographs. The rain that falls within these polygons is sorted into the precipitation calculation point associated with said polygon [30]. Figure 2.10 shows the pluviographs that measure the point rainfalls within Limburg as well as the Thiessen polygons in blue.

Based on soil data inputted into the HBV model, the model calculations the amount of soil infiltration given the entry of water into the system (from precipitation, snow melt, and many others). This runoff is then sorted into an upper reservoir for fast runoff and the lower reservoir for the slow runoff components. Together, the fast and slow runoff components are summed up to return the total runoff in an area given the initial inputs. This process is illustrated in the conceptual model of the program shown in Figure 2.11.

The HBV model programmed to represent the Geul River catchment is designed to calculate runoff primarily from precipitation events. The outputs of the Geul River HBV model are discharge amounts at boundary and lateral points. The current model used in Delft-FEWS was calibrated in 2014 [27]. To create data used for the modelling of the discharge and water level, the Delft-FEWS model for the Geul uses the HBV model to convert precipitation data into discharge conditions at the boundaries of the rivers as well as lateral discharges experienced at various virtual points throughout the Geul River, which are highlighted in Figure 2.12. Using the rain data from KNMI and the temperature and evaporation conditions in the atmosphere, the HBV model interpolates the precipitation data for each location into precipitation specific to the six catchments along the Geul River: Azijnfabriek, Eys, Hommerich, Meersen, Partij, and Sippenaeken (as seen in Figure 2.12).

The HBV model contains data regarding the type of soil present in the area. Conversations with experts at HKV and the Limburg Waterboard revealed behavior patterns of this soil and the assumptions made to reflect this in modelling. It is known that the soil in the area consists mostly of loess, which can experience a crusting effect and cause more runoff than infiltration. However, infiltration still occurs in this soil [17]. The HBV model assumes no infiltration at all due to the crusting effect on purpose. This assumption results in an overestimation of discharge, but the decision was made so that the HBV discharge results would reflect the worst-case scenario to assist in decision-making.

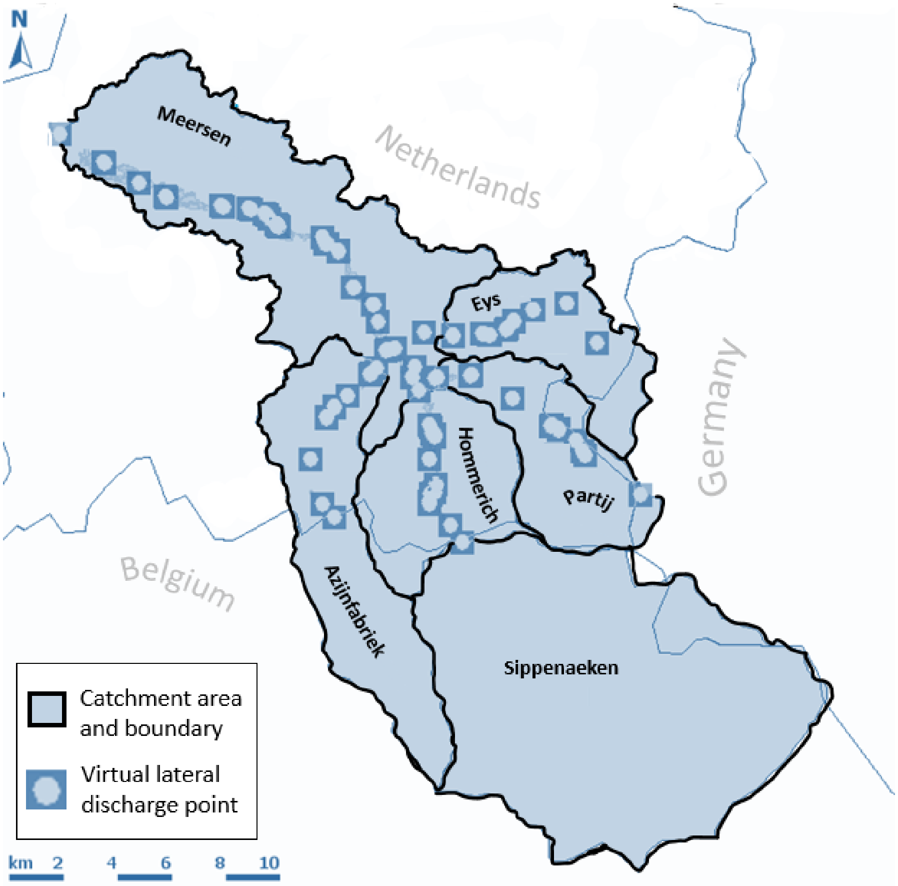



**Figure 2.12:** The borders of the six subcatchments that make up the Geul catchment found within the HBV model: Sippenaeken, Azijnfabriek, Hommerich, Parij, Eys, and Meerssen. The lateral discharge points used by HBV are highlighted along the Geul River and its tributaties.

### 2.5.4. The Delft-FEWS SOBEK-Rural Model

The SOBEK model calculates the one-dimensional flow of water in open channels and is used in predicting floods, demonstrating the functions of drainage systems, irrigation systems, and many more applications. The program makes use of the Saint-Venant shallow water equations, which represents the unsteady flow of water in open channels [32]. The boundary and lateral discharge results $Q$ calculated from HBV is inputted into SOBEK, which outputs the water levels, water velocities, and change of discharge over time at different points along the Geul. The existing SOBEK model for the Geul and the various nodes used to model the water levels of the Geul River is illustrated in Figure 2.13.

Many versions of SOBEK exist for various applications, such as SOBEK-1D-FLOW for both rural and urban applications, SOBEK-2D-FLOW for overland flow, SOBEK-RR for rainfall-runoff, and more. The existing Delft-FEWS for the Geul uses SOBEK-1D-FLOW Rural because, of all the available versions of SOBEK, 1D-FLOW Rural is the most capable of representing the characteristics of the Geul River. The Geul is located in a rural area with more natural areas and farms than urbanized areas. Furthermore, the 1D-Rural model allows for the representation of hydraulic structures, including weirs, bridges, culverts, pumps, etc., which are found throughout the Geul River [32]. The river bathymetry, or cross-sectional geometry of the Geul river, is customized at each measurement point to ensure accurate water level and discharge calculation.

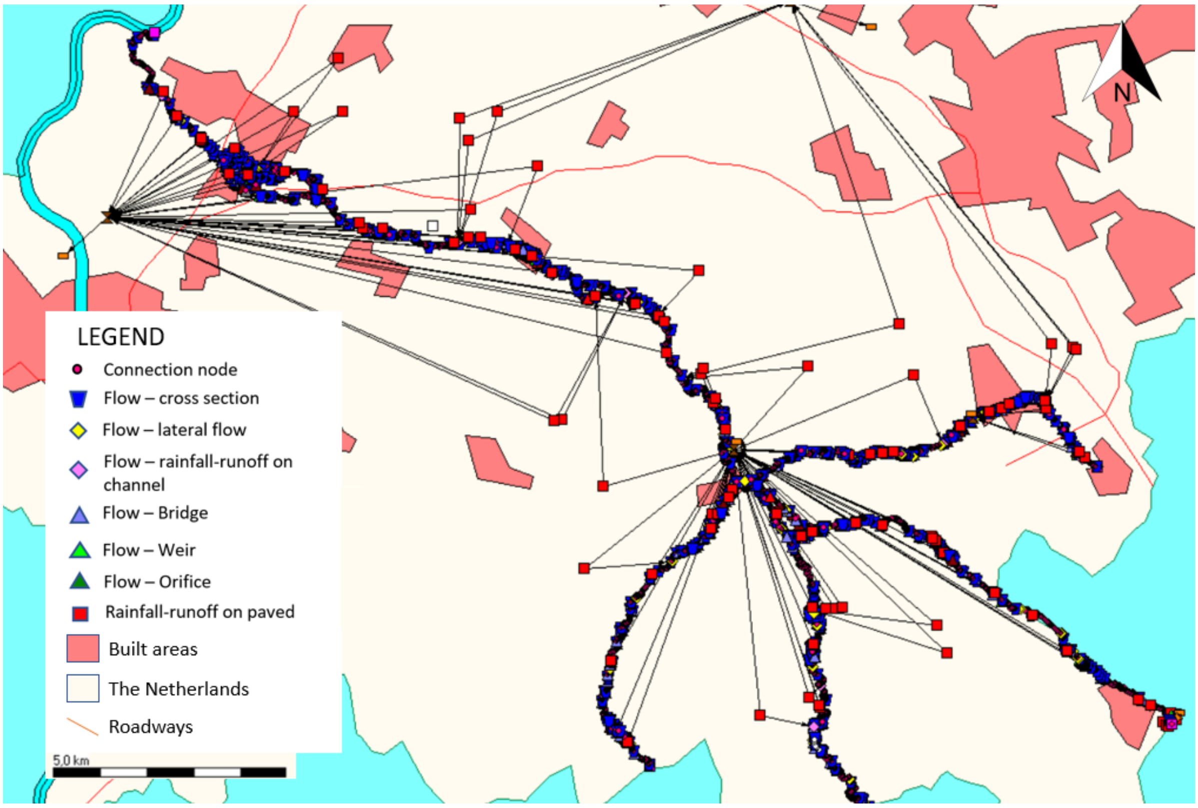



**Figure 2.13:** Entire SOBEK model used in Delft-FEWS as seen in SOBEK213.

The SOBEK model used in the Delft-FEWS models one-dimensional flow of water in rivers as well as two-dimensional overland flow. Deltares designed a coupled SOBEK 1D2D model that models flood patterns in the Geul Valley, but the inclusion of 2D calculations also increases the model run-time significantly. The calculation time of the 1D-FLOW Rural is approximately two hours, while the 1D2D-coupled model takes up to six hours of calculation time.

## 2.6. Communication of Warnings

Communication of warnings with proper timing and accuracy ensures that the FEWS succeeds in preparing citizens for possible disasters **UNDRR2017UNISDR2016-2021**. In the event a potential disaster is forecasted and the residents are not warned in time — or if they are not given sufficient information — then the system is not effective in reducing damage costs, even if the precipitation data or modelling results are accurate. An effective warning should be delivered with enough lead time to allow the threatened population to evacuate, which is at least 1.5 - 2.5 days [33]. Communicating warnings of potential scenarios too early leads to false alarms, which erodes citizen trust in the Geul FEWS and leads to failure of the system [34].

To reduce false alarms, experts that are familiar with the hydrological behavior of the Geul Catchment can monitor the system to verify the validity of the simulation if a potential extreme event is detected [35], [36]. Experts monitoring FEWS are able to do ”second checks” of the data and forecasts, which involves waiting a certain amount of time after the initial alert of a possible event to see whether the forecasts increase in certainty or potentially decrease. The possibility of a second check depends on the behavior of the monitored area. In areas where forecasting is calculated seven days in advance, second checks are possible. However, if an area is highly reactive to changes in precipitation, second checks reduce necessary lead time for preparation and evacuation [9] [37].

Proper communication also depends on the sources of data used within the FEWS. The two sources of data often used for river FEWS are precipitation and discharge of the river. Usage of either of these data sources again presents a trade-off between accuracy of the forecasts and timing of the warning.

During the July 2021 event, monitoring stations were able to detect an extreme precipitation event two days before the precipitation fell and three days before the flood occurred. The discharge forecasts did not detect an extreme event until the rain began to fall, one day before the flood [9]. Had the warnings been delivered based on the detected precipitation event, then there would have been enough time to evacuate, but it was still uncertain whether this rain would have caused a flood. If the warning was delivered based on the river discharge, then there would only have been one day to evacuate, which is not sufficient [33]. For a river catchment, forecasts using discharge data may be used for areas where a lead time of 12 hours is sufficient [33]. If longer lead times are necessary, then forecasted rainfall must also be used in the FEWS [33].

The communication chain of warnings for the Geul River utilizes a multi-layer safety (MLS) approach, which is a method of water management used throughout the Netherlands to better prepare an area against flooding [38], [39]. This approach involves alerting groups responsible for crisis management before alerting the citizens so that these groups are better prepared to assist citizens in disaster preparation [38]. For the Geul catchment, an expert at the Waterboard is assigned to monitor the warning system in case a high water event is detected. If a potential high-water event is detected, the expert must communicate this information to the rest of the Waterboard, which scales up or down based on the level of the foreseen threat. The Waterboard then informs the Safety Region of the alert, whose responsibility is to coordinate with emergency services. The Safety Region then warns the citizens and communicates the potential risk as well as possible courses of action [38]. Given that there are three (possibly four) steps between the detected threat and citizens alerted (see Figure 2.14), this potentially leads to less lead time for the citizens to act. Furthermore, more ”links” in the command chain increases the potential of failure [40].

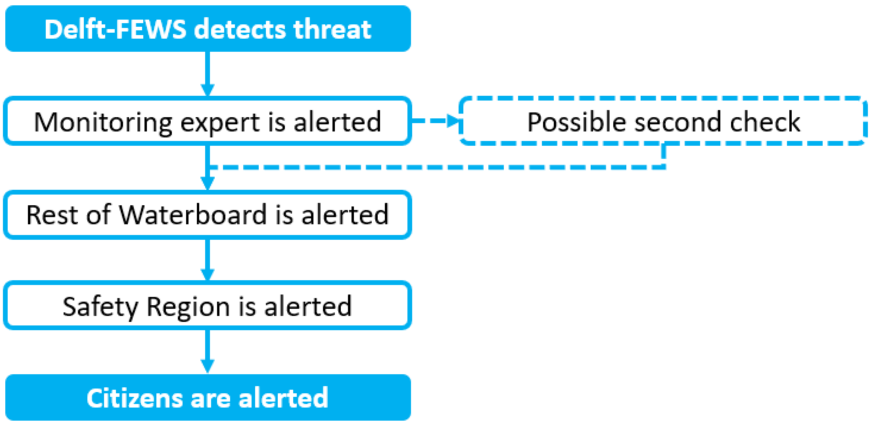



**Figure 2.14:** Current workflow of warning communication for Delft-FEWS Geul

Advancements in technology have resulted in faster and more effective communication of warnings to the general population. Warnings are delivered through door-to-door communication, community leaders, local alarms, word-of-mouth, and cellular devices [41]. Nowadays, the most effective method is through cellular devices, which communicates warnings through direct text messages to the user or through social media [41], [42]. In the Netherlands, communication of extreme precipitation happens via the KNMI through mobile alerts of residents in possible affected areas as well as over social media [43]. When the Safety Region decides to warn the population based on Waterboard advice, the warnings are communicated through all possible methods — text messages, word-of-mouth, door-to-door information, etc. The Netherlands also has infrastructure to warn the population through the public warning systems, which is used in events threatening national security or during natural disasters [44]. The Netherlands is therefore equipped to warn the population quickly in the event of a potential threat.

## 2.7. Evacuation

Evacuation is defined as the temporary removal of people from an area that is believed to be at risk as a result of an extreme event [45]. Local authorities may opt to evacuate residential and commercial areas if a natural disaster is expected to occur. Evacuations can be recommended or mandated for different natural disaster events all over the world, with such events as examples: forest or brush fires in the United States and Australia; hurricanes in tropical regions; flash floods in Europe and Asia; and tsunamis in the Pacific region. [45] [46] [47] [48]

Two kinds of evacuation methods can be called in an area: horizontal evacuation, and vertical evacuation [48]. Horizontal evacuation is defined as the horizontal movement of people entirely out of an area deemed at risk, whereas vertical evacuation is defined as the movement of people to higher ground [48]. Vertical evacuation is possible in limited circumstances, for example when a residential or commercial building has more than one flood, or when a population has access to shelter on a higher elevation within the area. Furthermore, not all natural disasters that may prompt an evacuation can be avoided using vertical evacuation. Horizontal evacuation is recommended when the integrity of structures in the area is at risk, such as during hurricanes, tornadoes, or fires. Vertical evacuation is reliable in smaller-scale floods that do not restrict access to emergency services [49] [48] [50].

Approximately 1 1/2 to 2 1/2 days is necessary for horizontal evacuation from an area, including communication of warnings and movement time [33] [48]. This time frame allows the responsible authority to disseminate all potentially vulnerable residents with enough time for them to act. It is also important to the effectiveness of the evacuation to give residents enough time to leave the area to prevent potential traffic jams that hinder everyone's ability to evacuate [33]. Furthermore, response to the warnings and the action of the citizens depends on how much the population trusts the system to deliver accurate warnings [33] [34]. While the authority can mandate an evacuation, it is up to the residents to decide how to respond to the warnings given that they are provided with sufficient information on how they can protect themselves [33] [47] [45] [51].

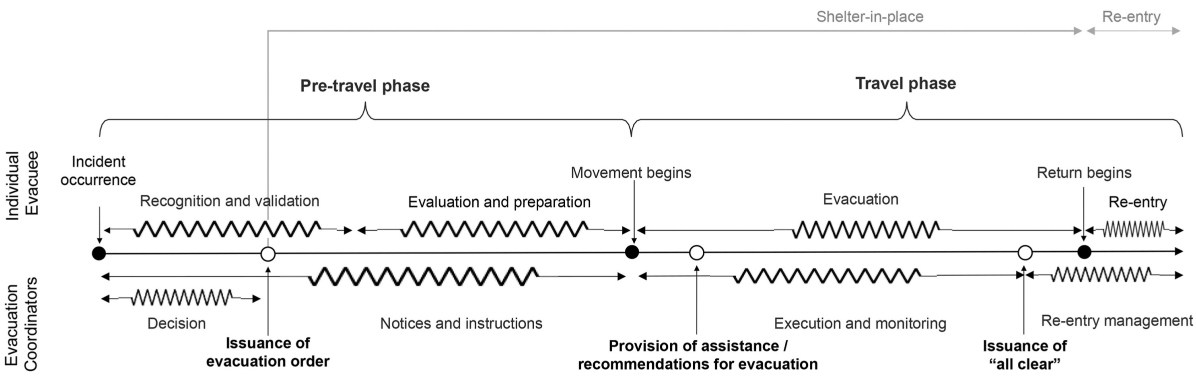



**Figure 2.15:** Evacuation timeline comparing the actions and responsibilities of the evacuation coordinators to the actions of the individual evacuee. For Valkenburg, the evacuation coordinator is the Safety Region South Limburg [51]

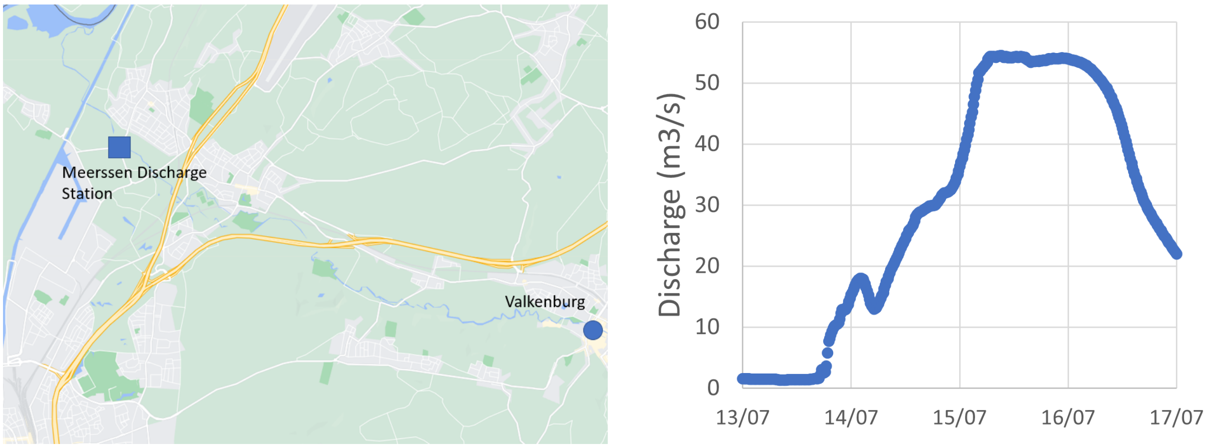
Mandating evacuation in the area has several costs both tangible and intangible, prompting the communication of warnings to consider the effect of a false alarm on the population [52], [47]. Costs of evacuation to be considered include the direct and indirect monetary costs that come as a result of the disruption of leaving one's home or ability to work. Costs of evacuation can also be non-tangible in the form of emotional or mental distress caused by an extreme event [52]. Although evacuation is meant to save lives from a natural disaster, it can still put certain groups of people at physical risk. Elderly people as well as people that require hospitalization or other medical intervention have a higher chance of not surviving an evacuation than not surviving the natural disaster that prompted the evacuation [9] [53].

# 3 Simulation of the July 2021 Flooding Event

The FEWS for the Geul River uses meteorological and geographic data to create predictions of discharge and water level. The network contains the necessary framework to create forecasts and warnings for river conditions of the Geul, but at the time of the flood, the system was offline for maintenance. According to experts familiar with the framework, the Delft-FEWS would not have been able to successfully model the July 2021 flood event [9]. To test this theory, past data pertaining to the precipitation that occurred in July 2021 were inputted to create a forecast of the discharge and water level that caused the flood. Comparing the results to the observed data available from the July 2021 flood can reveal possible flaws in the programs that must be corrected for the system to work properly in future modelling.

## 3.1. Methodology

The precipitation data available within the system from 13 to 17 July 2021 is first analyzed and compared to existing records describing the amount of precipitation that fell in the Netherlands. The raw data is used to create hindcasts for both discharge and water level to test whether the Delft-FEWS interface could effectively simulate the July 2021 event. Then, the data is inputted into HBV, which calculates discharge in cubic meters per second ($m^3$/s) at virtual lateral and boundary discharge points along the Geul. There is no discharge measuring station in Valkenburg, and the nearest measuring station is located in Meerssen. The recorded discharge data at the measuring station peaks at about 55 ($m^3$/s). However, the expected discharge value is between 100 - 130 ($m^3$/s) [9] [13]. The boundaries that determine this range can be found in Appendix B. The HBV discharge result will be compared to the 100 - 130 ($m^3$/s) range and the simulation is expected to provide insight into why the expected discharges differ from the data found within the historic discharge data.




**(a)** Location

**(b)** Recorded discharge data in July 2021

**Figure 3.1:** Location and measurement data of Meerssen discharge measuring station

The HBV model is run using the *HBV update run hindcast* option available within Delft-FEWS starting from 00:00 12 July 2021. The discharge inputs calculated at all four of the points in Figure 3.2 (11_001_B Start Eyserbeek, 12_001_B, 10_001_B Cottessen, and 13_001_B Start Gulp bij Slenaken) are summed to represent the total amount of water that entered the Geul River and its tributaries in the Netherlands and passed through Valkenburg, causing the July 2021 flood. This summed value is compared to the reported discharge, which is estimated to be within the range of 100 - 130 $m^3/s$. It is hoped that the simulations can provide insight into the difference between the expected discharge range and the recorded discharge through Meerssen in Figure 3.1.

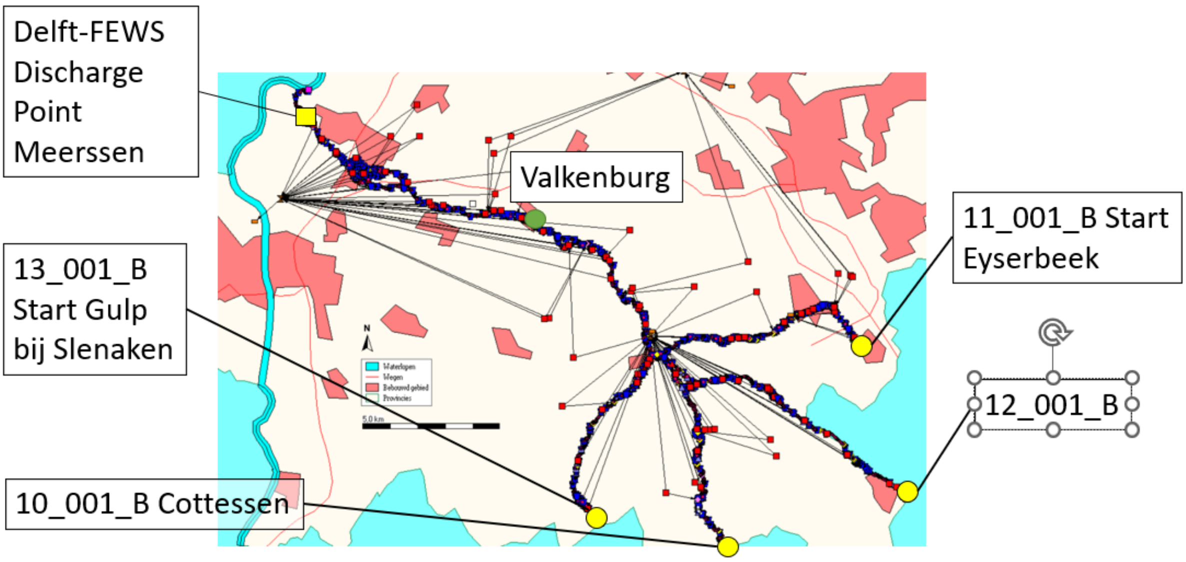
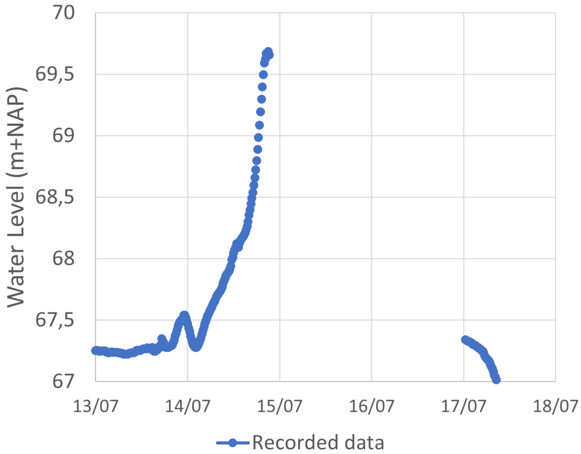



**Figure 3.2:** The location of Valkenburg and the five main discharge boundary points

The HBV discharge data are then inputted into the SOBEK model, which calculates the water levels throughout the Geul River in the Netherlands. For this simulation, the water level data is taken at Valkenburg Hertenkamp station. The location of Valkenburg Hertenkamp and the available water level data recorded during the July 2021 event is shown in Figure 3.3.


**(a)** Location




**(b)** Recorded water level data in July 2021

**Figure 3.3:** Location and measurement data of Valkenburg Hertenkamp measuring station

The Hertenkamp station is chosen not only for its central location but also because of the gap in the recorded data starting at approximately 11:00 14 July 2021 until 00:00 17 July 2021. This gap is due to the floodwater submerging the measuring station, causing it to malfunction [9]. Using the discharge inputs from HBV, the SOBEK hindcast is expected to return a result that shows the water level of the Geul during this data gap from 11:00 14 July - 00:00 17 July 2021. The expected water level is around 70 - 71 m+NAP. The process of estimating the expected water level can be found in Appendix A. The SOBEK run starts at a beginning date of 00:00 13 July 2021.

SOBEK also calculates discharge as it passes through the Geul River. The Delft-FEWS SOBEK model does not have a discharge measuring point located within Valkenburg. Therefore, the discharge calculated in SOBEK is instead compared to the HBV discharge at the Meersen station, shown in Figure 3.2.

Since experts familiar with the Geul FEWS believe the FEWS models would not have worked during the July 2021 event, there is a possibility that the discharge and/or water level results will not match the expected values [9]. If this is the case, then adjustments to the model are made where necessary. The answer to the first research question is expected to be the precipitation file that most accurately represents the July 2021 precipitation event as well as any necessary adjustment that must be made to the models to produce results representative of the July 2021 flood.

## 3.2. Meteorological Inputs

The data inputs necessary to compute discharge and water level is found in the Delft-FEWS system and compared to recorded data to confirm that the available data is representative of the July 2021 precipitation event. The data ranges over a time period from 13 to 17 July 2021. This data is inputted into HBV, which finds the average precipitation for each of the six catchments using the method of Thiessen polygons, which calculates the average precipitation in a catchment by weighting the rainfall stations based on the area the pluviograph station data represents [27] [54]. The pluviographs and Thiessen polygons within Delft-FEWS are shown in Figure 2.10.

The real-time data for the July 2021 rainfall is not available since the radar stations missed the event entirely (see Figure 3.4). The early reanalysis product should have been made available up to two days after the rainfall event, but this data is not available in Delft-FEWS. The final reanalysis data is available within Delft-FEWS, which was made available one week after the event. The comparison of the real-time data and final reanalysis data as seen in the Delft-FEWS is shown in Figure 3.4.

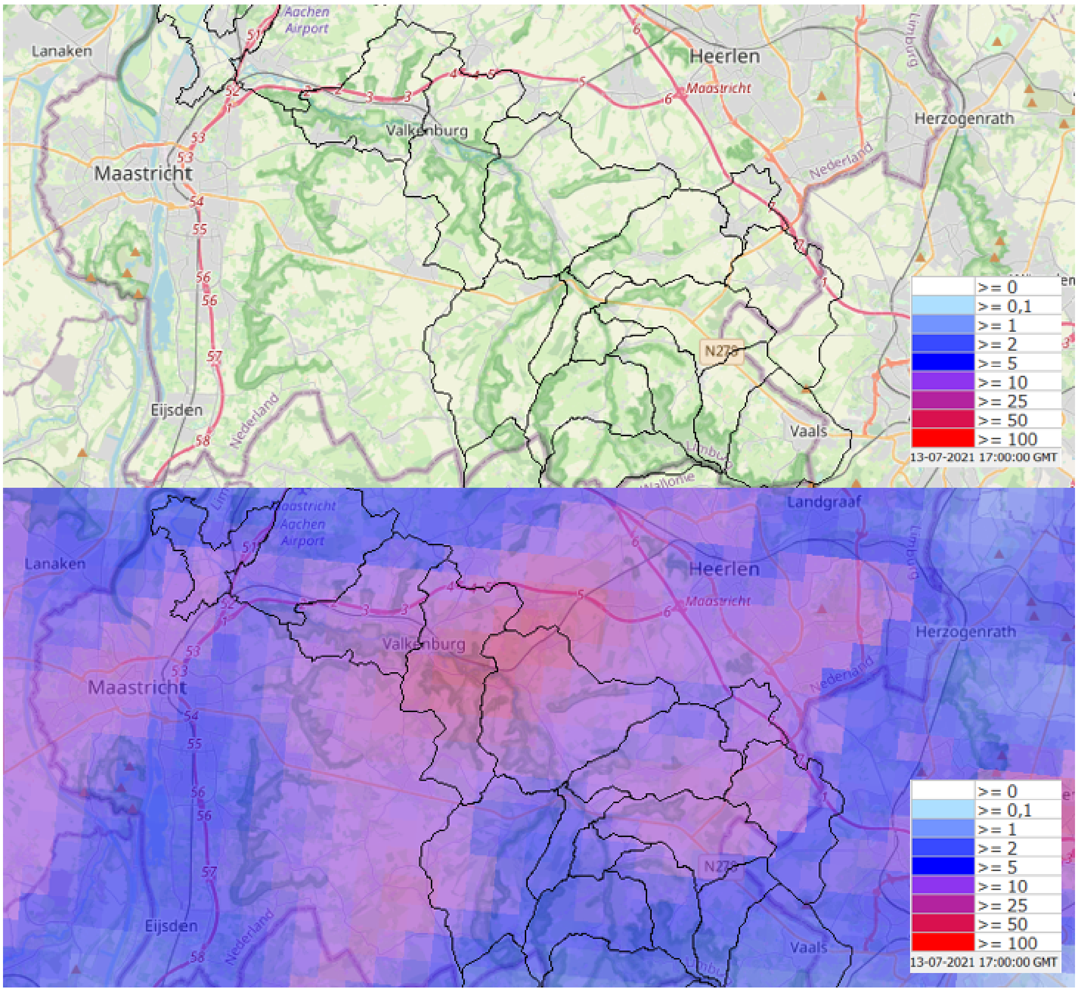
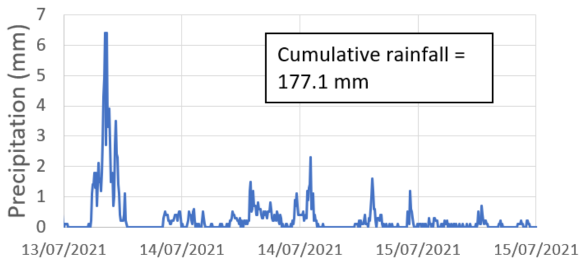


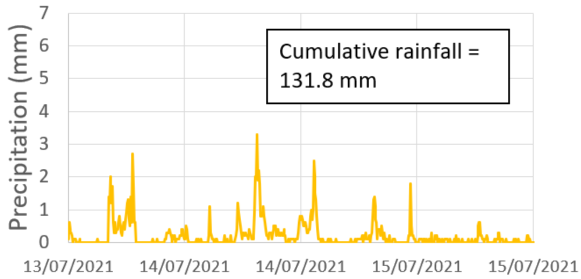

**Figure 3.4:** Comparison of the real-time observation data to the final reanalysis precipitation product available in Delft-FEWS.

Precipitation data collected by each of the KNMI pluviographs from 13 July and 17 July can be seen in Figure 3.5. The scale for this rainfall data is amount of precipitation for every five minutes. The precipitation data is compared to existing reports of observed precipitation. It is reported that the most amount of rain fell over Voerendaal, where 98 mm is said to have rained from 08:00 on 13 July 2021 to 08:00 on 14 July 2021 [55]. Voerendaal is located closest to the Ransdaal pluviograph, which recorded the highest peak of rainfall between 13 and 14 July (Figure 3.5a). The total rainfall recorded in Ransdaal from 13 - 15 July is 177.1 mm. The two pluviographs with the lowest recorded rainfall are Maastricht and Schimmert - Spaubeek, with 94.7 mm and 87.2 mm respectively [55].

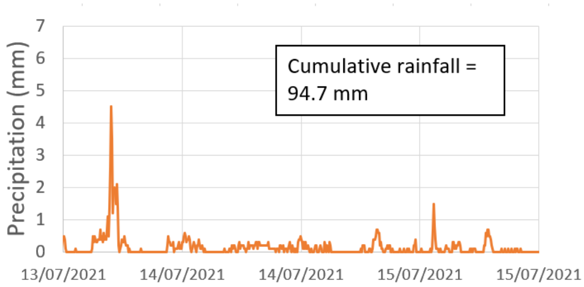
The precipitation data in Figure 3.5 is inputted into HBV, which uses the Thiessen polygons in Figure 2.10 to calculate the average precipitation in each of the six catchments for every hour. The interpolated precipitation data calculated by HBV is seen in Figure 3.6.



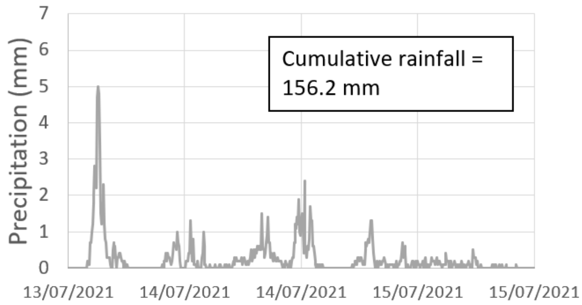

**(a)** 10.P.30 - Ransdaal



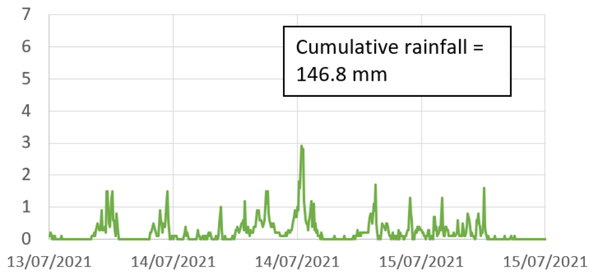

**(b)** 15.P.41 - Noorbeek



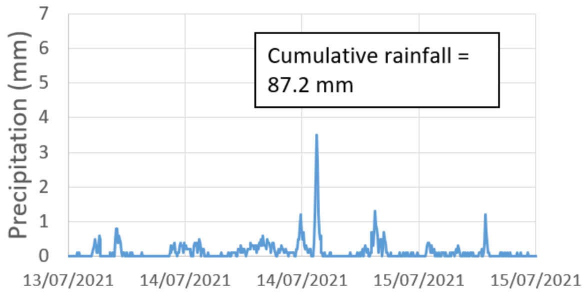

**(c)** 10.P.36 - Maastricht




**(d)** 18.P.37 - Kaffeberg




**(e)** 12.P.25 - Vaals




**(f)** 6.P.40 - Schimmert - Spaubeek

**Figure 3.5:** Cumulative rainfall for each of the six catchments located in the Geul valley calculated by HBV using the method of Thiessen polygons.

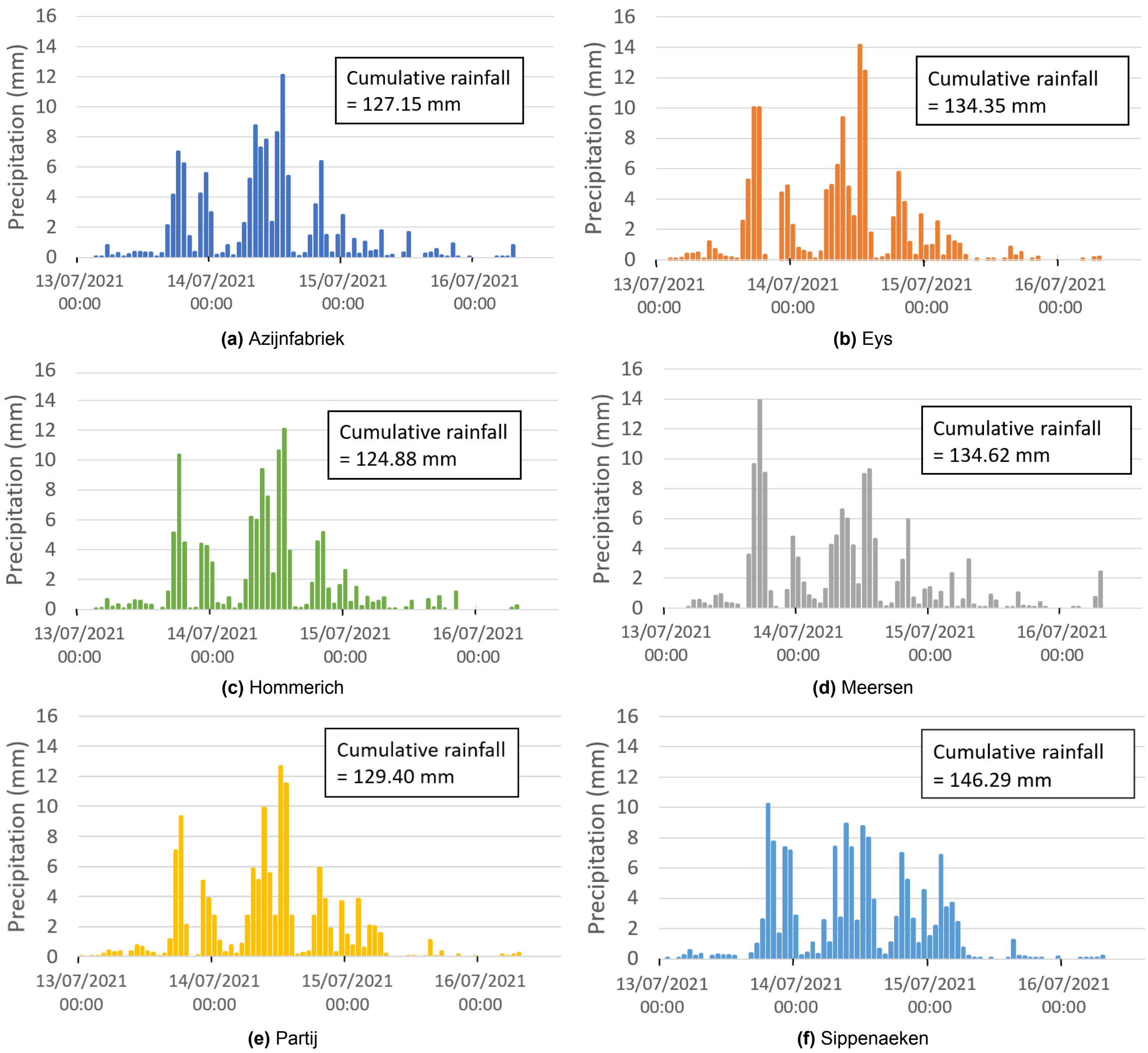



**Figure 3.6:** Cumulative rainfall for each of the six catchments located in the Geul valley calculated by HBV using the method of Thiessen polygons.

The precipitation converted by HBV shows that most of the water entered the system between 14 and 15 July. Recorded data shows that the highest concentration of rainfall occurred in areas located in the Eys and Meersen catchments, which have a high cumulative precipitation. The highest cumulative precipitation is seen in Sippenaeken (Figure 3.6f), even though reported data indicates that areas along the Dutch-Belgian border did not get as much precipitation (42 mm and 51 mm respectively). However, it is known that heavy rainfall also occurred in Belgium and that much of the discharge that flowed through the Geul came from the Belgian Geul catchment [9]. Because of the similarity of the HBV precipitation data to the reported precipitation records pertaining to the July 2021 event, no additional steps are necessary to adjust the data. The data in 3.6 is therefore used to simulate the discharge.

## 3.3. Results

### 3.3.1. First Run: 1D Model

The four discharges from the boundary discharge points in Figure 3.2 were summed up in Figure 3.7 to represent the total discharge that flowed through Valkenburg on 14 July 2021.

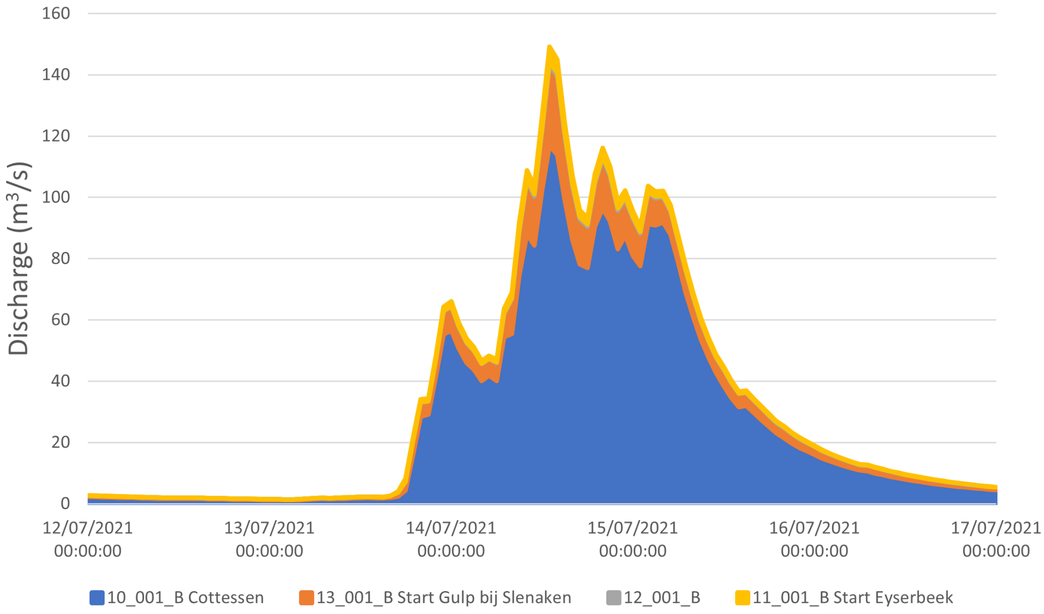



**Figure 3.7:** Results of discharge simulation conducted by Delft-FEWS HBV model

The resulting water level data calculated by the HBV discharge results was compared to both the recorded water level data and the expected water level in Figure 3.8. The discharge calculated by SOBEK at Meerssen was compared to the expected range of discharge and to the HBV discharge results in Figure 3.9.

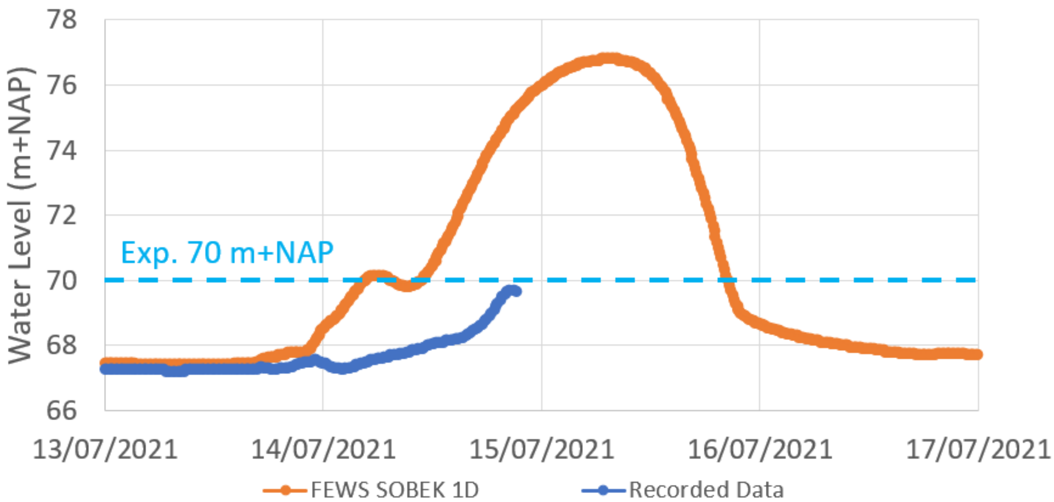



**Figure 3.8:** Comparison of discharge calculations between SOBEK 1D Rural and HBV

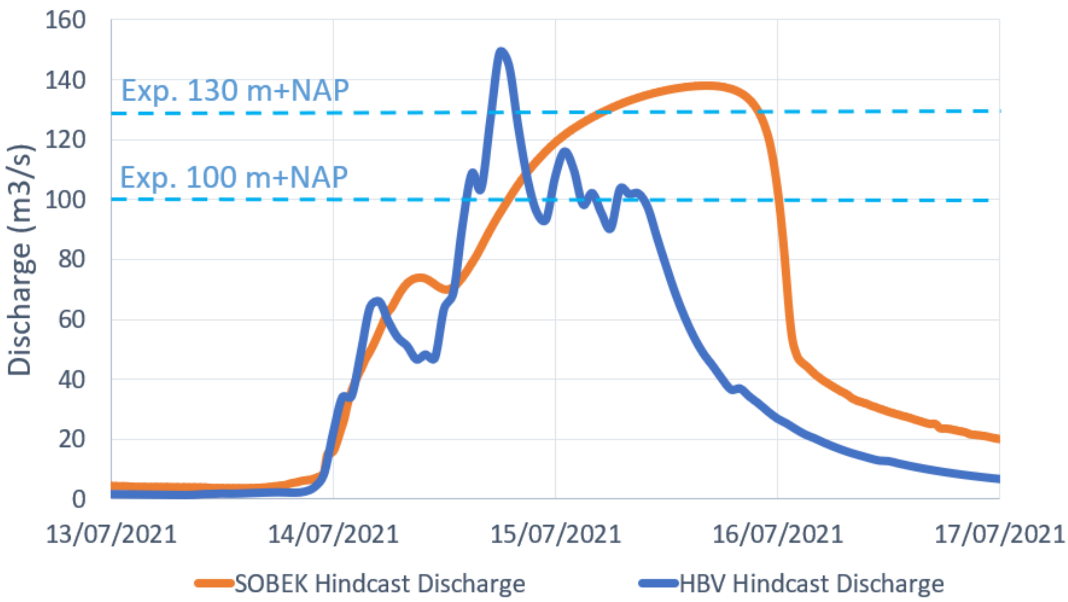



**Figure 3.9:** Comparison of discharge calculations between SOBEK 1D Rural and HBV

The resulting water level exceeded the expected water level by 6.5 m+NAP. The discharge amount also peaks around 140 $m^3/s$ but the flood wave tilts backward, which does not match theoretical behavior of a flood wave [56].

### 3.3.2. Creating the 1D2D Coupled Model

Because the results of the SOBEK model did not meet expectations, the program is modified. The data inputs are not modified as they matched the observed rainfall data. The HBV model is also not modified despite exceeding the expected range by 10 $m^3/s$ because this value falls within a 10% margin of error to the maximum expected discharge value. The rise in the water level as calculated by SOBEK exceeded the expected rise in water level by a factor of four, which is significant. The discharge result calculated by SOBEK showed a discharge that behaved outside he expected behavior of a flood wave [56]. Therefore, the SOBEK model is coupled with a 2D grid to calculate overland flow and attempt to lower the water level result in Figure 3.8.

To create the coupled model, a topographic map of Valkenburg is used to select a test area that will be inputted into the SOBEK 1D model. The chosen test area is created considering accuracy of the calculation as well as a reasonable run-time (maximum two hours per run). To keep run-times low, the area is selected based on location of the population of Valkenburg, the area most likely to flood, and the type of topographic map used. Two topographic digital models are available: the digital surface model (DSM) and the digital terrain model (DTM). The DSM includes the elevation of nature as well as built objects, such as buildings, whereas the DTM does not contain building elevation data [57]. Given that the goal of this project is to see which buildings are vulnerable to the natural flow of water, the DTM is used. Furthermore, both DSM and DTM have two grid sizes: 5 m × 5 m and 0.5 m × 0.5 m. Given that the more accurate grid (0.5 x 0.5) would result in higher run-times, the DTM5 grid used to create the topographic grid for the 1D2D coupled model [57].

An area of interest smaller than the entire Geul catchment had to be chosen using the DTM5 topography grid. A SOBEK runtime of the Geul Valley from Gulpen to Meersen takes approximately a week, so the topography grid is reduced to an area surrounding the most densely populated area of Valkenburg located within the Geul Valley. Consultation of the map showing the extent of the July 2021 floodwaters in Figure 2.7 shows that the floodwaters were limited to the area within the Geul Valley that had a topography of 69 - 71 m+NAP [9]. Figure 3.10 shows the topography of Valkenburg as well as the location of the river and buildings. The chosen area, outlined in white, is limited to the area at the lowest elevation around the river and encapsulates as many buildings located within this elevation as possible.

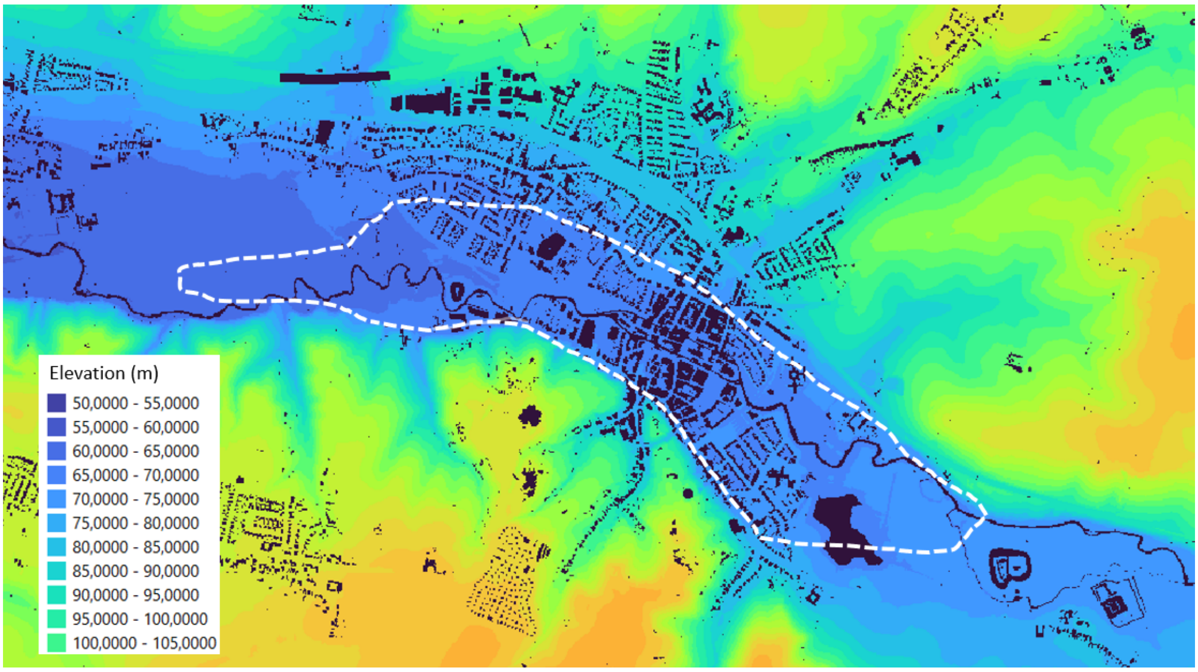



**Figure 3.10:** Area of interest (outlined in white) around Valkenburg based on population and elevation.

The chosen area is then converted into a raster file and implemented within the existing SOBEK 1D model to create an area capable of modelling 2D overland flow, creating a coupled 1D2D model specific to Valkenburg. The grid within the model can be seen within the SOBEK model in Figure 3.11 along the Geul River profile and calculation points found within the original model.

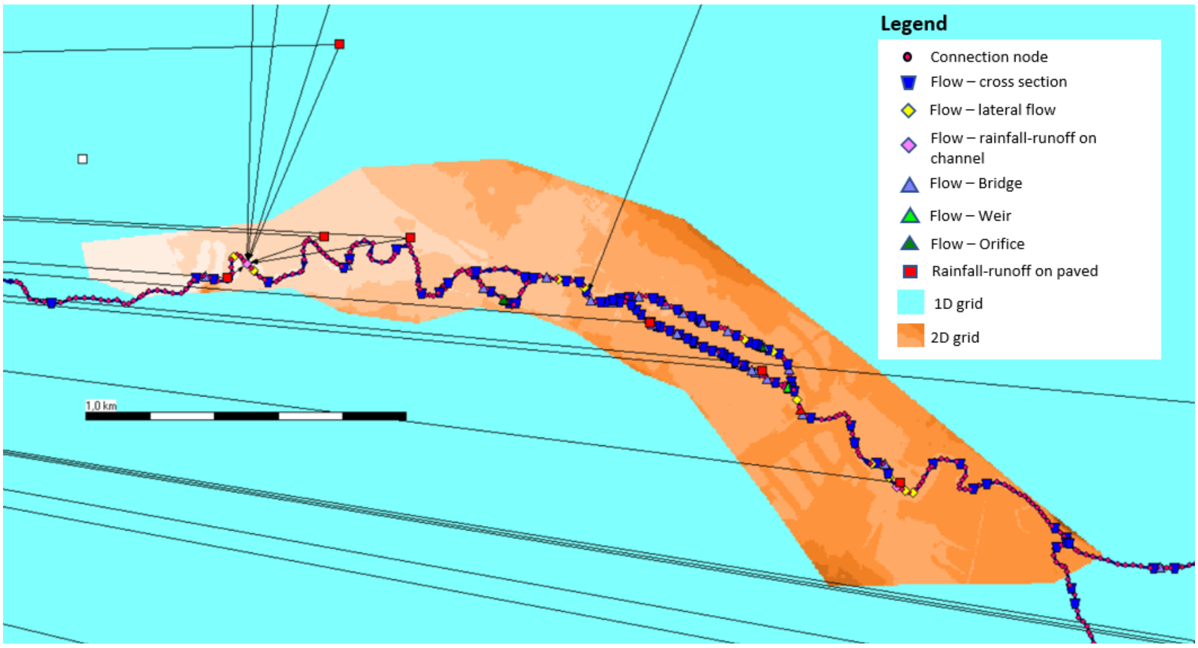



**Figure 3.11:** QGIS section coupled within SOBEK 1D to allow for 2D flow in the simulation.

Because the 2D grid area does not include the area around the Meerssen discharge measuring point, the discharge results in Figure 3.9 are not expected to be affected by the addition of the 2D grid. Instead, a side view along a section of the Geul River to show the change in discharge along the river profile during the event is taken to observe the differences between the discharge calculations along a one-dimensional profile and the discharge calculations over the 2D grid in Valkenburg. The section of the river from Gulpen to Meerssen is approximately 17 km long and the location and distance of the 2D grid of Valkenburg is visualized in Figure 3.12. The distance is represented along the x-axis and the location of the 2D grid is highlighted along the x-axis in green.

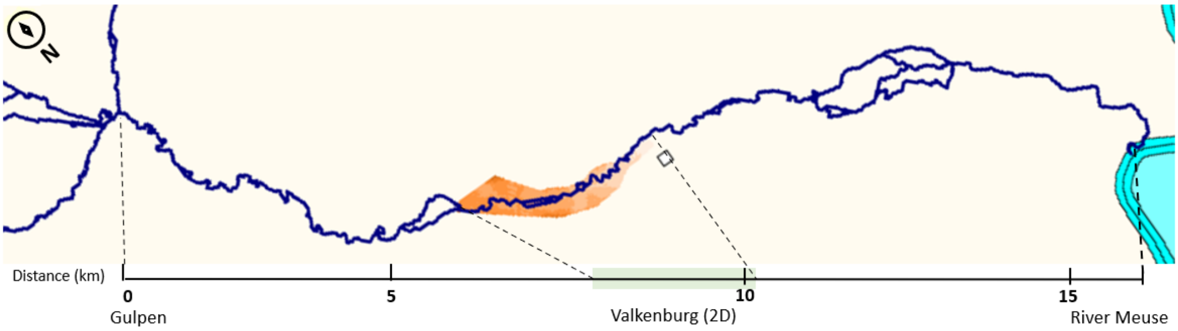
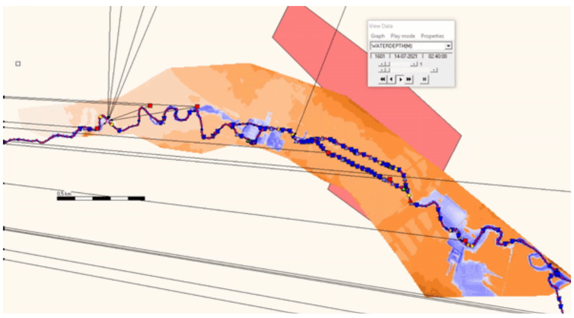


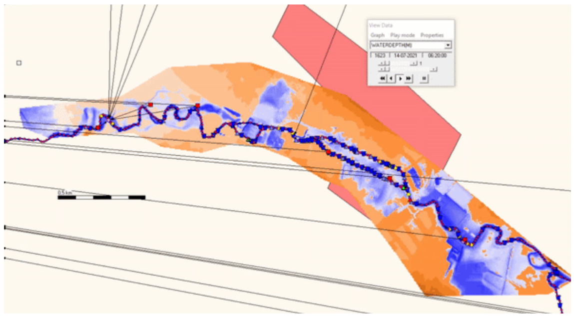

**Figure 3.12:** Distance grid used for the side view showing the location of the Valkenburg 2D map in green

### 3.3.3. Second Run: 1D2D-Coupled Model

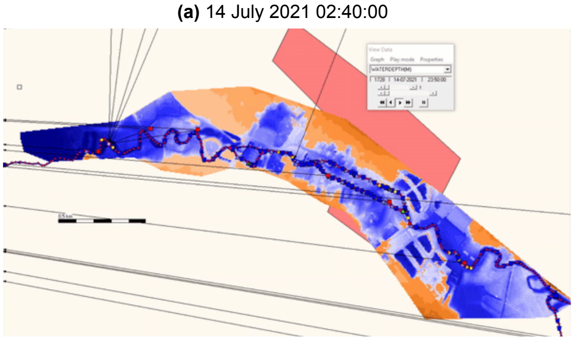
Inputting the same discharge inputs originally calculated by HBV resulted in a succession flood simulation shown in Figure 3.13.



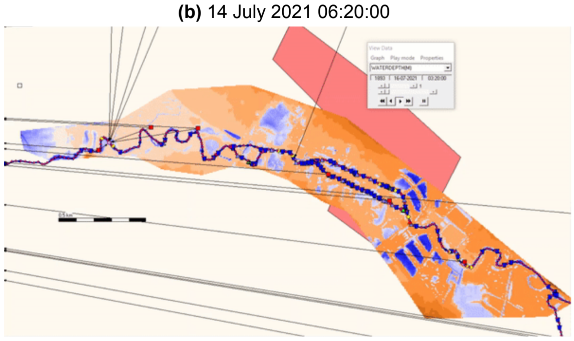
**(a)** 14 July 2021 02:40:00



**(b)** 14 July 2021 06:20:00



**(c)** 14 July 2021 23:50:00



**(d)** 16 July 2021 03:20:00

**Figure 3.13:** Progression of flood simulated using 1D2D coupled model.

The water level results of the 1D2D simulation at Valkenburg Hertenkamp were compared to the recorded water level data and the expected water level of 70 m+NAP in Figure 3.14.

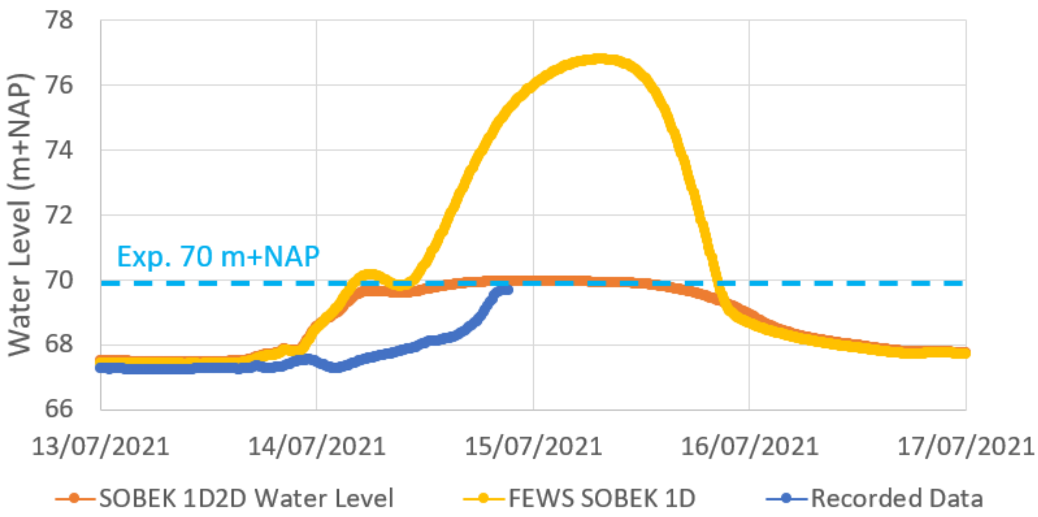
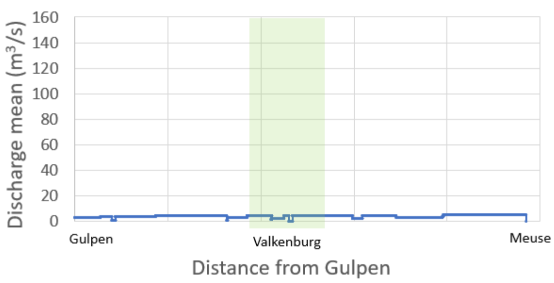
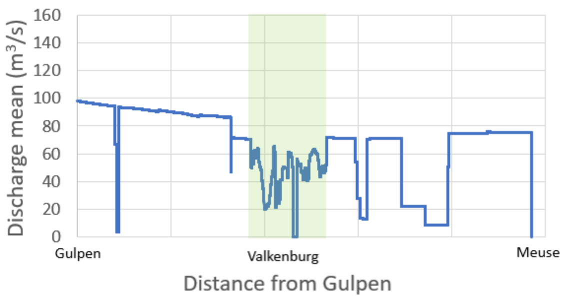



**Figure 3.14:** Results of water level simulations for the July 2021 event conducted by both original 1D-Rural and 1D2D-coupled SOBEK models

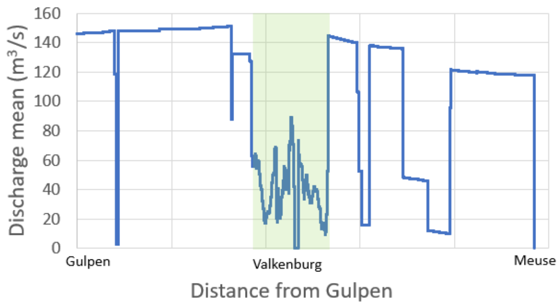
The comparison of the discharge calculations over the 1D grid to the 2D grid is shown as a progression over time in Figure 3.15. The area representing the 2D grid in Valkenburg is highlighted in green



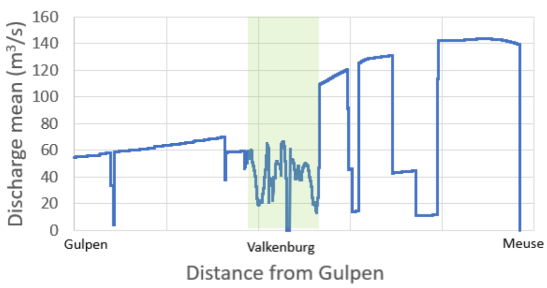

**(a)** Discharge at 12 July 2021 15:00:00




**(b)** Discharge at 14 July 2021 11:00:00




**(c)** Discharge at 14 July 2021 21:20:00




**(d)** Discharge at 15 July 2021 16:10:00

**Figure 3.15:** Discharge calculations viewed along the side profile shown in Figure 3.12 at different points in time with the 2D grid calculations highlighted in green

## 3.4. Discussion and Recommendations

Comparing the HBV precipitation data to the amount of precipitation formally reported can determine the plausibility of the data. It is reported that the most amount of rain fell over Voerendaal, where 98 mm is said to have rained from 08:00 on 13 July 2021 to 08:00 on 14 July 2021 [55] [9]. Voerendaal is located in the Meersen catchment, which experienced the highest peak of rainfall between 13 and 14 July (Figure 3.6d). Recorded data shows that the highest concentration of rainfall occurred in areas located in the Eys and Meersen catchments, which have a high cumulative precipitation. The highest cumulative precipitation is seen in Sippenaeken (Figure 3.6f), even though reported data indicates that areas along the Dutch-Belgian border did not get as much precipitation (42 mm and 51 mm respectively). However, it is known that heavy rainfall also occurred in Belgium and that much of the discharge that flowed through the Geul came from the Belgian Geul catchment (see Figure 2.6) [9].

Many technological problems within Delft-FEWS and in third-party data collection points were detected in this project. To create reliable predictions for scenarios as they occur, the real-time data must be accurate. The ability of the Delft-FEWS Geul network to ensure this accuracy is limited. For some existing warning systems, the rainfall data collected by measuring tools in the field can be multiplied with a constant value to improve the quality of the results. However, this works best for simplistic rain gauges in smaller catchment areas. In the case of the Delft-FEWS Geul network, the data is collected from advanced KNMI radar stations. While it is possible to manipulate the results of the KNMI radar data by a constant to increase or decrease the amount registered in Delft-FEWS, calculating this constant is very complex. Precipitation can vary based on multiple factors in the atmosphere: air pressure, evaporation, temperature, wind, and many other factors that change very often and very quickly. Any multiplication factor would have to vary spatially as well as temporally. This is very difficult to accomplish and not practical.

Because the source of the data comes only from within the KNMI, the warning system has no choice but to trust that KNMI supplies Delft-FEWS with the most accurate information. If the information is not accurate, then it is up to the data collectors to improve the technology. Currently, KNMI is indeed working to improve the quality of the collected data and has written an unpublished report on the progress and improvements made. There are other precipitation data collection sources in Belgium and Germany that have their own data collection points. If the warning system could collect data from Belgium and Germany, the accuracy of the forecasts of the system could be improved. This would require international cooperation between Belgium, the Netherlands, and Germany for information to protect Limburg and the nearby areas outside the Dutch borders. Another issue, which is seen in Figure 3.3, is that the data collection points for water level are not equipped to collect data in the event of a flood. There is also no discharge data collection equipment available within Valkenburg. The improvement of this technology would allow for better and more accurate data collection which in turn improves forecasting within Delft-FEWS.

The HBV discharge results at the four boundaries showed that almost all of it came from Cottessen. This reflects what happened during the July 2021 event, where the flood came from Belgium as a result of the heavy rainfalls over Belgium and Germany. The total amount peaked slightly higher than the anticipated maximum discharge of 130 $m^3/s$, peaking at over 140 $m^3/s$. However, the rest of the discharge peak fluctuated at around 100 $m^3/s$. Initially, it was considered that the total discharge was too high by a significant amount, as it was initially reported that the discharge that flowed through the Geul River was 100 $m^3/s$ [9]. However, during the duration of the research project, a report from Deltares contained a discharge result that fluctuated around the 130 $m^3/s$ mark (see Appendix A). The result from Deltares suggests that the HBV calculation result is more representative of the flood wave of the July 2021 event than initially thought. The HBV result was still higher than that of Deltares by about 7%, which is suspected to come from the purposeful overestimation of discharge that is programmed into the HBV model.

The initial HBV run did not explain why the expected discharge range differed from the recorded discharge data. However, the discharge calculations over the side view of the Geul in Figure 3.15 show a difference in discharge calculated over the 1D grid and over the 1D2D grid. In the discharges shown alone the sideview, the discharges calculated along the 1D grid were more than 100 $m^3/s$, but the discharges over the 2D grid were significantly less, fluctuating between 20 and 80 $m^3/s$. This is a similar order of magnitude to the recorded discharge data at Meerssen shown in Figure 3.1, which was 55 $m^3/s$. The results show that the HBV program simulates the total discharge flowing through the entire catchment including overland flow, while the discharge measuring station measured only the amount of discharge that was still in the river banks and did not include the discharge that had flown over into the floodplain. Knowing that a total of approximately 100 - 130 $m^3/s$ entered the Geul but only 55 $m^3/s$ was registered at Meerssen, that means that around 45 - 75 $m^3/s$ flooded the area around the measuring station. Meanwhile, in Valkenburg, knowing that 20 - 80 $m^3/s$ was within the river banks and a maximum of 140 $m^3/s$ flowed through the area, 60 - 120 $m^3/s$ flowed into the city and flooded the area according to the simulations.

Introducing a 2D grid into SOBEK lowered the simulated water level in the calculation by 6.5 m, resulting in a maximum water level of 70 m+NAP, putting it within the expected water level range (Figure 3.14. However, both 1D and 1D2D SOBEK calculations of the water level show a rise in water level that occurs earlier than the recorded water level data. At first, it was theorized that the issue of timing had to do with the friction assigned to the terrain through which the water was running, but changing the Manning coefficient had no effect on the timing of the results. It is theorized that the earlier flood is the result of the limited 2D grid within the model. Because the flooding upstream from Valkenburg within the model is still calculated using a 1D grid, there is no overland flow upstream, so the water does not experience friction from the floodplains, moving faster upstream. This possible explanation was not tested in this work due to the runtime required for the 2D grid for the entire Geul catchment.

In a one-dimensional flow calculation, water flow is only calculated along calculation points placed along the modelled river, as illustrated in Figure 3.16. When there is a greater amount of discharge than normal flowing through such a system, the total discharge $Q_{tot}$ ($m^3/s$) is equal to the discharge flowing in the riverbank, $Q_1$ ($m^3/s$). Because all the discharge in the system is within the riverbank, the calculation results in a high water level $h_1$ (m) (Figure 3.16).

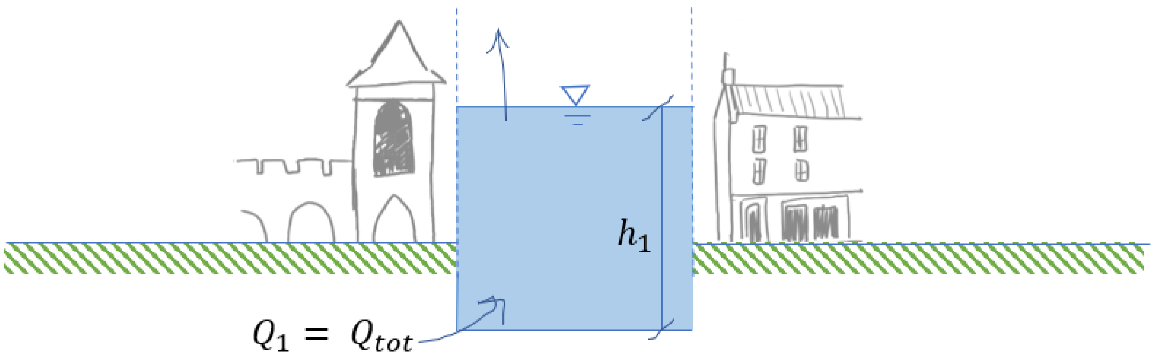



**Figure 3.16:** Conceptual model depicting behavior of a flooding river model in a 1D simulation that does not consider floodplains

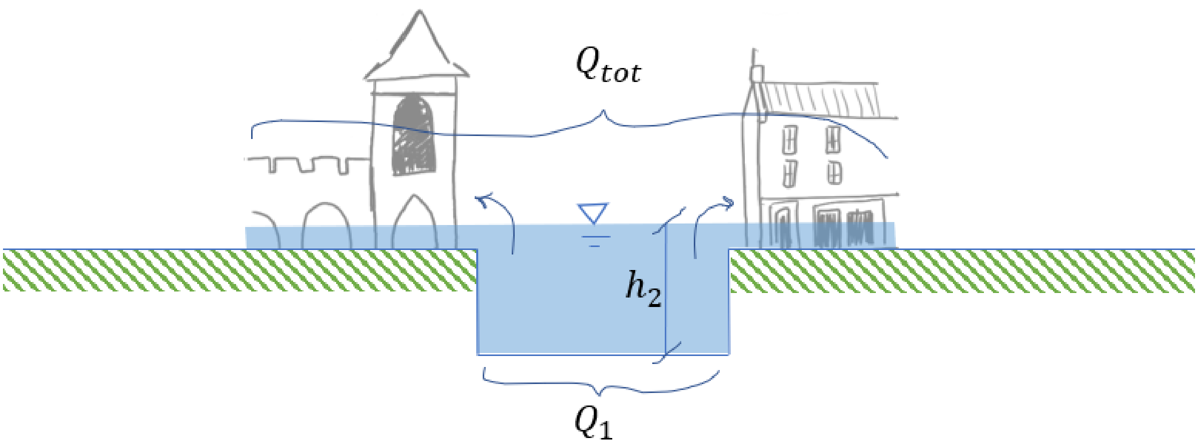



**Figure 3.17:** Conceptual model depicting behavior of a flooding river model in a 2D simulation that considers floodplains and overland flow

The discharge calculations shown along the side view in Figure 3.15 shows the differences between the discharge calculations over an area with a 2D grid, representing Valkenburg, and the areas without a 2D grid, resulting in a 1D calculation of water flow. The discharge calculations over the Valkenburg 2D grid is more varied and much lower than the discharge calculations for the areas between Gulpen and Valkenburg and between Valkenburg and the River Meuse. Where there is no 2D grid, all the discharge that is put into the system is considered to flow along the 1D line that represents the river. This discharge value includes not only the water that would normally flow within riverbanks in a flood, but also the water that would flow out of the riverbanks, as shown in Figure 3.16. This amount of discharge also raises the water level. With a 2D grid calculation, the river banks fill to the maximum height. Any amount of discharge that results in an exceedance of the height of the river banks flows into Valkenburg, resulting in a water level resulting in a water level lower than the water level illustrated in Figure 3.16. This phenomenon is illustrated in Figure 3.17. Figures 3.16 and 3.17 also illustrate why the recorded discharge at Meerssen differed so much from both the expected discharge ranges as well as the HBV discharge simulation results. The expected range and HBV simulation results were measuring the total amount of discharge as $Q_1 = Q_{tot}$ in Figure 3.16 whereas the Meerssen measuring station registered the discharge only within the river banks just like $Q_1$ in Figure 3.17.

The results from the runs with the two different models show that more accurate results can be acquired through the use of a model with a coupled 1D-2D grid. The implementation of a 2D grid resulted in a lower and more accurate water level, suggesting that the model within Delft-FEWS must take overland flow into account to increase accuracy and therefore effectiveness. The accuracy of the timing can be further improved with the implementation of a 2D grid over the entire Geul area. Furthermore, the 2D grid allows for a visualization of overland flow, which gives stakeholders a better idea of which areas are more vulnerable and plan accordingly. However, the bigger the 2D grid, the longer the run time of the SOBEK program, increasing the amount of time between precipitation detection and water level predictions and reducing the amount of time that Valkenburg residents have to prepare themselves. The original 1D model had a run time of up to two hours, whereas the coupled model had a run time of up to six hours. An attempted run using a 1D2D coupled model that covered the reach of the Geul from Gulpen to Meerssen took 30 days but failed at some point during the simulation.

A possible solution to creating a model that accounts for 2D flow while also considering a reasonable run-time length (1-2 hours maximum) is to create a quasi-1D model. This kind of model would not have a 2D grid in the same way as the coupled model created in this chapter would. In a quasi-1D model, a 1D river profile would be used to model the flow of the river within the riverbanks, just as in the original SOBEK model for the Geul River found within the Delft-FEWS model. The overland flow would be modelled by two river profiles to the left and right of the original river profile, similar to the improvement for the model of the Dinkel River in Germany [58]. This, of course, requires a complete overhaul of the existing model, though a working model that makes accurate predictions in a timely manner for the protection of citizens is worth the effort.

# 4

# Behavior of Delft-FEWS Under Different Catchment Conditions

The simulation of the July 2021 flooding event has provided insight into the capabilities and potential weaknesses of the programs found within the Delft-FEWS interface. These programs were further tested in non-flooding conditions to discover other potential issues that may prevent the models from properly modelling the behavior of the Geul River. In this chapter, the effect of evaporation and soil moisture was tested through the simulation of different precipitation events that did not cause flooding to observe whether HBV and SOBEK can effectively demonstrate the effects of these conditions on the Geul.

## 4.1. Methodology

Differences in seasonal temperatures and saturation of soil are two factors are tested to see their effect on how an area experiences flooding [59] [16]. Extreme temperatures that stay constant over a period of time can affect the amount of water in the system as well as the dryness of the soil [59]. A rainfall event that occurred during a period of consistently warm temperatures, defined as greater than 20°C, (summer storm) and an event that occurred during a cold period, less than 10°C (winter storm) are chosen to compare this effect. Another factor, saturation of soil, also affects how much deposited rainwater becomes runoff, therefore affecting the likelihood of an area flooding after a rainfall [16]. This is tested by comparing a period that experienced several subsequent rainfall events (rainy period) to a period that experienced a rainfall event after experiencing none (dry period).

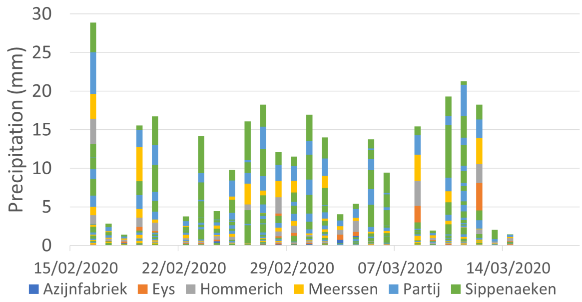
With these factors in consideration, the following four scenarios are to be tested in HBV and SOBEK: winter rainfall, summer rainfall, wet period rainfall, and dry period rainfall. The rainfall events are selected using the available historic precipitation data for the Geul catchment found within the Delft-FEWS system, which consists of precipitation data from 8 December 2018 to 25 December 2021.

| Event | Date range | Cumulative Rainfall (mm) |
|---|---|---|
| Rainy period | 24 February - 10 March 2020 | 622.7 |
| Dry period | 20 March - 10 April 2020 | 30.12 |
| Summer storm | 4 June - 10 June 2019 | 282.7 |
| Winter storm | 24 January - 5 February 2021 | 577.82 |

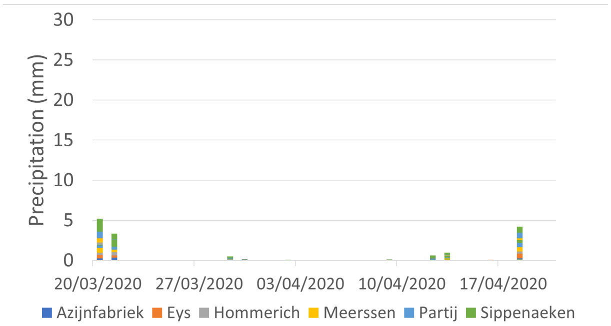
**Table 4.1:** Precipitation events tested in HBV and SOBEK

Rainfall events to use for simulation are selected based on availability of recorded data at Valkenburg Hertenkamp. Only water level data is recorded at Valkenburg Hertenkamp (see Figure 3.3). There are no discharge measurement stations within the city of Valkenburg. Unfortunately, there are large gaps within the data record where no water level data was recorded, so some of the resulting water levels cannot be compared to recorded data.

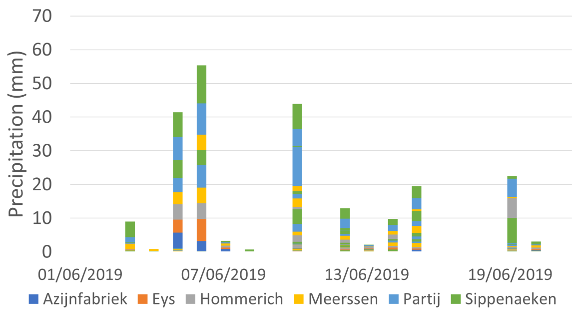
With the temperature and soil saturation factors in consideration, the following precipitation events are selected.



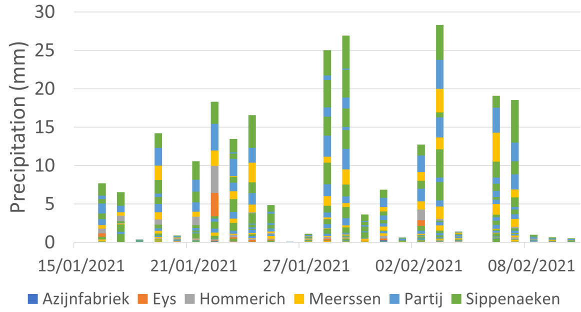

**(a)** Rainy period




**(b)** Dry period




**(c)** Summer storm




**(d)** Winter storm

**Figure 4.1:** Historical test rain and catchment data

These precipitation events are inputted into HBV to produce corresponding discharge data, which are then inputted into SOBEK to produce corresponding water level data. The discharge is compared to the corresponding water level of each of the four scenarios using the following criteria [60] [61]:

1. The changes in water level data for a particular event follows a similar pattern in both time and space to the changes in discharge data.

2. Peaks and troughs of both discharge and water level data occur at the same time.

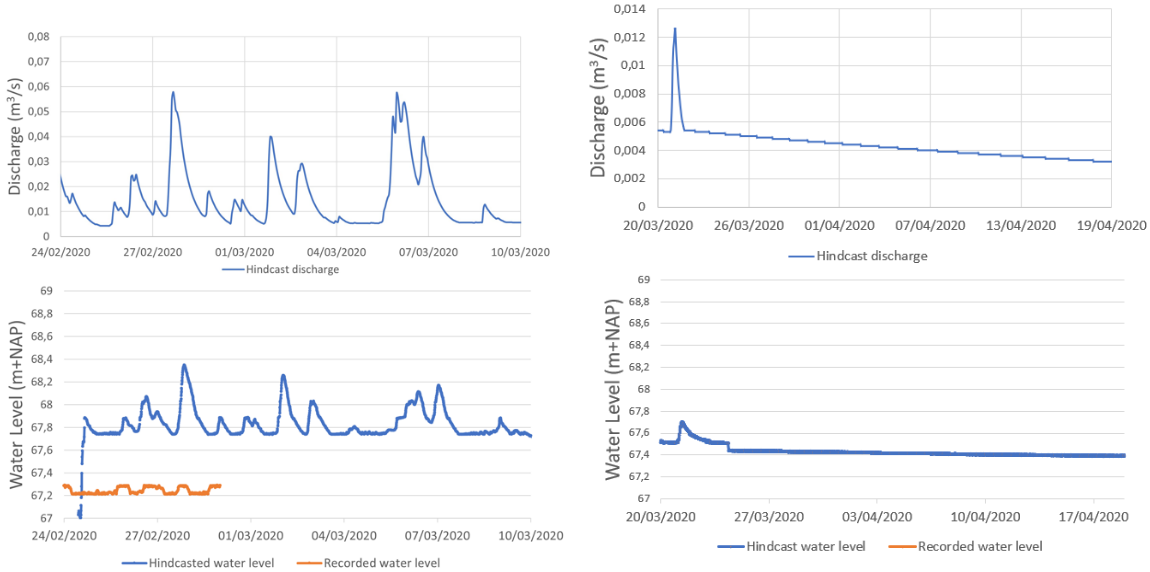
3. The water level data is within a range of $\pm$ 0.5 m to the recorded data, compared where available.

The four different scenario results are compared at the Valkenburg Hertenkamp measuring station (see Figure 3.3). Finally, one scenario is then selected based on availability of recorded data and compared across multiple measuring stations to see if the pattern between the discharge and water level results is the same or similar across the whole catchment. The chosen measuring stations are Grote Molen, Eyserbeek Eys in the Eys catchment, Cottessen bovenstrooms in the Sippenaeken catchment, and Buffer Nijswiller beneden in the Hommerich catchment. The location of the four measuring stations are shown in Figure 4.2 as well as the relative distance from Valkenburg Hertenkamp measuring station.


**Figure 4.2:** Map of the measuring stations used in the comparison of discharge and water level modelling

## 4.2. Simulation Results

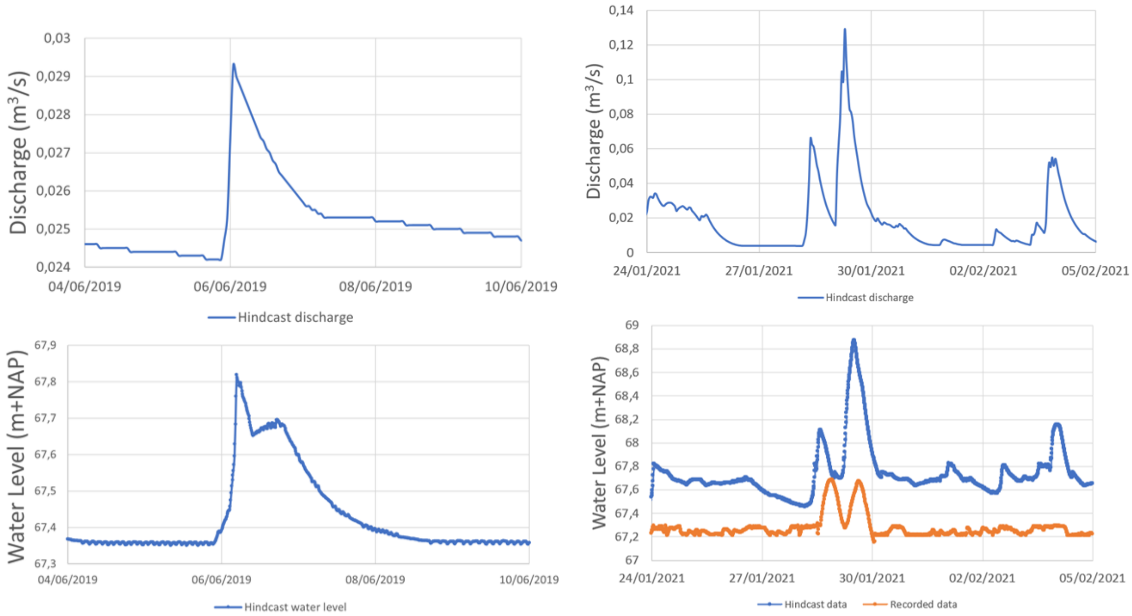
The results of the discharge and water level calculations using the precipitation scenarios in Figure 4.1 is shown in Figures 4.3 and 4.4. The results were compared to recorded water level data wherever available.




**(a)** Rainy period results

**(b)** Dry period results

**Figure 4.3:** Discharge and water level results for testing the effect of soil moisture on simulation results

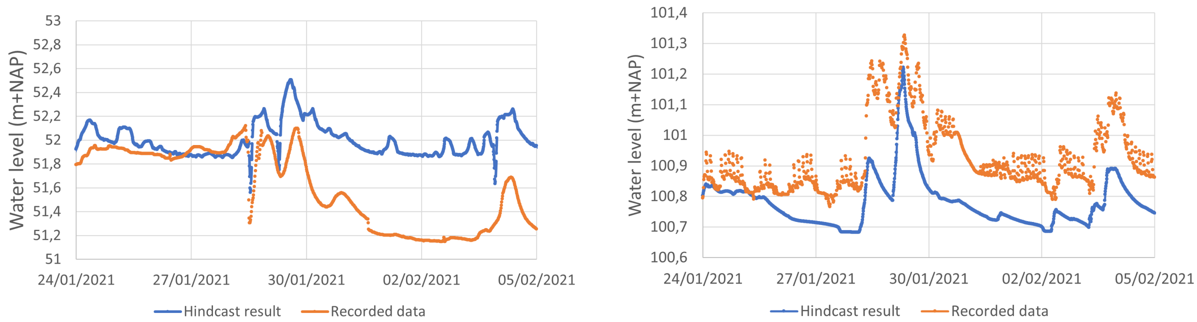



**(a)** Summer precipitation results

**(b)** Winter precipitation results

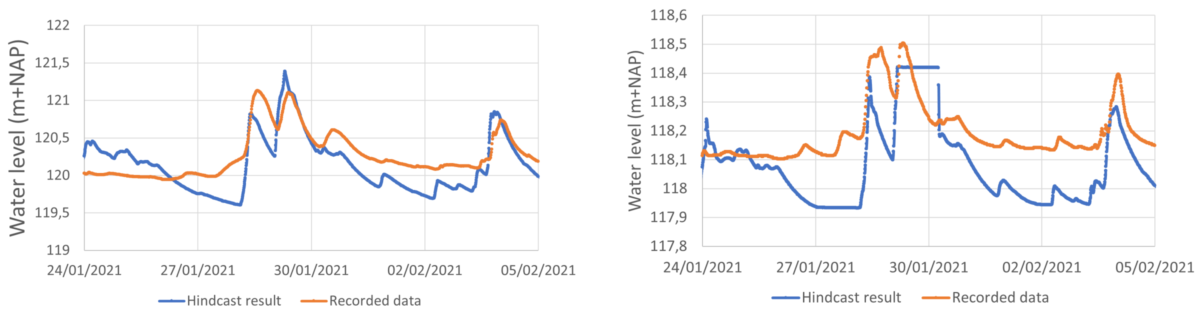
**Figure 4.4:** Discharge and water level results for testing the effect of temperature and evaporation on simulation results

The results of the water level simulation were then compared at the four other measurement points: Grote Molen, Eyserbeek Eys, Cottessen bovenstrooms, and Buffer Nijswiller beneden. The winter precipitation event results was selected because of the complete recorded data set that spans the entire precipitation event. The results of the comparison of the recorded data to the hindcasted data is shown in Figure 4.5.




**(a)** 10.H.18 - Grote Molen

**(b)** 11.H.61 - Eyserbeek Eys




**(c)** 10.H.56 - Cottessen bovenstrooms

**(d)** 12.H.34 - Buffer Nijswiller beneden

**Figure 4.5:** Comparison of differences in recorded versus simulated water level data at different measurement stations during the winter precipitation event (24 January - 5 February 2021)

## 4.3. Discussion and Recommendations

None of the four runs resulted in scenarios that demonstrated overland flow. Notably, unlike the runs representing the July 2021 floods, each of the results demonstrated water behavior that closer matched the theoretical motion of flood waves in that the water took a longer amount of time to decrease than increase [62] [56]. In each of the results (Figures 4.3 and 4.4), the discharge and water levels rises faster than it lowers, which was not demonstrated in the discharge SOBEK result shown in Figure 3.9. For each of the four scenarios, the water level peaks occur around the same time as the discharge peaks. The peaks in the discharges and water levels also have about the same magnitude in that large peaks in discharge cause large peaks in water level, and small peaks in discharge cause small peaks in water level. These similarities show a clear flow of information from precipitation inputs to HBV to SOBEK.

The effect of the soil moisture difference is seen in Figure 4.3. During the rainy period, precipitation was falling at a rate that was consistently above 10 mm/hr over the course of two weeks. Both the discharge and water level results peaked eleven times each. Meanwhile, during the period without rain, the discharge and water level in Figure 4.3b steadily decreased when there was no water entering the system through precipitation. The effect of temperature difference on the simulations is demonstrated in Figure 4.4. In the summer scenario (Figure 4.4a), the water level increases and decreases quickly, returning to the same starting water level as before the precipitation event occurred. Water did not stay in the system, suggesting that it evaporated quickly due to the higher temperature. In the winter storm scenario (Figure 4.4b), water remains in the system for longer after the precipitation event. The behavior of the river observed in the data is supported by recorded river behavior from two extreme events in the Netherlands. The 1993 and 1995 Meuse floods both occurred in the wintertime, and winter floods are more often expected in the Netherlands than in the summer due to heavier rainfall, lower temperatures, and snow melt [63].

The discharge and water level results demonstrate a clear link in information between the precipitation inputs and the discharge and water level simulations. The results also demonstrate river behavior that matches theory in terms of the shape of the flood wave. However, comparing the model results to recorded data reveals potential problems in the programs. Recorded data is unfortunately limited, so consistent comparison with all four precipitation scenarios is not possible. However, wherever data is available (Figures 4.3a and 4.4b), the simulation and the recorded data do not match. In the results of the rainy period in Figure 4.3a, the recorded data is 0.6 - 1 m below the simulated data. The greatest difference in water level between recorded and simulated data is visible in the peaks. A similar phenomenon is seen in the results of the winter precipitation in Figures 4.4b, but the simulated peaks are more than 1 m higher than the recorded peaks. The simulations did, however, succeed in predicting timing in water level peaks, as the increased water level in the simulations in both the rainy period and winter precipitation event occur at the same time as the peaks in the recorded data. The simulated data is also consistently greater than the recorded data.

If the difference between the simulated and recorded data observed in Valkenburg Hertenkamp is consistent throughout the Geul River, then the whole simulation is just offset by 0.5 - 1 m and recalibration would be simple. This is tested by analyzing the data pertaining to the winter precipitation simulation at various measurement stations throughout the Geul as shown in Figure 4.5. The winter precipitation event was chosen rather than the other three options because the winter precipitation event had the most complete recorded water level data set. Analysis of the simulation results at different measurements demonstrated differences between the simulated and recorded data at each measuring station, but the pattern in difference between the simulated and recorded data varies depending on the measuring station. For example, the measuring stations close to Cottessen bovenstrooms (Figure 4.5c), which is located closest to the boundary condition at Cottessen, has simulated water level results that closely resembles the recorded data. However, the results at Grote Molen (Figure 4.5a) show a hindcast result that is greater than the recorded data while the results at Eyserbeek Eys (Figure 4.5b) and Buffer Nijswiler beneden (Figure 4.5d) show results that are less than the recorded data. The results at Eyserbeek Eys provide a hint as to what may be going on, where the highly dynamic water level variations are visible throughout the spectrum of recorded data at that measuring station only, and do not occur at any other measuring station. After some discussions with hydrology experts familiar with the Geul catchment, it is theorized that the differences in the recorded and simulated water level results may come from hydraulic structures in the area, such as weirs. The behavior of weirs, especially those controlled by people rather than being automated, is difficult to simulate. This is also suggested in Figure 4.3a, where the recorded data does not go out of the bounds of 67.2 - 67.3 m+NAP, implying that a mechanism is controlling the water level in the area.

The results of the four precipitation scenario runs demonstrate the potential of HBV and SOBEK to accurately model the behavior of the Geul River. The HBV model behavior cannot be accurately analyzed in this study because of the lack of historic discharge records to which the simulated results can be compared. There is limited definitive conclusions that can be made for the HBV model, but since the last calibration was in 2014 [27], it may be time for another calibration. Because the difference between the historic and simulated water level data, it is easier to make recommendations in improving the SOBEK model. The current theory is that this inaccuracy comes from the hydraulic structures in the area and possible changes in land use. This can be improved within the SOBEK models. SOBEK 1D Rural has the option within the model to input the hydraulic structures present within the area. Calibrating these hydraulic structure nodes and ensuring accuracy between the simulated and the actual structures can increase the accuracy of the water level simulations.

Improvement of the measuring stations will also improve the quality of the models. Installing more discharge measuring stations along the Geul will provide more historic discharge data that the model can use to calculate more accurate discharge simulations. The presence of historic discharge data will also make it easier to gauge any possible issues in the discharge modelling. Consistently collecting historic discharge and water level data will also provide a complete set of historic data without gaps in between. Improving the recording technology will also ensure that data is collected even during a flood. During the July 2021 event, some measuring stations were flooded and went offline, which is exactly what is not supposed to happen. Raising the stations to a higher elevation or waterproofing the casing are possible solutions to this issue.

As previously stated, none of these simulations showed a flooding scenario and rather modelled the behavior of the Geul River within the river banks. Since these models are intended to be used to warn for floods, improving the models for simulating the behavior within the river banks is not the main priority. Implementing a 2D or quasi-2D grid into SOBEK is priority in improving the models for predicting floods. However, since the simulated water level data is higher than the recorded water level at Valkenburg, calibrating the models will lower the risk of potential false alarms.

# 5 Communication of Warnings

Calculating accurate models is only one component of an effective FEWS. It is also important that the programs calculate accurate models in a timely manner that allows for enough time to prepare and evacuate. Calculating a river model quickly and accurately depends not only on the modelling programs but also on the type of data inputs. Data availability and technological ability determine what kind of modelling is practical for the modelling of the Geul: real-time recording, nowcasting, or forecasting. Nowcasting is a form of short-term forecasting, predicting up to two hours into the future. In this chapter, data records containing historic precipitation and discharge measurements in the Geul are measured to calculate the travel time of a flood wave to reach Valkenburg from Cottessen. The travel time is compared to the necessary lead time for evacuation from Valkenburg, which is 1.5 - 2.5 days [33]. Recommendations are made regarding the data source determined to be better for the Geul FEWS.

## 5.1. Methodology

Two different data collection options are explored to see which one is better for the Geul FEWS: warning based on meteorological observations (precipitation) and warning based on fluvial observations (discharge). Discharge and precipitation are chosen as the tested inputs due to the availability of the data within the Delft-FEWS system and because these same data inputs were used in forecasting during the July 2021 event. Historic precipitation and discharge data from 2021 found within the Delft-FEWS interface is used for this research. The precipitation data is provided by KNMI pluviographs (Figure 2.10) and the discharge measurements are collected by the discharge measuring stations located along the Geul. Four precipitation events that have a noticeable peak in precipitation and cause a noticeable peak in the river discharge are chosen. The dates corresponding to the four events are listed in Table 5.1.

| Event | Date Range |
|---|---|
| 1 | 12 - 13 January |
| 2 | 13 - 14 March |
| 3 | 11 - 12 April |
| 4* | 3 - 5 June |

**This event contains two discharge peaks, labeled as ”a” and ”b.”*

**Table 5.1:** Peak rainfall and discharge events found within 2021 historical data

The travel time of the wave throughout the Geul is measured at the most upstream (10.Q.29 - Cottessen) and most downstream (10.Q.36 - Meersen) measuring stations located along the portion of the Geul River within the Netherlands. The locations of these measuring stations in comparison to Valkenburg is illustrated in Figure 5.1. There is no discharge station located within Valkenburg. Cottessen is located approximately 18 km upstream of Valkenburg and Meerssen, the nearest discharge measuring station to Valkenburg, is located approximately 8 km downstream. The calculated travel time of the discharge wave between Cottessen and Meerssen is longer than the travel time of the flood wave from Cottessen to Valkenburg. The discharge of the Geul River that flows through Belgium is also measured, but this data is collected by an international party and is not accessible available within the Dutch Delft-FEWS interface at the time of this study.


**Figure 5.1:** Locations of discharge stations Meersen and Cottessen relative to Valkenburg

The time between a detected peak in precipitation and a detected discharge peak in Meerssen (hereonafter referred to as *precipitation timing*) is compared to time elapsed between the detection of a discharge peak in Cottessen to the detection of that same discharge peak in Meerssen (hereonafter referred to as *discharge timing*). This value is compared to the necessary time required for Valkenburg to act in the event of a possible flood. In Valkenburg, 1.5 - 2.5 days are needed for vulnerable populations to safely evacuate the area if a major flood event is anticipated [9] [33]. If the travel time is greater than or equal to the 1.5 - 2.5-day range, then real-time recording and nowcasting of discharge and precipitation is possible. If the travel time is less than the 1.5 - 2.5-day range, then real-time recording and nowcasting is not possible and forecasting must be considered.

## 5.2. Results

The four tested events shown in Figures 5.2 to 5.5 highlight the precipitation and discharge peaks used to calculate the results in Table 5.2. The exact date and time of each of the peaks are called out.

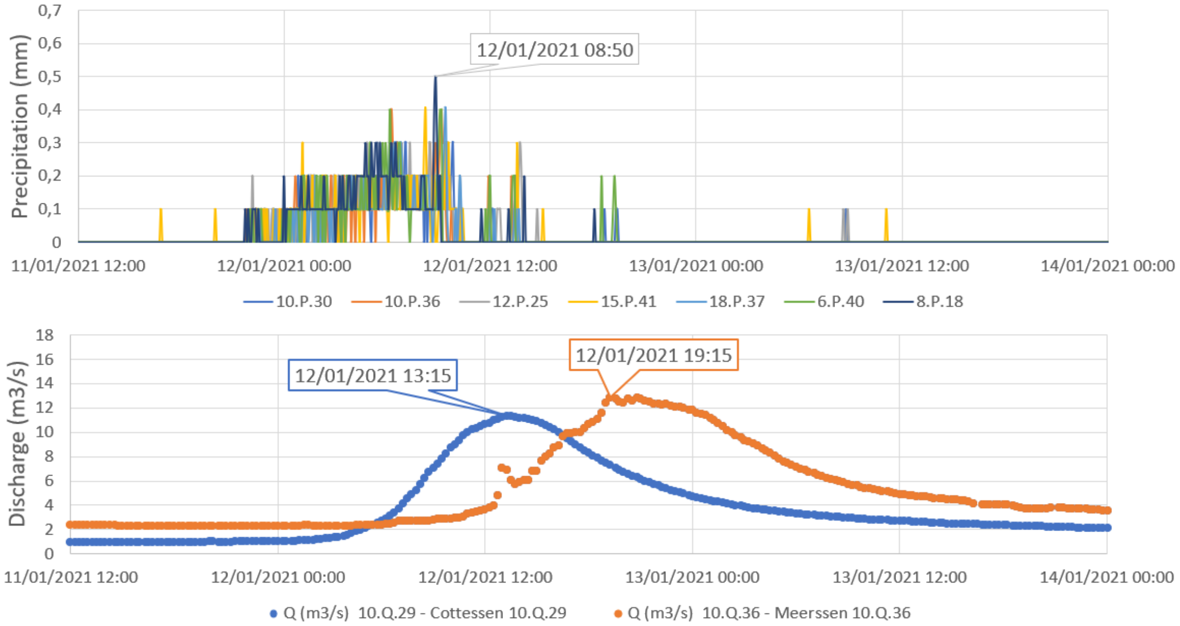



**Figure 5.2:** Precipitation and discharge event 1

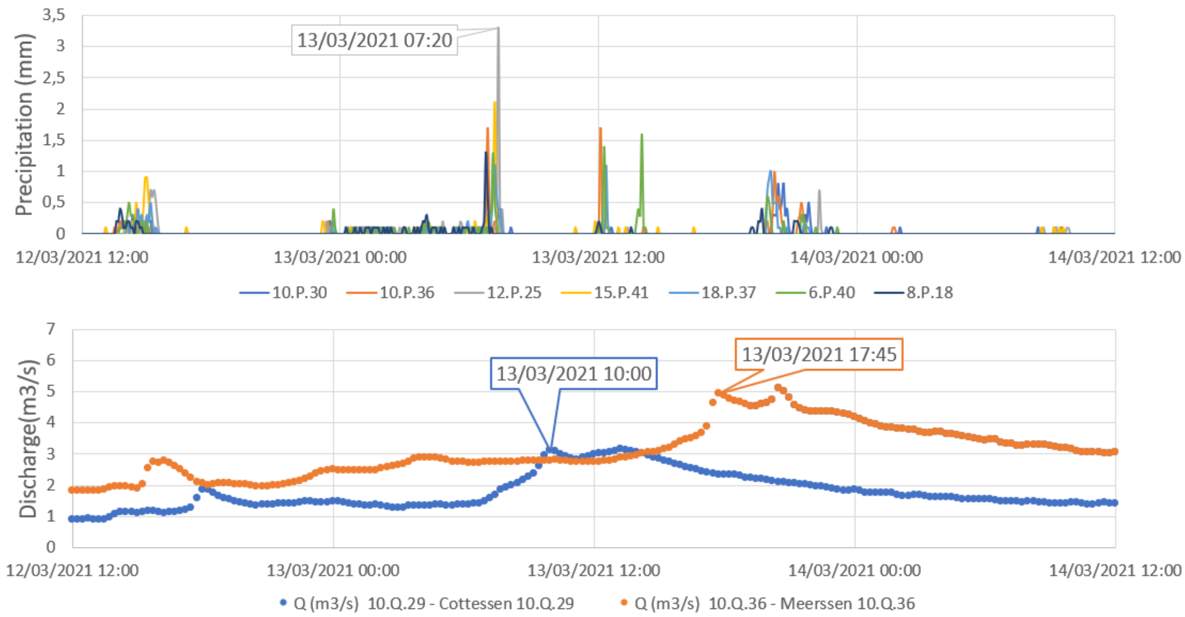



**Figure 5.3:** Precipitation and discharge event 2

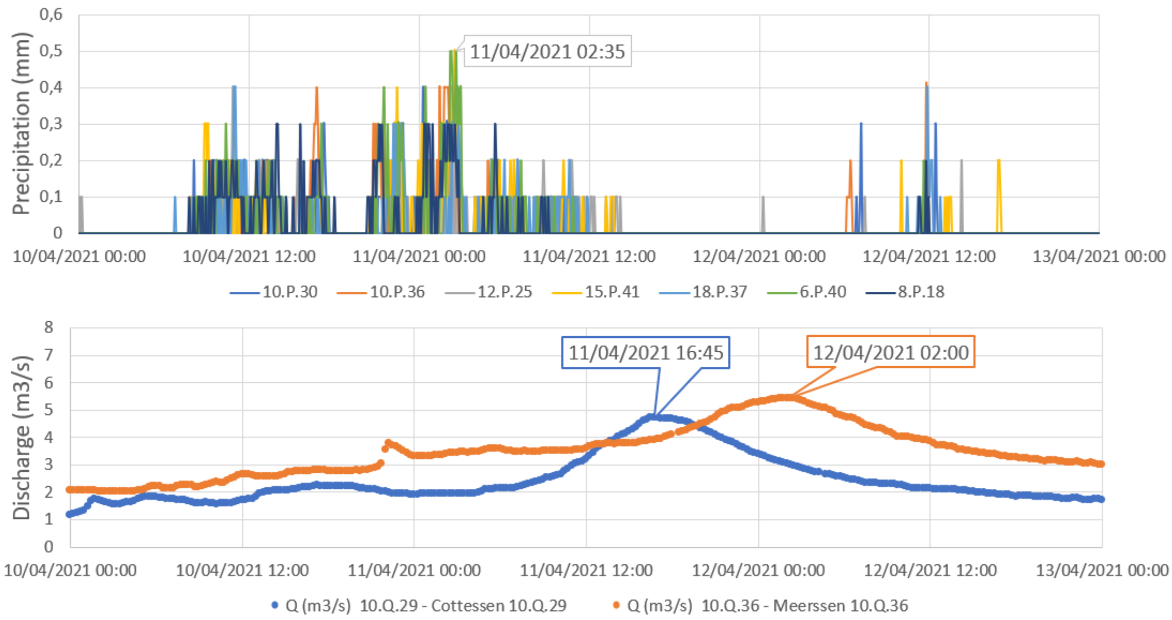



**Figure 5.4:** Precipitation and discharge event 3

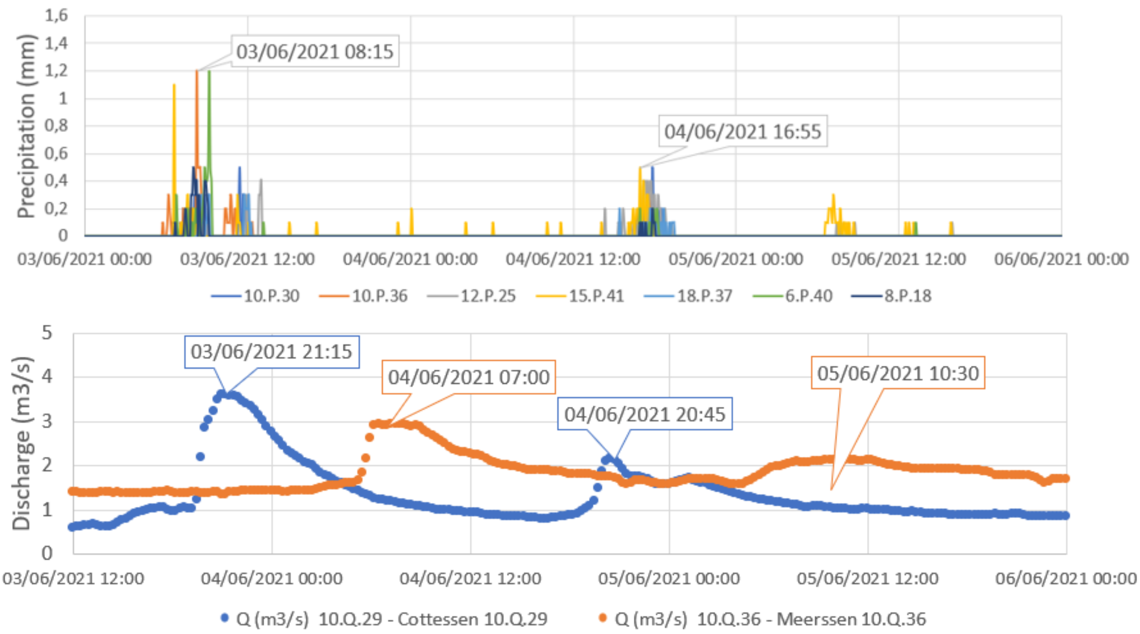



**Figure 5.5:** Precipitation and discharge event 4

The calculated travel time of the flood wave to Meersen starting with the precipitation peak and the discharge peak is summarized in Table 5.2.

| Event | Precipitation Timing | Discharge Timing |
|---|---|---|
| 1 | 10 hours 25 minutes | 6 hours 0 minutes |
| 2 | 10 hours 25 minutes | 7 hours 45 minutes |
| 3 | 23 hours 25 minutes | 9 hours 15 minutes |
| 4a | 22 hours 45 minutes | 9 hours 45 minutes |
| 4b | 17 hours 35 minutes | 13 hours 45 minutes |

**Table 5.2:** Difference in time between rain and flood peaks

## 5.3. Discussion and Recommendations

The Geul Catchment is highly reactive to excess precipitation. During the July 2021 event, the river flooded less than 24 hours after the precipitation began [9]. The current method of communication of warnings takes time and risks decreasing an already limited amount of time to act. The current practice involves a monitor receiving an alert and then deciding whether to inform the rest of the Waterboard. The Waterboard then informs the Safety Region of the alert, who then informs the population of Valkenburg (see Figure 2.14). The method of warning the population through cell phones can happen immediately, but there are three separate groups of people that are informed before this can happen Thus, ensuring a sufficient lead time of 1.5 - 2.5 days is very important preparation and safe evacuation for residents of Valkenburg. Accurate data and models can therefore lead to quick and decisive communication, optimizing the time for action.

Comparison of the precipitation timing and the discharge timing to the necessary lead time (1.5 - 2.5 days) indicates that, although the precipitation timing is longer than the discharge timing, neither option is suitable for real-time observation or nowcasting for the Geul FEWS. The discharge timing is less than 12 hours in all but event 4b. Given that Valkenburg is located upstream from the Meerssen discharge measuring point, the actual travel time of the flood wave from Cottessen to Valkenburg is even shorter than the calculated discharge time. The precipitation timing is longer, ranging from 10 hours to almost 24 hours. In a river with a slower reaction time, real-time precipitation observation or nowcasting based on precipitation data is possible. However, because the Geul River reacts very quickly, forecasting is the only viable option that can be used if the population of Valkenburg is to be warned in time to act.

The waves studied using historical data in Figures 5.2 - 5.5 move this distance of the Geul River in the Netherlands (25 km) quickly. The travel time of the flood wave from Cottessen to Meerssen varies in all four cases, ranging from approximately 6 - 14 hours. This variation depends on several factors that affect the velocity of water, such as the duration and intensity of the precipitation event. None of the discharge waves in Figures 5.2 - 5.5 are high enough to flood, and a wave of a similar magnitude to the wave in July 2021 would be expected to travel much faster. Flood waves that are dominated by resistance move faster as the wave gets bigger [56]. In a flooding event, the people of Valkenburg would have even less time than the results summarized in Table 5.2 to act if discharge at Cottessen was being monitored for the FEWS. The difference in precipitation peak and discharge peak in Meersen offers more time (10.5 - 23 hours), which has a better lead time than measuring from peak to peak, but still not enough time to evacuate [33].

During the July 2021 event, the precipitation and discharge conditions in the Geul catchment were monitored through forecasts. An anomalous precipitation event was detected on 11 July 2021, two days before the rain started to fall, whereas the discharge forecasts did not detect a flood wave resulting from the forecasted rain. Both the precipitation and discharge forecasts changed every hour up until the rain began to fall on 13 July. It wasn't until the precipitation event began that the discharge forecast detected a potential flood, less than 24 hours in advance [9]. The information regarding the forecasting that occurred during the July 2021 event suggests that precipitation forecasting can provide reliable information two days in advance. The results of this study indicate that real-time precipitation monitoring gives 10 - 24 hours' notice before a flood wave caused by a precipitation event affects Valkenburg. Therefore, using precipitation forecasts potentially gives Valkenburg 2 1/2 - 3 days lead time to prepare in the event that an anomalous event is detected [9] [33].

Forecasting using precipitation data or discharge data presents a trade-off between timeliness and accuracy. While precipitation data forecasts can be available several days in advance, they are more likely to quickly change due to the sensitivity of precipitation conditions on the atmosphere and may be more inaccurate. Precipitation forecasts in July 2021 suggested the possibility of a large event two days before the beginning rainfall and three days before the flood peak in Valkenburg, but the amount of precipitation changed every hour until the event actually happened, which can be seen in Figure 2.5 [9]. Discharge data at Cottessen or somewhere more upstream in the Geul is far more accurate and leaves little doubt that a flood is actually occurring, but the results in Table 5.2 suggests very little time for action. Despite the precipitation forecasts detecting a high rainfall event, the discharge forecasts did not detect the possibility of an unusual event until the rain started falling, which was one day before the flood peak in Valkenburg [9]. This suggests that trusting the precipitation forecasts despite the chances of changing can result in more accurate warnings and a greater chance to prepare effectively for a disastrous event.

While precipitation and discharge real-time monitoring alone are not sufficient to deliver information to protect Valkenburg, it is possible to use multiple forms of predictive modelling to improve the accuracy of the monitoring. Precipitation forecasting is able to detect anomalies two days in advance, and forecasting the discharge along with the precipitation can also reduce the chance of a false alarm. The discharge forecasts were insufficient during the July 2021 event, but this can be improved with more information provided to the system. The Geul River begins in Belgium, more than 25 km upstream from Cottessen, where the discharge is also monitored [64]. Belgian discharge data was unavailable in the Delft-FEWS interface that was used in this study, so the travel time of the flood wave through Belgium could not be determined. However, because approximately half of the river is located in the Netherlands and the total length of the Geul river is 58 km, monitoring the discharge in the Belgian portion of the Geul has the potential to double the lead time from 6 - 14 hours to 12 - 24 hours. Using Geul discharge data collected in Belgium provides more data regarding the behavior of the Geul, which can possibly increase the accuracy of the forecasted models. International collaboration of water management authorities in Belgium and the Netherlands can lead to saving more lives and preventing more damage from future river floods. Thankfully, this is currently being applied in the real-time water level and discharge monitoring website WaterStandLimburg.nl, which provides real time river data using data from both Belgium and the Netherlands to inform people in Limburg [65].

What can further increase the lead time, besides improved data collection and modelling, is delivering information to the population sooner in the chain of communication. This can be done either by shortening the chain of communication or by ensuring that the methods used for communication between the necessary parties is quick and efficient. One possible solution is to inform the population of Valkenburg earlier. Instead of the Safety Region delivering the information to the population, the Water Board can deliver the information to the population and to the Safety Region simultaneously. Although this communication chain is standardized throughout the Netherlands, it may be possible that an exception can be made in Limburg given that the Geul River is highly reactive and information must be delivered as soon as possible. If this cannot be done, then steps must be taken to ensure that warnings are communicated and acted upon immediately to avoid delays due to technological or human error.

This study was limited not only to data collected within the Netherlands, but also to historic data records. Although the July 2021 event used forecasted data to model potential outcomes, this study was limited only to prerecorded data and did not collect or forecast new data based on historic records. Future studies on the forecasting of precipitation and discharge data have the potential to improve the forecasting technology to make more accurate models. The study was also limited to suggestions of technological improvement rather than suggesting better methods of communication, as the methods of communication are standardized throughout the Netherlands and is more political than scientific.

# 6

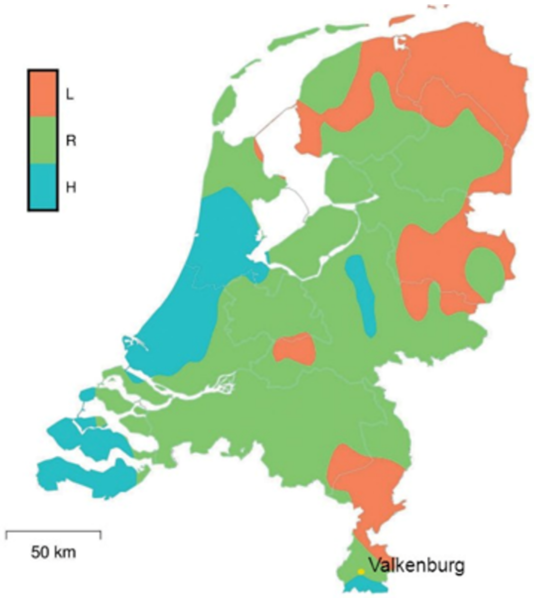
# Flood Extent Map for Valkenburg

To properly warn residents of a certain location of the flood risk they may be exposed to, studying the likelihood of flooding frequency and intensity provides vital information to stakeholders. With good knowledge of the flood risk of the area, flooding patterns can be better understood and vulnerable residents can be warned more effectively. Making flood risk information available also allows residents to take precautionary measures to protect their homes and businesses against flooding. This chapter describes the process of creating a flood extent map for Valkenburg using rainwater statistics inputted into the predictive modules adapted in Chapter 3. Rainwater statistics for the Netherlands were used to create test rainstorms for seven different return period cases. These test rainstorms were then inputted into the HBV module in Delft-FEWS and then the SOBEK-1D2D model created in Chapter 4. The floods created in the coupled model were then used to create a flood map, which provides more information on how Valkenburg can possibly flood in different scenarios.

## 6.1. Methodology

Test precipitation events are designed to create simulated floods that are used to create the flood map. To create the test rainstorms, the historic precipitation data for the July 2021 event was manipulated to create floods associated with precipitation events of a certain return period, which is chosen according to available rainfall statistics in the Netherlands [66]. The floods resulting from these test precipitation events are compared to the July 2021 flood extent as a control (see Figure 3.13). Seven test precipitation events were created using statistics with the following return periods: one-year, five-year, ten-year, twenty-five year, fifty-year, hundred-year, and thousand-year [66]. This precipitation data is summarized in Figure 6.1. Using precipitation events that have known return periods are used to simulate flood extents that can be associated with probabilities of occurrence. This is especially useful for communication of warnings and evacuation planning.

The total precipitation experienced by the Geul catchment during the July 2021 flood is about 146 mm (see Figure 3.6) and the return period associated with the event is 1200 years [9]. However, according to Figure 6.1, the return period for this precipitation amount should be within the 250- to 500-year range. To create precipitation events that are more specific to the Geul catchment, area reduction factors (ARFs) are applied to the rainfall statistics to convert point-averaged estimates into estimates more accurate to the Geul [67],[68]. ARFs are most effective when calculated specifically for the catchment area for which they are applied. No ARF is available specifically for the Geul catchment, so ARFs calculated for the Netherlands in general are used instead. These values are shown in Figure 6.2 [68]. Several assumptions are made in applying the ARFs to the test precipitation events as the data is limited and not specific to the Geul. The total area is equal to the areas of all six catchments, which equals approximately 330 $km^2$. The ARF values are not available for precipitation periods longer than one day. According to the reduction factor graphs, ARFs are higher for lower return period precipitation events than they are for higher return periods. Using ARF data for precipitation event durations of one day, the appropriate ARFs for the four-day precipitation events are interpolated [66] [69] [68].




| R | | | | | |
|---|---|---|---|---|---|
| | Dagen | | | | |
| Gehele jaar | 1 | 2 | 4 | 8 | 9 |
| 2× per jaar | 30.4 | 38.6 | 50.4 | 68.3 | 72.3 |
| 1× per jaar | 36.8 | 46.0 | 59.3 | 79.4 | 83.8 |
| 1× per 2 jaar | 43.8 | 54.0 | 68.6 | 90.5 | 95.3 |
| 1× per 5 jaar | 54.2 | 65.5 | 81.4 | 105.1 | 110.2 |
| 1× per 10 jaar | 63.0 | 74.9 | 91.6 | 116.1 | 121.4 |
| 1× per 20 jaar | 72.6 | 85.0 | 102.1 | 127.0 | 132.4 |
| 1× per 25 jaar | 75.9 | 88.5 | 105.6 | 130.5 | 136.0 |
| 1× per 50 jaar | 86.9 | 99.5 | 116.6 | 141.5 | 146.9 |
| 1× per 100 jaar | 98.9 | 111.4 | 128.1 | 152.3 | 157.6 |
| 1× per 200 jaar | 112.1 | 124.2 | 140.0 | 163.2 | 168.3 |
| 1× per 250 jaar | 116.7 | 128.5 | 143.9 | 166.7 | 171.7 |
| 1× per 500 jaar | 131.7 | 142.5 | 156.4 | 177.5 | 182.2 |
| 1× per 1000 jaar | 148.2 | 157.5 | 169.4 | 188.3 | 192.7 |

**Figure 6.1:** Rainfall statistics for average rainfall region in the Netherlands used to calculate the flood extents for the flood map [66]

According to these statistics shown in Figure 6.1, Valkenburg is located in an area experiencing average rainfall [66]. Given that the control precipitation file contains rain data that lasted three-and-a-half days, rainfall values associated with rainfalls of four days are used. The ARF data used to convert the point rainfalls to area-averaged rainfalls in the Geul catchment are shown in Figure 6.2.

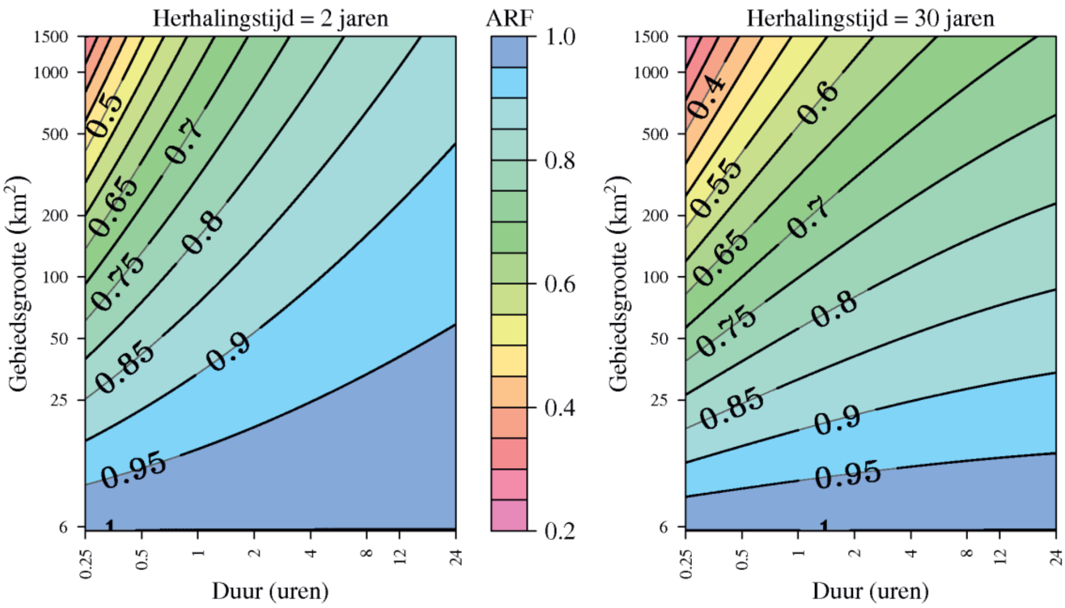



**Figure 6.2:** The area reduction factor values assigned to the Netherlands based on the size of the catchment, the duration of the storm, and the return period of the storm. [68].

The precipitation files made with this data are inputted into HBV to calculate discharges associated with the return periods of each of the precipitation scenarios. The calculated discharges are then inputted into the SOBEK 1D2D-coupled model created in Chapter 4. The SOBEK 1D2D-coupled model simulates floods from the calculated discharges and returns water depth and velocity files associated with each of the test precipitation scenarios. The simulated floods are named for the return period associated with the data used to design the corresponding precipitation event.

To compare the water depth and velocities of the different flood scenarios, three points for water depth and three points for velocity are also selected along the river profile over the 2D grid. Points for the water depth and velocity were chosen at the city center, to the east of the city center, and to the west of the city center to examine water behaves during a flood in Valkenburg. The water depth files for each of the test precipitation scenarios are converted into shapefiles and then layered atop one another in QGIS, creating a flood extent map for Valkenburg.

## 6.2. Data Inputs

Table 6.1 contains the total rainfall amount for each of the calculated precipitation events. The July 2021 event was not adjusted with an ARF and serves as a comparison. The probability $p$ of each event occurring represents the average probability of occurrence of each event over an indefinite period [70].

| $T_0$ | $p$ | Original Rainfall Amount (mm) | Estimated ARF | Adjusted Total (mm) |
|---|---|---|---|---|
| 1 | 1 | 59.3 | 0.95 | 56.3 |
| 5 | 0.2 | 81.4 | 0.9 | 73.3 |
| 10 | 0.1 | 91.6 | 0.85 | 77.8 |
| 25 | 0.04 | 105.6 | 0.8 | 84.5 |
| 50 | 0.02 | 116.6 | 0.8 | 93.28 |
| 100 | 0.01 | 128.1 | 0.8 | 102.48 |
| 1000 | 0.001 | 169.4 | 0.8 | 135.52 |
| July 2021 | 0.00083 | N/A | N/A | 146 |

**Table 6.1:** Rainfall amounts per return period converted to area-averaged precipitation amounts based on the associated area reduction factor [68]

## 6.3. Results

The precipitation data for all seven test events were then manually inputted into the HBV module in Delft-FEWS to return corresponding discharges. The rainfall was inputted into the model from 13 - 17 July to compare the discharge results to the simulated July 2021 flood event, and the results are compared to the July 2021 discharge in Figure A.2. A comparison of the same discharge data inputted during different seasonal conditions can be found in Appendix B.

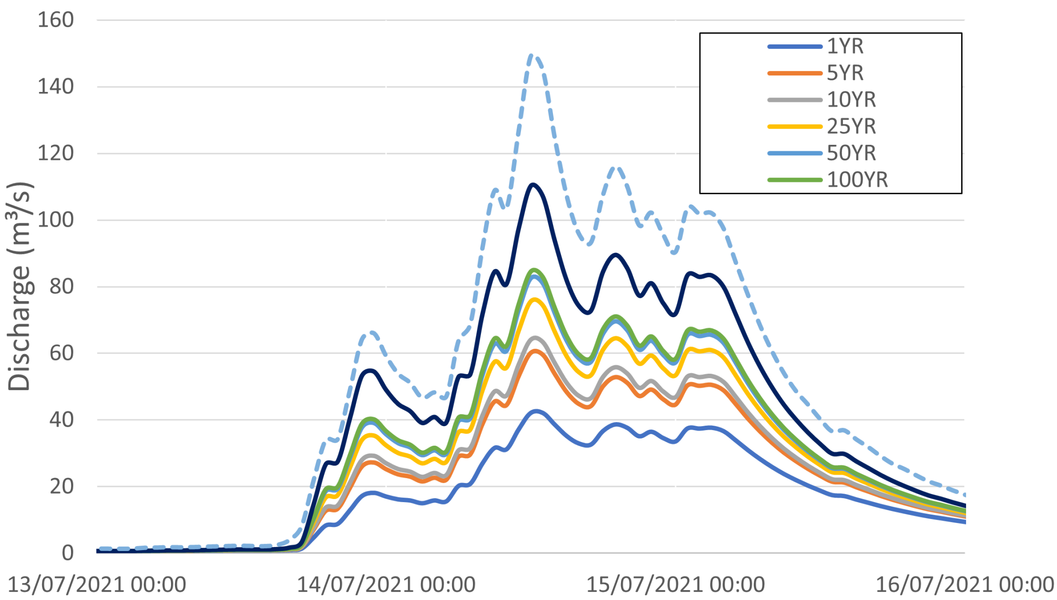



**Figure 6.3:** Discharges for each of the seven return periods calculated using the precipitation inputs summarized in Table 6.1

The discharges were inputted into SOBEK1D2D to return water depth and velocity files. To compare the results of each of the seven results, the water depths and velocities for each of the runs were compared at the chosen points shown in Figure 6.4. The points are labeled according to the assigned label in the existing SOBEK model.

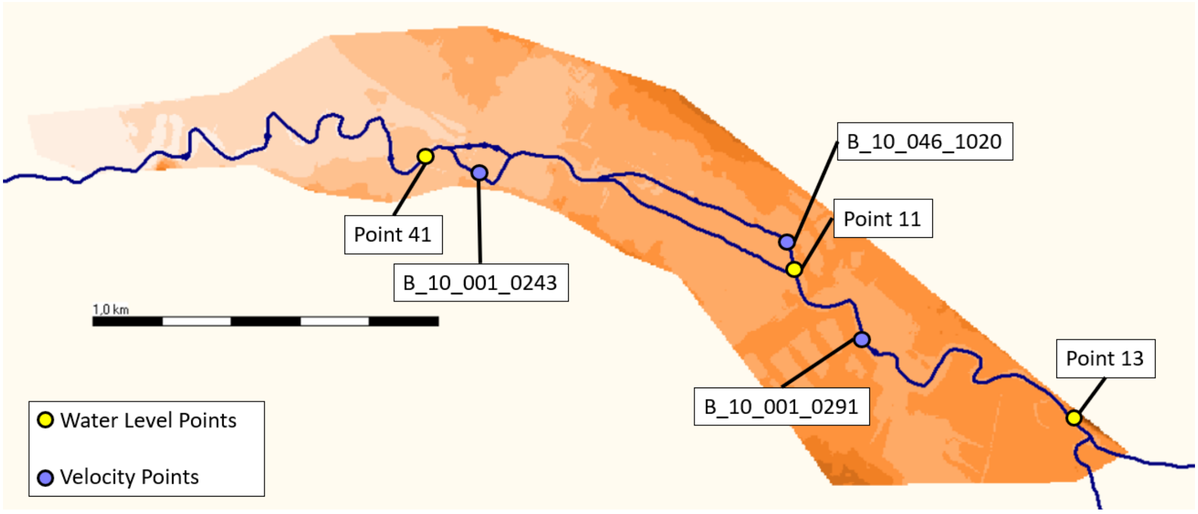
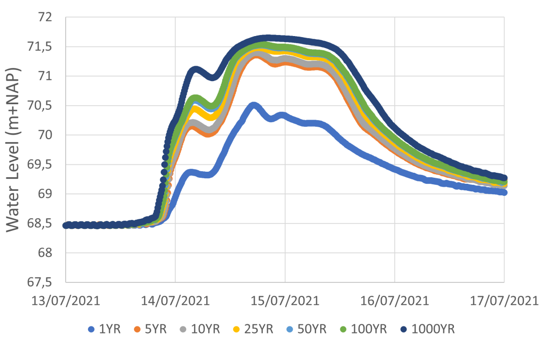
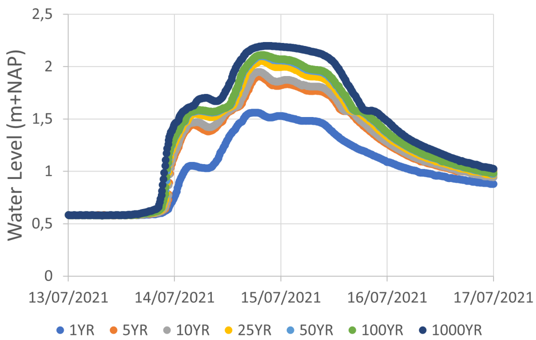



**Figure 6.4:** Locations of water level and velocity points on the 1D2D coupled SOBEK model

The water depth and velocity results at each of the points are compared in Figures 6.5 to 6.7.

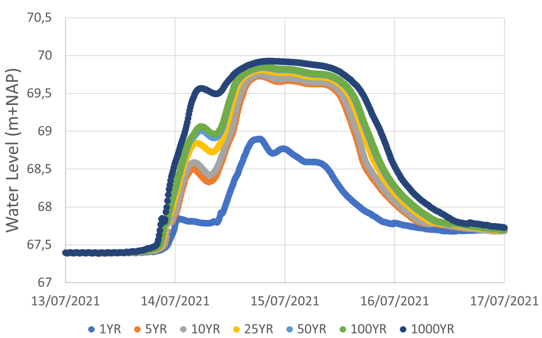



**(a)** Water level at Point 13

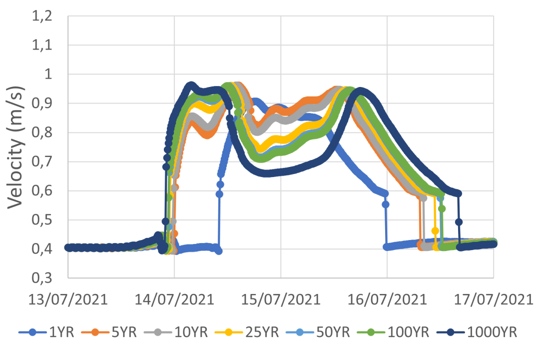



**(b)** Velocity at B_10_001_0291

**Figure 6.5:** Comparison of water level and velocity upstream of Valkenburg center

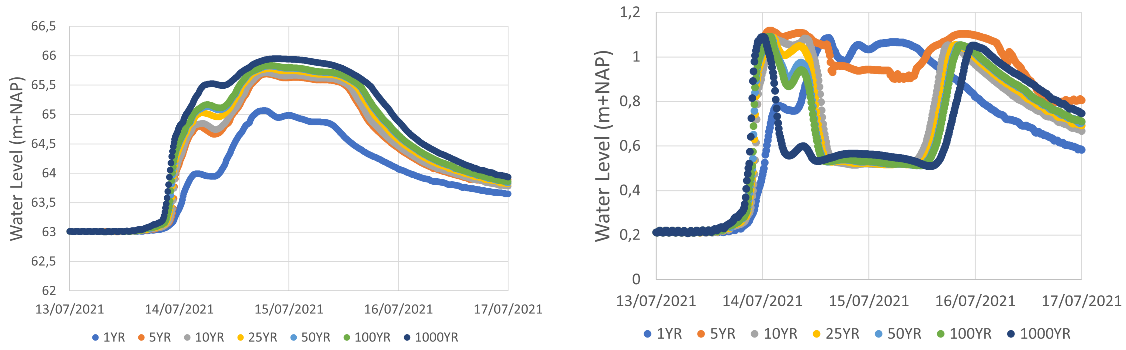



**(a)** Water level at Point 11




**(b)** Velocity at B_10_046_1020

**Figure 6.6:** Comparison of water level and velocity at Valkenburg center




**(a)** Water level at Point 41

**(b)** Velocity at B_10_001_0243

**Figure 6.7:** Comparison of water level and velocity downstream of Valkenburg center

Each of the seven flood simulations outputted an associated water depth file. The seven water depth files were converted into shapefiles in QGIS. Each file was homogenized to one color to show the extent of the simulated flood. The seven homogenized files were then layered on top of one another to create the flood map showing each of the seven flood extents associated with the return period precipitation event used to create said extent. The result can be seen in Figure 6.8. The individual SOBEK flood files that show the water depths can be found in Appendix B.

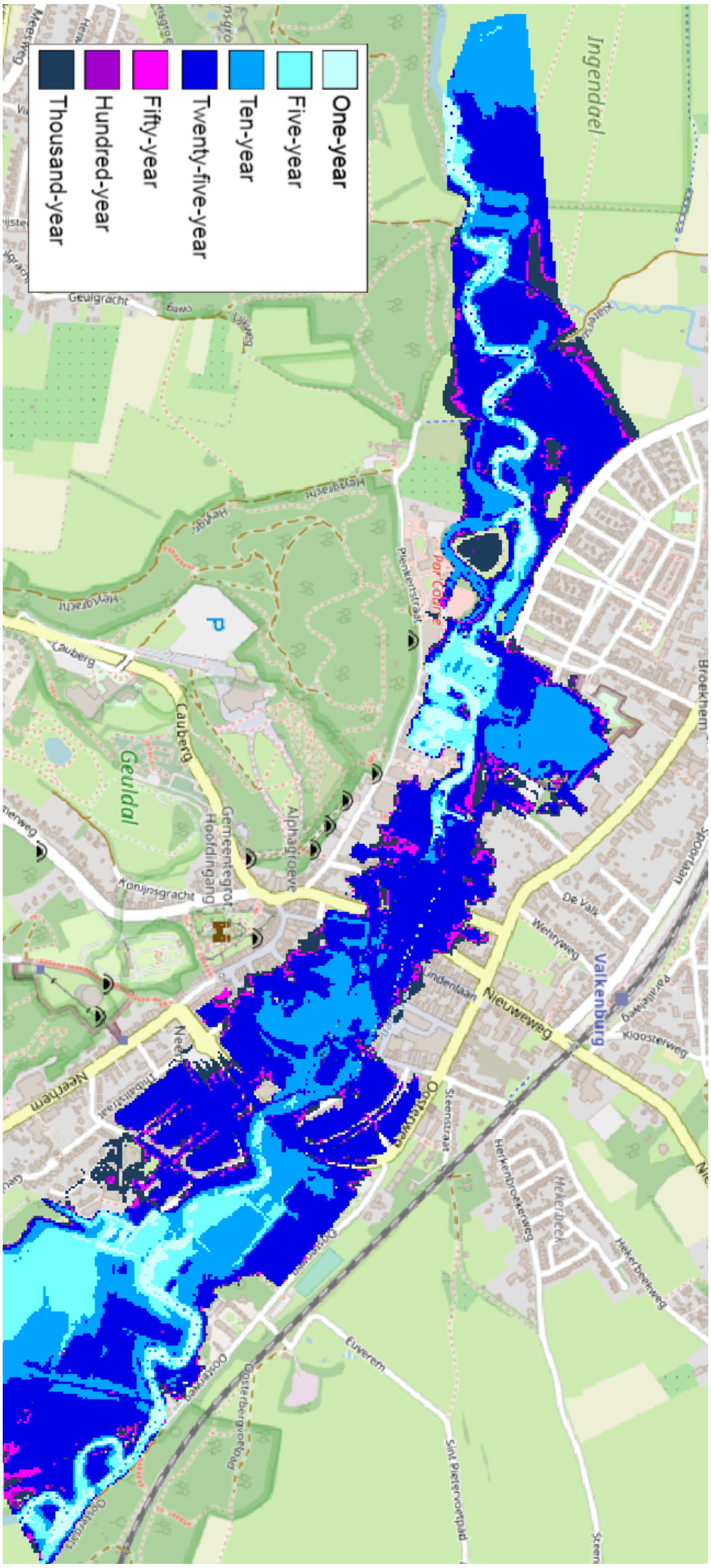



**Figure 6.8:** Flood risk map for Valkenburg created from simulating seven different precipitation events of various return periods, listed in the legend

## 6.4. Discussion and Recommendations

The flood map was simulated and layered using data sets that come from several assumptions. First, the data upon which the simulations are based comes from the rainfall of the July 2021 flood. This rainfall was already an extreme event due to its amount of precipitation as well as its duration of three and a half days. The simulated rainfalls were based on this extreme event using statistics pertaining to four day rainfall events, which is a duration and amount greater than the control data. This was chosen due to the lack of data available for the exact duration of the July 2021 flood and statistics for four-day rainfall events were the closest available relevant statistic. Using overestimated statistics may have contributed to higher discharges for each of the scenarios. The high statistics resulted in almost every scenario flooding, as a discharge of more than 47 $m^3/s$ leads to flooding the Geul [13]. Use of these statistics have resulted in six of the seven scenarios flooding (Figure A.2), though the flooding in the simulation does not enter residential or business areas until the twenty-five-year scenario (Figure 6.8).

The statistics used to calculate the design precipitation events also did not specify whether the rainfall amounts corresponded to a particular season, and it can therefore be assumed that the statistics consider rainfall throughout the whole year. The discharge used to create the flood extent map was calculated by running the inputs through the HBV model from 12 - 17 July 2021 in the summer time. Running the same results in the winter time, from 12 - 17 January 2021, showed different results and can be found in Appendix B. The results were not used in the creation of the flood map found within this chapter and this comparison was done mostly to test how the discharge results would differ when run during different seasons. Overall, the discharge results for the calculations during winter were about double the results of the corresponding summer discharge results. The summer discharge results were chosen because they were most comparable to the July 2021 floods, as all other factors for the discharge calculation during the summer were identical to the original July 2021 flood simulation except for the precipitation amounts.

The ARFs used to calculate the discharges may also be a source of error. The ARFs were used to reduce the total amount of rainfall [66] to an amount more comparable to the July 2021 event, which was estimated to have a return period ranging from 1000-1500 years. The data used to determine the appropriate ARF were also calculated using statistics pertaining to the Netherlands rather than to Limburg, which has different topographic features and therefore may not be appropriately represented by the available ARFs [68] [66]. Furthermore, ARF data specific to Limburg is unavailable, and calculation of this data can improve result in more accurate discharges.

The scenarios in the extent map in Figure 6.8 are labeled using the precipitation data inputted into the HBV and SOBEK models. An extent labeled ”10-year” means that it was reached using discharge resulting from the 10-year return period of a four-day storm, which is not the same as 10-year flood. Because precipitation events that last a full four days do not happen very often [66], the true return period for the floods is likely much higher if the probability of the duration of the storm is taken into account. However, the map is still effective in showing which areas are most vulnerable based on how often they flooded, as well as general flooding patterns for the area. The simulations suggest that the center of Valkenburg is most susceptible to major flood events, while the forks in the Geul River to the east and west of the center create a bottleneck effect resulting in more frequent floods. The two areas flooded in every simulation. Map data suggests that the areas to the east and west are not as populated as the north and south areas of Valkenburg, but a senior home is located to the east of the center, which had to be evacuated [9]. The flood extent map also does not specify the water depths in the area and instead only highlights the areas where water was simulated to have flowed. As a result, the area denoting the twenty-five year flood results in Figure 6.8 appears to be nearly identical to the hundred-year area and the thousand year area. It can be incorrectly surmised that a flood from a storm with a twenty-five year return period is just as strong as a flood from a storm with a thousand-year return period. The individual flood extents, shown in Appendix B, contain the flood simulation results for each of the seven scenarios.

Although the map is effective in showing which area experienced flooding under which scenario during the simulation, it does not give insight into how badly the building in this area would be damaged. For this reason, the water levels and velocities at various points in Valkenburg were selected to briefly demonstrate the differences. Figures 6.5 to 6.7 show the comparison of the water level and velocity in each of the scenarios at the points shown in Figure 6.4. Because all the discharges except the discharge associated with the one-year precipitation scenario exceed 47 $m^3$/s (see Figure A.2), all the scenarios flood except for the one-year precipitation event flood. This is visible in Figure 6.6. The research in Chapter 4 indicates that Valkenburg floods when Hertenkamp (Point 11) exceeds 69 m+NAP, which occurs in every scenario except for the one-year scenario. The velocities show different behaviors of the water at different points. For the velocities at the points in the center and at the west of Valkenburg (B_10_046_1020 and B_10_001_0243) the velocity of the water slows down, but at the the point to the east of Valkenburg (B_10_001_0291) the velocity increases. This is likely due to the behavior of water as the water separates into the two tributaries at Valkenburg Hertenkamp. Meanwhile, most of the water entering Valkenburg during the July 2021 came from the east, which explains the higher velocity in the east. This suggests that the buildings to the east of the center are more susceptible to damage from the force of the water whereas the buildings to the west and at the center are more susceptible to damage due to water remaining in the area longer.

# 7
# Cost-Benefit Analysis of FEWS and Evacuation

Having a warning system in a community allows for residents and business owners to protect their goods, their properties, and most importantly, themselves, in the event of a potential flood. A working FEWS gives residents time to take actions that can lessen the cost of damage, such as relocating moveable goods, placing sandbags or guards outside doors and windows, and evacuating. Investing into a FEWS as well as an evacuation plan has the potential to reduce the cost of damage from a flood compared to the cost of damage of the same flood without any warning or prior preparation. This chapter shows the calculation of the costs of damage without a FEWS and the costs of damage with a FEWS. These values are compared in a small-scale cost-benefit analysis in the case study of a forecasted precipitation event that has a small chance of causing a high-impact flood. The values are then compared for all explored flood possibilities to determine how much in damage costs the FEWS saves for the people of Valkenburg. These cost benefit analyses answer the fourth research question. Modelling the potential floods that may harm a city is only one portion of a working FEWS. The only way for vulnerable citizens to respond to warnings is for that warning to be properly communicated to the parties responsible for keeping the community safe. However, determining whether to warn along the Geul River is a unique challenge. The probability of flooding depends on the location of the precipitation event due to the hilly nature of Limburg. The Geul catchment is also highly reactive to extreme precipitation events, so a huge flood could occur two days after an extreme precipitation event, which was the case for July 2021 [9]. A warning that correctly predicts a flood event in time for action could save lives and moveable goods, but a warning that incorrectly predicts a flood happening (also known as a false alarm) could result in unnecessary evacuation costs as well as emotional harm [48]. This chapter focuses on the data that can be used to make a warning in time to allow for appropriate stakeholder reaction as well as the monetary consequences of warning through a cost-benefit analysis.

## 7.1. Methodology

### 7.1.1. Costs of Damage for Each Scenario

The cost benefit analyses compare the costs of damage with and without FEWS for each of the flood scenarios explored in Chapter 6. To calculate the costs of damages, the water depth and velocity files outputted during the simulations of each of the seven flood scenarios are inputted into the Damage and Casualties Model (Schade en Slachtoffer Model, hereinafter referred to as *SSM2017*) [52]. The program outputs the direct damage costs, the number of affected people, and the number of expected casualties for each flood scenario. The direct damage cost value is adjusted to reflect other costs that come as a result of flooding, such as indirect damages and monetary valuation of loss of life [48], [71]. To estimate the costs of damage with and without preparation, the following formula was developed [48] [72] [52]:

$$D = D_{SSM} - (f_1 \times D_{mov}) + (f_2 \times D_{Cas}) + (f_3 \times D_{Ind}) \tag{7.1}$$

where:

| | |
|---|---|
| $D$ | is the damage calculated for the particular case (€) |
| $D_{SSM}$ | is the damage calculated using the SSM2017 model (€) ([52]) |
| $D_{Mov}$ | is the calculated damage of moveable goods found within the SSM2017 model (€) |
| $D_{Cas}$ | is the monetary valuation of loss of life (€) ([71]) |
| $D_{Ind}$ | is the indirect costs of damage (€) |
| $f_1$ | is the factor of human behavior for moveable goods (-) |
| $f_2$ | is the factor of human behavior for loss of life (-) |
| $f_3$ | is the factor of human behavior for indirect damage (-) |

The direct cost of damage $D_{SSM}$ (€) is the SSM2017 cost result. The cost of moveable goods $D_{Mov}$ (€) is calculated using the SSM2017 result calculations. For each scenario, the costs of damage to the following categories within the SSM2017 are summed to get the cost of damage to moveable goods in ($D_{Mov}$): "Overige: Vervoermiddelen" (vehicles), "Woningen: Begane grond apartamenten (inboedel)" (household effects in ground-floor apartments), and "Woningen: Eengezinwoningen (inboedel)" (household effects in single-family homes) [48], [52]. The monetary valuation of loss of life $D_{Cas}$ (€) is calculated by multiplying the monetary value for loss of life used for flood risk calculations in the Netherlands by the number of casualties estimated per flood scenario by SSM2017. This monetary value does not represent the economic value of a human life, but rather how much money is willing to be spent to protect a human life. This value is calculated at €6.7 million in 2012 [71] [73]. All damage costs are adjusted for inflation to reflect the 2022 value cost.

Indirect damages $D_{Ind}$ include costs incurred from displacement or lack of revenue so long as the damaged building cannot be used as intended. For this research, the indirect cost of damage is taken to be the same cost per day as evacuation. The cost of evacuation and the cost of indirect damage both involve the cost of displacement of the population for both businesses and residents **2012ACountries** [46]. For this research, the cost of evacuation is calculated using a time frame of three days: one day to leave, one day for the event to occur, and one day to come back [48]. The costs of evacuation include the costs of transportation away from the area as well as the costs of lost wages due to business closure or other circumstance resulting in the inability to work. In the event that citizens are evacuated for more than three days due to the severity of the event, the costs for every day more than three days is factored into indirect damage costs.

The number of affected buildings and the costs of evacuation for each group is determined using the SSM2017 model, map data, census data, and expert estimation. The costs for transportation is determined using the price of fuel or trains. The costs of lost wages per business The indirect damage costs are considered the same as the cost of evacuation per day, but are calculated over a longer time frame depending on the severity of the flood event. These time frames are based off personal estimations from people who experienced floods in Hurricane Sandy in 2012 as well as the July 2021 flooding event [46], [47].

The factors of human behavior $f_1$, $f_2$, and $f_3$ are meant to represent human response due to several factors, including but not limited to effectiveness of the FEWS, effectiveness of communication, trust of the population in the FEWS, and knowledge of effective preparation techniques [72]. The damage was calculated for worst-case scenario and best-case scenario. Worst-case scenario, $D_1$, sets the factors for human behavior in Equation 7.1 to $f_1$ = 0, $f_2$ = 1, and $f_3$ = 1.

$$D_1 = D_{SSM} + D_{Cas} + D_{Ind} \tag{7.2}$$

Best-case scenario, $D_2$, assumes that the FEWS works perfectly and the human response prevents any kind of ectra damage. These assumptions set the factors for human behavior in Equation 7.1 to $f_1$ = 1, $f_2$ = 0, and $f_3$ = 0.

$$D_2 = D_{SSM} - D_{Mov} \tag{7.3}$$

The values $D_1$ and $D_2$ are calculated for each scenario to better understand the economic impact of investing in FEWS. These values are to be used in both cost-benefit analyses. The files associated with the July 2021 event were also used to calculate associated $D_1$ and $D_2$ values to serve as a comparison to the rest of the scenario results.

### 7.1.2. Cost-Benefit Analysis of Possible Flood Event

A cost-benefit analysis is conducted to understand the economic impact of successfully warning and preparing for a potential flood event. The analysis is conducted given a scenario where a potential anomalous precipitation event is detected, but its severity is uncertain. The analysis considers a scenario that have three possible outcomes based on the floods simulated in Chapter 6. The probability values associated with each outcome are not based on an actual event and rather are chosen to reflect a scenario where there is a small chance of a disaster happening, which occurs often in disaster management [48] [74]. The calculations for this scenario are done deterministically to simplify the demonstration.

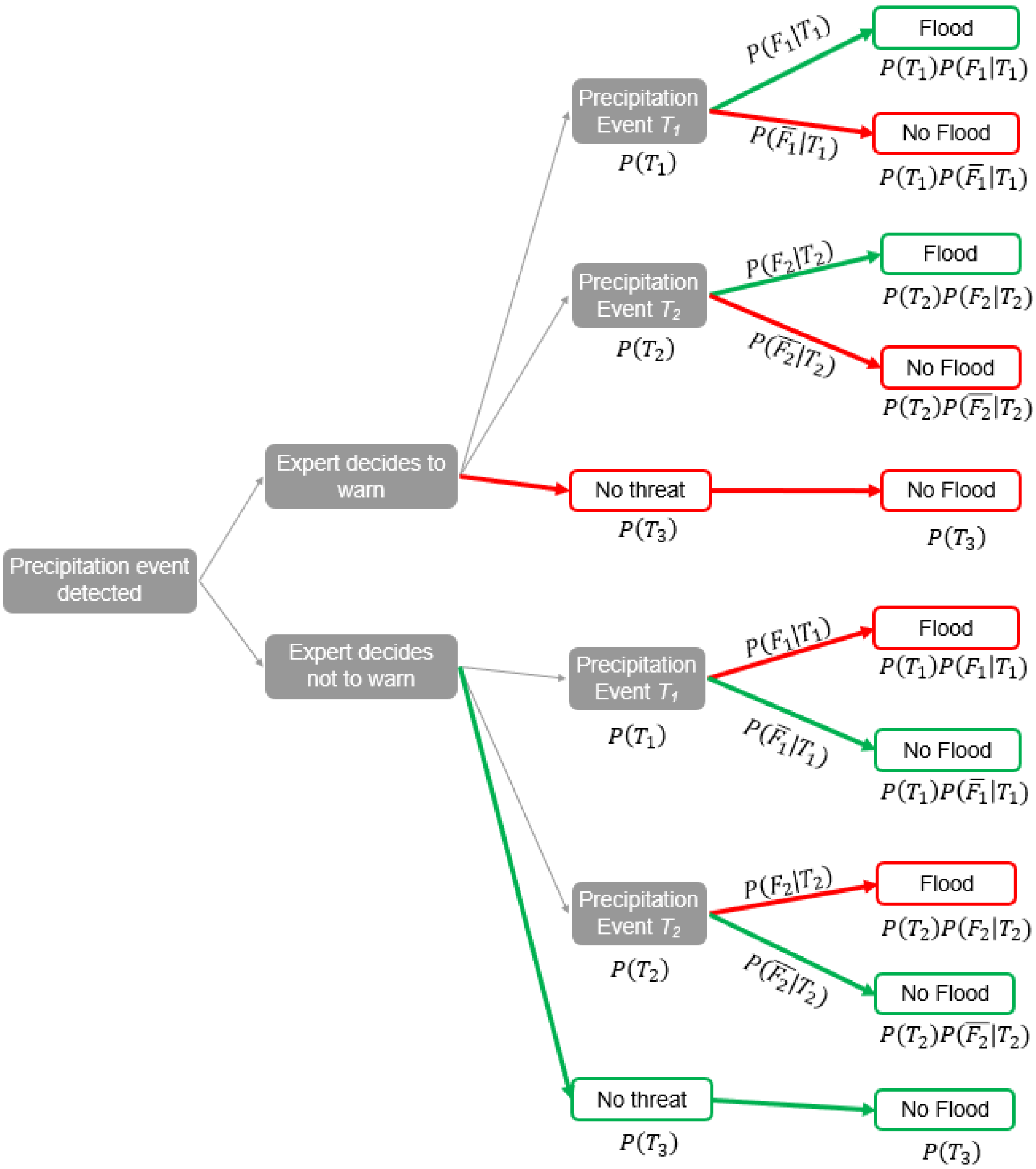



**Figure 7.1:** Deterministic decision tree for decision-making case study. Green indicates a correct decision where the expert decision correctly predicts the final outcome. Red indicates an incorrect decision where the expert decision does not predict the final outcome.

For this hypothetical scenario, the expert assigned to monitor the Delft-FEWS interface receives an alert that an event might occur that might cause a flood in Valkenburg. Given the findings from Chapter 5, the alert is based on precipitation forecasting. At this point in time, it is uncertain how the precipitation event will develop, as it could cause a flood of minimal consequence (Scenario $T_1$) or a flood of significant consequence (Scenario $T_2$). There is also a chance that the scenario will devolve and result in no flood in Valkenburg (Scenario $T_3$). For each of these three scenarios there is an assigned probability of the scenario occurring, $P(T_n)$. Given the hilly terrain in Limburg, a second probability $P(F|T_n)$ reflects the probability of the precipitation event causing a flood if it rains over the Geul Catchment. Figure 7.1 shows the possible outcomes of the potential scenario as well probabilities associated with each scenario.

The main question being explored through the cost-benefit analysis is whether it is economically justifiable to pursue a warning. The final costs for each of the possible end scenarios in Figure 7.1 depend on whether or not the monitoring expert decides to issue a warning, prompting people to act and prepare for the event. The probabilities for all scenarios with and without warning are explored using the decision tree in Figure 7.1. When warning, there is the chance that the expert will make the correct decision (warning and flood occurs, or warning and flood does not occur) or the incorrect decision (warning and flood does not occur, or not warning and a flood occurs). Making the incorrect decision can negatively impact the trust in the system, therefore eroding its effectiveness in future. In Figure 7.1, the ”incorrect” decisions are highlighted in red and the ”correct” decisions are highlighted in green.

The final comparison of the cost-benefit analysis is the difference in costs between the scenario where the warning is issued and the citizens prepared and the scenario where no warning was issued. The damage costs $D_1$ and $D_2$ for each of the scenarios in Figure 7.1 are calculated and compared. The formulas and costs considered for each of the scenario are shown in Table 7.10 [70].

| | Event | | Probability | Cost |
|---|---|---|---|---|
| Warn | T1 | Flood | $P(T_1) \times P(F_1|T_1)$ | $D_2$ + evacuation (no zones) for $T_1$ |
| | | No Flood | $P(T_1) \times P(F_1'|T_1)$ | Evacuation (no zones) for $T_1$ |
| | T2 | Flood | $P(T_2) \times P(F_2|T_2)$ | $D_2$ plus evacuation for $T_2$ (zones 1, 2, and 3) |
| | | No Flood | $P(T_2) \times P(F_2'|T_2)$ | Evacuation for $T_2$ (zones 1, 2, and 3) |
| | No threat | No Flood | $P(T_3)$ | No cost |
| Don’t Warn | T1 | Flood | $P(T_1) \times P(F_1|T_1)$ | $D_1$ for $T_1$ |
| | | No Flood | $P(T_1) \times P(F_1'|T_1)$ | No cost |
| | T2 | Flood | $P(T_2) \times P(F_2|T_2)$ | $D_1$ for $T_2$ |
| | | No Flood | $P(T_2) \times P(F_2'|T_2)$ | No cost |
| | No threat | No Flood | $P(T_3)$ | No cost |

**Table 7.1:** Associated probabilities and costs for each of the outcomes of Figure 7.1 with and without warning

### 7.1.3. Cost-Benefit Analysis of System Investment

A cost-benefit analysis is conducted to explore whether the use of only a warning system as a means of flood protection is financially feasible or has some kind of economic benefit. This is accomplished by comparing the reduction of damage costs with the FEWS (including Delft-FEWS monitoring software, an effective communication and evacuation plan, as well as local trust in the system) for all seven precipitation scenarios explored in Chapter 6 to the cost of investing in a FEWS network. The following formula is used for this comparison [70]:

$$I < E(\Delta D) \tag{7.4}$$

where $I$ is the cost of investment and $E(\Delta D)$ is the change in expected damage. If the change in damage costs is greater than the cost of investment, then the investment can be considered worthwhile.

First, the investment costs are calculated. The investment consists of the cost of investing in FEWS and is represented by the following formula:

$$I = I_{FEWS} + I_{Evac} + I_{Annual} \tag{7.5}$$

where $I_{FEWS}$ is the initial cost of FEWS, $I_{Evac}$ is the cost of evacuation, and $I_{Annual}$ is the annual cost of hosting the system. The cost of evacuation varies depending on the severity of the expected flood scenario. Therefore, the cost of evacuation for each scenario is found and graphed over the probability. The total expected cost of evacuation over all scenarios is calculated by finding the area under this curve. The method of calculation is illustrated in 7.2.

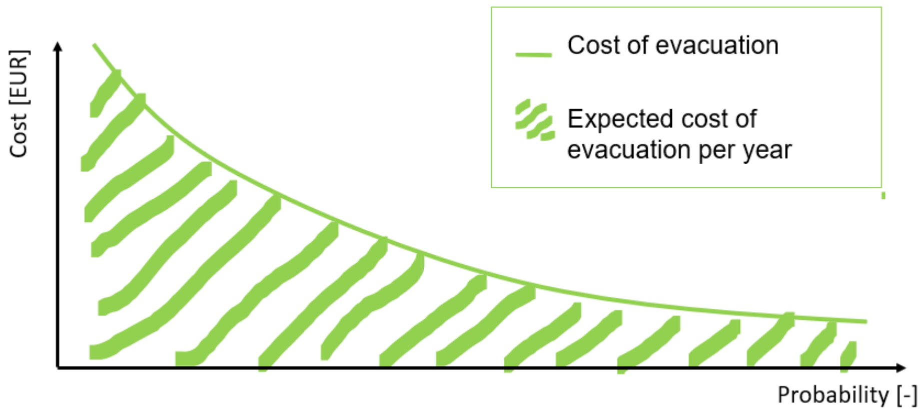



**Figure 7.2:** Calculation of total expected cost of evacuation per year **JonkmanFloodNOTES**

The probability over which the evacuation costs are plotted is calculated by the inverse of the return period. This value represents the average frequency of occurrence and represents the probability of the seven scenarios occurring over an indefinite period of time.

The FEWS network also has an annual cost for maintaining the system and keeping the network online. The net present value (NPV) of the annual cost over the lifetime of the FEWS ($t \to \infty$) is calculated. The NPV of the annual investment costs of FEWS is calculated using the following formula:

$$I_{Annual} = \sum_{n=1}^{\infty} \frac{C_i}{(1+r)^n} \approx \frac{C_i}{r} \tag{7.6}$$

where $C_i$ is the yearly cost and $r$ is the interest rate.

The change in the expected cost of damages $E(\Delta D)$ is calculated by finding the difference between the yearly expected cost of damage for the scenario with FEWS and the yearly expected cost of damage for the scenario without FEWS. To find the expected yearly costs for both $D_1$ and $D_2$, the same method as the calculation for the expected costs of evacuation illustrated in Figure 7.2 is used. The values $D_1$ and $D_2$ are calculated for each of the seven scenarios and plotted over the probability of occurrence, and the area under the $D_1$ and $D_2$ curves is found and taken as the expected yearly cost. The change in damages $E(\Delta D)$ is found by subtracting the areas under the curves shown in Figure 7.3.

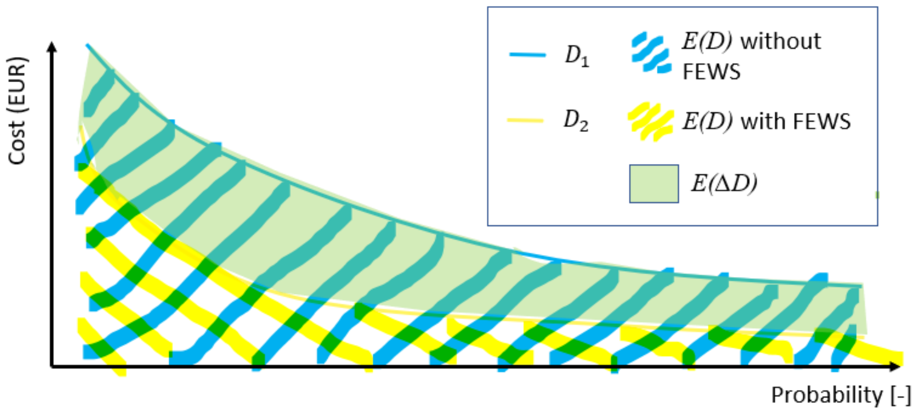



**Figure 7.3:** Calculation of total expected damage **JonkmanFloodNOTES**

After calculating the areas under the curves as shown in Figure 7.3, the NPV for the difference in total expected damage is calculated using Equation 7.6. The interest rate $r$ is also assumed to be 4%. This value is then compared to the total cost of investments in FEWS and evacuation to draw a comparison between the costs and benefits of FEWS in Valkenburg.

The sensitivity of equations 7.2 and 7.3 to the human factors $f_1$, $f_2$, and $f_3$ for $D_{Mov}$, $D_{Cas}$, and $D_{Ind}$ are tested by calculating the total cost of damages excluding one of the factors. Doing so tests which of the three damage sources $D_{Mov}$, $D_{Cas}$, and $D_{Ind}$ have the greatest impact on the total damage costs. The results of $D_1$, $D_2$, and the damages excluding each of the three damage sources based on human behavior factors are compared. Conclusions are drawn regarding which of the factors has the greatest impact on decreasing damage costs.

## 7.2. Inputs

### 7.2.1. Cost of Evacuation Assumptions

Evacuation assumptions were made with the help of the flood extent map in Figure 6.8, resulting in the determination of evacuation "groups" shown in Figure 7.4. The costs of evacuation of these groups were also calculated for both horizontal and vertical evacuation.

Campgrounds located to the east and west of Valkenburg center are determined to be Group 1. These areas were inundated in all flooding scenarios shown in Figure 6.8. Campgrounds are leisure businesses that would not be enjoyed in flooding situations. Only horizontal evacuation is possible from campgrounds. The only cost considered for evacuation is loss of revenue to campground management. Map data suggests that there are approximately 10 campgrounds with 100 spots each. The calculations are made assuming half capacity to average out the peak and off-peak seasons over a whole year. The costs per spot found using business websites of the campgrounds average to €50 per spot.

Group 2 is determined to be ground-flood businesses and apartments located in the center of Valkenburg. Looking at Figure 6.8 suggests that the center of Valkenburg floods in more extreme flooding circumstances (25-year scenarios or more). The affected parties include restaurants, cafes, and stores, senior homes, and ground-floor apartments due to the damage experienced during the July 2021 flood [9]. Vertical evacuation is not possible as these businesses and residences do not have access to a second floor [75]. Evacuation of businesses was calculated by assuming the revenue for restaurants, cafes, and stores using census data. Map data suggests 20 restaurants, 12 cafés, and 15 shops located in the area. It is assumed that restaurants would lose €1000 per day whereas cafés and shops would lose €500 per day. The research assumes that shops will have the option to relocate their goods to a different location, resulting in reduced damage costs. Evacuation of people from senior homes and households includes the cost of transportation, food, and shelter. Evacuation of apartment households assumes the residents travel together and stay with relatives or friends elsewhere. It is also assumed

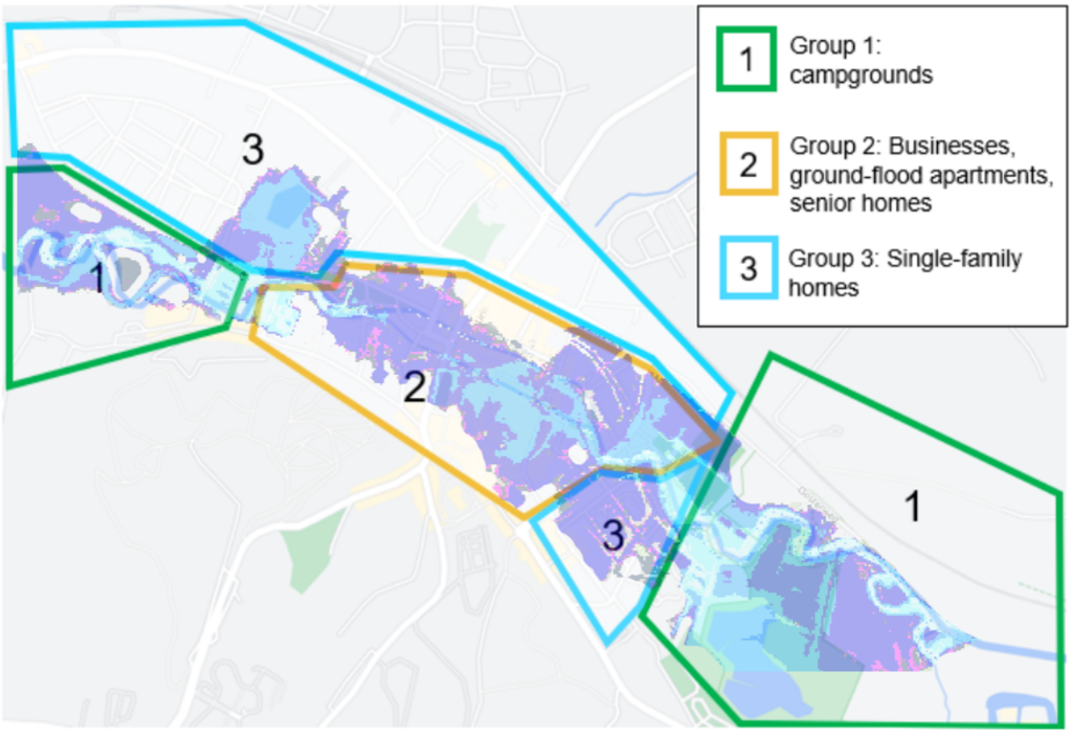



**Figure 7.4:** Approximated area locations of evacuation groups within the Geul Valley in Valkenburg using the flood map Figure 6.8.

that paid time off or work-from home eliminates the possibility of lost wages, reducing evacuation costs to €100 per household per day. Evacuation of 193 people [9] from senior homes requires greater care than evacuation of people from apartments due to the senior evacuees being deemed an at-risk group [47] [45], assumed €150 per person per day.

Group 3 considers residents of single-family homes that experience severe flooding in the most extreme circumstances (Figure 6.8). Many single-family homes in Valkenburg have a second or third floor to which residents can vertically evacuate in the instance of a smaller flood (less than 1000 year return period) at a cost of €0 per household per day. For the more extreme floods that are expected to last longer, such as 100-year and 1000-year floods, horizontal evacuation is recommended [75] [48]. The same assumptions for households of ground-floor apartments are made for the households of single-family homes (300 in total).

Given the assumptions, Table 7.2 summarizes the costs of both horizontal and vertical evacuation. It is assumed that three days are needed for evacuation: one day to leave, one day for the event, and one day to come back. Any extra day longer than three days is considered the result of a flood preventing a safe return, and this is factored into indirect costs.

| Group | Evacuees | Business Closure | Vertical | Horizontal |
|---|---|---|---|---|
| 1 | None | 10 campgrounds | N/A | € 25,000 |
| 2 | 193 people in senior homes<br>267 apartment households | 20 restaurants<br>12 cafes<br>15 shops | N/A | € 200,000 |
| 3 | 300 households | N/A | € 0 | € 38,600 |

**Table 7.2:** Assumptions and costs for horizontal and vertical evacuation for a period of three days

### 7.2.2. Probabilities of Each of the Seven Scenarios

The probabilities of each of the seven scenarios is the reciprocal of the return period, which represents the average frequency of occurrence. These values are calculated and summarized in Table 7.3 below.

| RP | Probability of occurrence |
|---|---|
| 1 | 1 |
| 5 | 0.2 |
| 10 | 0.1 |
| 25 | 0.04 |
| 50 | 0.02 |
| 100 | 0.01 |
| 1000 | 0.001 |

**Table 7.3:** Average probability of occurrence per scenario

### 7.2.3. Cost of Evacuation and Indirect Damage

The assumptions made for evacuation were done using Figure 7.4. The summary of evacuation costs is found in the table below. Evacuation is calculated over three days: one day to leave the area, one day away from the area, and one day to come back to the area. Evacuation is short because it is assumed that the evacuees go elsewhere within the Netherlands, where travel to any point in the country can be done within much less than a day.

| RP | Evacuation Group | Cost (3 Days) |
|---|---|---|
| 1 | None | € 0 |
| 5 | Group 1 | € 75,000 |
| 10 | Group 1 | € 75,000 |
| 25 | Groups 1 and 2 horizontal, 3 vertical | € 675,000 |
| 50 | Groups 1 and 2 horizontal, 3 vertical | € 675,000 |
| 100 | Groups 1 and 2 horizontal, 3 vertical | € 675,000 |
| 1000 | All horizontal | € 789,600 |

**Table 7.4:** Cost of evacuation per scenario

Indirect damages are calculated using the same costs used to calculate evacuation, as the damages are incurred from business closure or residential displacement. The time of closure or displacement is assumed depending on the severity of the scenario. Since evacuation is assumed to last three days for these calculations, any day that people are evacuated for longer than three days is factored into indirect damages [47].

| RP | Assumed Displacement Period (days) | Indirect Costs |
|---|---|---|
| 1 | 0 | € 0 |
| 5 | 3 | € 75,000 |
| 10 | 7 | € 175,000 |
| 25 | 14 | € 3,684,800 |
| 50 | 30 | € 7,896,000 |
| 100 | 180 | € 54,443,000 |
| 1000 | 365 | € 96,068,000 |

**Table 7.5:** Cost of indirect damage per scenario

### 7.2.4. Cost of Damage Without FEWS

To calculate the cost of damage without FEWS, Equation 7.2 was used. A summary of the results of the seven different test rainstorms are compared to the result of the July 2021 simulation in Table 7.6. The results from the files associated with the July 2021 simulation are also included for comparison. For the calculation of indirect costs for July 2021, the length of displacement was assumed to be the same as for the 1000-year return period determined in Table 7.5. The SSM outputs for each of the seven scenarios are listed in Appendix C.

| RP | Cas. | $D_{Cas}$ | $D_{SSM}$ | $D_{Ind}$ | Total Cost of Damage |
|---|---|---|---|---|---|
| 1 | 0 | € 0 | € 0.22 million | 0 | € 0.22 million |
| 5 | 0 | € 0 | € 0.22 million | € 75,000 | € 0.29 million |
| 10 | 0 | € 0 | € 6.08 million | € 175,000 | € 6.26 million |
| 25 | 2 | € 16.8 million | € 40.9 million | € 3.68 million | € 61.4 million |
| 50 | 2 | € 16.8 million | € 44.7 million | € 7.89 million | € 69.4 million |
| 100 | 2 | € 16.8 million | € 45.9 million | € 54.4 million | € 117 million |
| 1000 | 3 | € 25.2 million | € 54.6 million | € 96.06 million | € 176 million |
| July 2021 | 3 | € 25.2 million | € 61.8 million | € 96.06 million | € 208.9 million |

**Table 7.6:** Cost of $D_{Cas}$, $D_{Ind}$, and $D_1$ per scenario

### 7.2.5. Cost of Damage with FEWS

The calculation of moveable goods $D_{Mov}$ for each of the seven scenarios as well as the July 2021 scenario can be found summarized in Table 7.7. It was found that moveable goods make up approximately 20% of the total damage costs calculated using the SSM2017 model.

| RP | Vehicles | Household Goods (Single Family) | Household Goods (Ground-floor Apartment) | Total Cost Moveable Goods |
|---|---|---|---|---|
| 1 | € 1,289 | € 37,392 | € 0 | € 38,681 |
| 5 | € 1,289 | € 37,392 | € 0 | € 38,681 |
| 10 | € 104,442 | € 657,599 | € 335,296 | € 1.1 million |
| 25 | € 2.57 million | € 7.61 million | € 3.86 million | € 14.04 million |
| 50 | € 2.82 million | € 8.12 million | € 4.12 million | € 15.06 million |
| 100 | € 2.82 million | € 8.25 million | € 4.12 million | € 15.19 million |
| 1000 | € 3.48 million | € 9.54 million | € 5.03 million | € 18.05 million |
| July 2021 | € 3.99 million | € 10.1 million | € 5.67 million | € 19.72 million |

**Table 7.7:** Cost of damaged moveable goods $D_{Mov}$ per scenario [52]

Equation 7.3 was used to calculate the damage costs with FEWS ($D_2$) for each of the seven test scenarios and the results are compiled in Table 7.8.

| RP | $D_{SSM}$ | $D_{Mov}$ | Total |
|---|---|---|---|
| 1 | € 0.22 million | € 38,681 | € 181,368 |
| 5 | € 0.22 million | € 38,681 | € 181,368 |
| 10 | € 6.08 million | € 1.1 million | € 4.98 million |
| 25 | € 40.9 million | € 14.04 million | € 28.6 million |
| 50 | € 44.7 million | € 15.06 million | € 29.6 million |
| 100 | € 45.9 million | € 15.19 million | € 30.7 million |
| 1000 | € 54.6 million | € 18.05 million | € 36.5 million |
| July 2021 | € 61.8 million | € 19.7 million | € 42.1 million |

**Table 7.8:** Cost of damage $D_2$ (with FEWS and evacuation)

# 7.3. Results

## 7.3.1. Cost-Benefit Analysis of Decision-Making for Warning

The cost-benefit analysis was done for the scenario assigning $T_1$ as one year and $T_2$ as 100 years and using the flood extent scenarios corresponding to both return periods in Chapter 6. The probabilities assigned to the events in Figure 7.1 are listed in Table 7.9.

| Assigned Values | | | | Total Probability | |
|---|---|---|---|---|---|
| $P(T_1)$ | 0.35 | $P(F_1\|T_1)$ | 0.3 | $P(T_1) \times P(F_1\|T_1)$ | 0.105 |
| | | $P(F_1'\|T_1)$ | 0.7 | $P(T_1) \times P(F_1'\|T_1)$ | 0.245 |
| $P(T_2)$ | 0.1 | $P(F_2\|T_2)$ | 0.1 | $P(T_2) \times P(F_2\|T_2)$ | 0.01 |
| | | $P(F_2'\|T_2)$ | 0.9 | $P(T_2) \times P(F_2'\|T_2)$ | 0.09 |
| $P(T_3)$ | 0.55 | - | - | $P(T_3)$ | 0.55 |

**Table 7.9:** Values assigned to each probability included in the decision tree in Figure 7.1

Using equations 7.2 and 7.3, the damage and evacuation costs are calculated for the one-year ($T_1$) and hundred-year ($T_2$) scenarios and multiplied by the probabilities associated with the events. The resulting costs for each scenario with and without warning are listed in Table 7.10. The difference between the flood costs with and without warnings are included in the table for easier comparison.

| Event | | $P\times$ Cost with warning | $P\times$ Cost without warning | Difference |
|---|---|---|---|---|
| T1 | Flood | € 1.9 $\times 10^4$ | € 2.31 $\times 10^4$ | € 4.06 $\times 10^3$ |
| | No Flood | € 0 | € 0 | € 0 |
| T2 | Flood | € 3.14 $\times 10^5$ | € 1.17 $\times 10^6$ | € 8.58 $\times 10^5$ |
| | No Flood | € 6.08 $\times 10^4$ | € 0 | - € 6.08 $\times 10^4$ |
| No threat | No Flood | € 0 | € 0 | € 0 |

**Table 7.10:** Calculation of costs of evacuation and flood scenarios

## 7.3.2. Cost-Benefit Analysis of Expected Damge

The cost of FEWS is calculated using values estimated by experts familiar with the project. According to them, the cost to program a working FEWS is €100,000. The yearly cost is estimated to be about €20,000 to keep the system online. Using Equation 7.6 and an interest rate assumed to be 4%, the NPV of the yearly cost is calculated to be of €500,000. Therefore, using Equation 7.5, the total cost of investing in FEWS is €600,000.

The costs of damage without evacuation ($D_1$), damage with evacuation ($D_2$), and cost of evacuation ($Evac$) calculated in this chapter are summarized in Table 7.11 below for all seven scenarios.

| RP | $D_1$ | $D_2$ | $Evac$ |
|---|---|---|---|
| 1 | € 0.22 million | € 181,368 | € 0 |
| 5 | € 0.22 million | € 181,368 | € 75,000 |
| 10 | € 6.26 million | € 4.98 million | € 75,000 |
| 25 | € 61.4 million | € 28.6 million | € 675,000 |
| 50 | € 69.4 million | € 29.6 million | € 675,000 |
| 100 | € 117 million | € 30.7 million | € 675,000 |
| 1000 | € 176 million | € 36.5 million | € 789,600 |

**Table 7.11:** Summary table of values for $D_1$, $D_2$, and $Evac$

The values in Table 7.11 were plotted over the probability of occurrence found in Table 7.3 as shown in Figure 7.5. The detailed calculations for the total areas under the curves in Figure 7.5 are included in Appendix C.

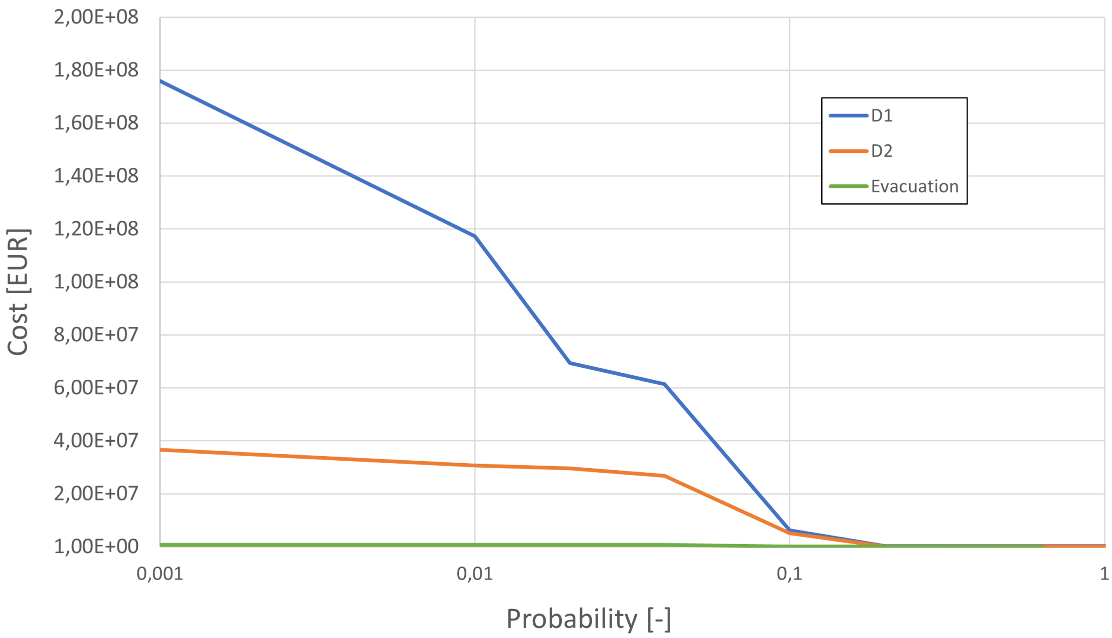



**Figure 7.5:** Comparison of of $D_1$, $D_2$, and $Evac$

By finding the total area under the cost of evacuation curve in Figure 7.5, the expected cost of evacuation was calculated to be €139,000 per year, and the NPV assuming an interest rate of 4% is calculated to be €3.48 million. Therefore, using Equation 7.5, the total cost of investments is:

$$I = \text{€}600,000 + \text{€}3.48 \text{ million} = \text{€}4.08 \text{ million} \tag{7.7}$$

Using the areas under the curves in Figure 7.5, the total expected cost of damage without FEWS and preparation resulted in an expected €10.7 million per year and the total expected cost of damage with FEWS and preparation is €4.11 million per year. The difference between these two values ($E(\Delta D)$) is €6.47 million per year. The exact calculations for the total expected costs can be found in Appendix C. The NPV of this value was calculated using Equation 7.6 and an interest rate of 4%, resulting in a cost of €162 million. These values are compared using equation 7.4.

$$\text{€}4.08 \text{ million} < \text{€}162 \text{ million} \tag{7.8}$$

The comparison shows that the benefits of investing in the FEWS outweighs the cost by a factor of 40.

### 7.3.3. Sensitivity of Damage Cost Sources

The three damage cost variables influenced by human behavior ($D_{Mov}$, $D_{Cas}$, and $D_{Ind}$) have an effect on the total possible damage that can occur as a result of the flood. To better understand the magnitude of impact of each of the three cost variables, their corresponding factors $f_1$, $f_2$, and $f_3$ where changed so that the effect of excluding one of the damage cost variables could be seen. This is visible in Figure 7.6. The results of the damage costs without each of the three damage cost variables is compared to $D_1$ and $D_2$ for each of the seven scenarios in Figure 7.6. The results for $D_1$ and $D_2$ serve as the maximum and minimum, respectively, of the costs of damage, with the range of possible values between the minimum $D_2$ and maximum $D_1$ shaded in blue.

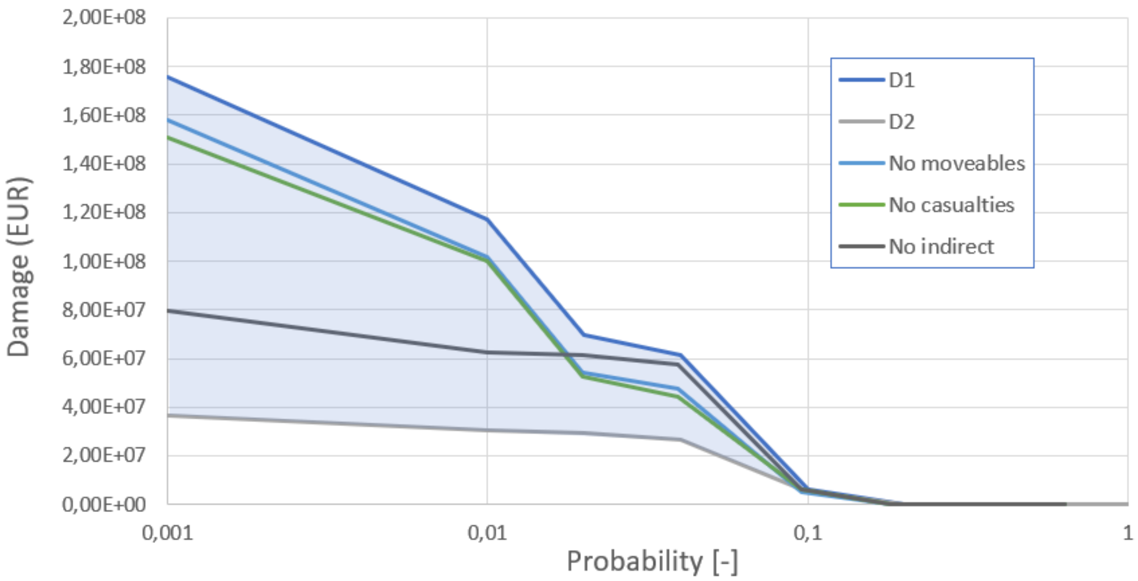



**Figure 7.6:** Comparison of effects of damage cost variables $D_{Mov}$, $D_{Ind}$, and $D_{Cas}$ on total damage costs

## 7.4. Discussion and Recommendations

The initial flood extent calculated using data pertaining to the original July 2021 event was inputted into the SSM2017 to test the system with an event of a known cost. The direct cost of damage calculated by the SSM2017 severely underestimated the damages of the July 2021 event. The calculated damage was €48 million unadjusted for inflation [52], while the actual damage was reported to range between €350 - 600 million, with €200 - 250 million attributed to the direct damages within Valkenburg alone [9]. The mayor of Valkenburg reported €400 million in damage, with half of that attributed to direct costs [23].

The SSM2017 result was underestimated by a factor of nearly 4, prompting the decision to consider a new equation meant to increase the damage costs. This new equation considered the costs of factors that could be changed without much structural intervention: moveable goods, casualties, and indirect damages [48]. Even the additional damage costs were not able to reproduce the costs of the July 2021 flood, so instead the damage costs were considered more of an estimate for how much in damage costs can potentially be saved with a working FEWS trusted by the citizens who are informed in what they can do. Improving the SSM2017 model by adjusting the value factors within the model (see Appendix B) and adding more damage factors if necessary may improve the accuracy and comparability of the results.

The decision tree in Figure 7.1 used for the calculation of the damage and evacuation are deterministic for ease of calculation and proof-of-concept and do not accurately reflect the many uncertainties that would be present in a real-life scenario. Scenarios $T_1$ and $T_2$ are assumed to be the same as the scenarios in Figure 6.8 and that each of the scenarios in Figure 6.8 has a fixed cost for the damage with and without preparation. In an actual monitoring situation, Delft-FEWS will not tell the monitor the exact scenario that will occur, nor will it tell the percentage chance of the event happening. Furthermore, many outside factors can influence the associated damage costs with and without preparation. These factors include both meteorological and fluvial that can affect the nature and the intensity of the flood as well as the human factor, which determines the response and how much in damage costs can be saved.

The calculations made for the cost of damage with FEWS, preparation, and evacuation ($D_2$) assumes very optimistic scenario where every salvageable item and vulnerable person was saved. The calculations for $D_2$ also assume that the preparations were so effective that businesses and residential homes were saved and did not have any indirect damage costs as well. This is an unrealistic expectation, but allows for the comparison of the costs with and without any kind of preparation or warning. With this optimistic calculation, the damage was able to be reduced by half in the most extreme cases. The cost of damage without preparation or evacuation in this chapter not only represents a town hit without any warning but also represents what could happen if citizens do not have trust in the system. This lack of action could happen because citizens may not trust the FEWS and have opted to ignore the warning.

The cost-benefit analysis suggests that warning and, if necessary, evacuation, is economically beneficial in both scenarios. For the smaller event $T_1$, preparation is estimated to cost €0 in actual spending. Action is not necessarily free, but steps such as moving valuables to higher elevations have minimal disruption on day-to-day life. This cost is not affected whether or not the flood actually occurs. Preparing for the greater flood $T_2$ costs €230,000 based on the assumptions made, but according to the results of the cost calculations, the reduction in damage costs is equivalent to approximately €26.67 million. This result suggests that sending a warning may be worthwhile even if the event doesn't happen because the cost of the money saved in damage reduction is ten times greater than the economic costs of preparation for this event.

What was not reflected in the decision tree or cost-benefit analysis is the consequences of preparation for the wrong event. For example, if a warning is given out for event $T_1$ but event $T_2$ occurs, then then €0 was spent on preparation but €88 million in damages occurred. In the event of over-preparation, where the population prepares for $T_2$ but $T_1$ occurs, then the cost of evacuation as well as the disruption of daily life that comes as a result is not justified. Because the evacuation costs for $T_1$ are 1/10 of the reduction in damage costs for the same event, it can be concluded mathematically that up to nine false alarms are economically justifiable, but when one takes into consideration the emotional impact of the evacuations and false alarms on the citizens, it can be argued that only one false alarm is the maximum amount. Even one false alarm may be considered one too many by some members of the population before trust and cooperation in the system begins to erode [76] [77].

Calling for evacuation when the event does not occur may cause unnecessary emotional distress and disruption of daily life, but warning a population of the chances of an event can give members of the population options. For example, the scenario $T_2$ has high consequences, but a low probability of occurring. If one were to act on the 90% chance that the event would not occur (or the 90% chance that no flood occurs even if the precipitation occurs) and *not* warn the population and the event ends up occurring, then the authority is partially responsible for not communicating this information. On the other hand, communication of every possible chance of flooding can lead to unnecessary panic. It is the responsibility of the authority to clearly communicate the possibilities of extreme events to the population along with made available that can help minimize damages and protect citizen lives. Then, the burden of action can be placed upon the citizens to take advantage of this information and do with it what they will.

In the comparison of various factors that affects cost reduction (moveable goods, casualties, and indirect damages), reveals that the effect of the different factors varies based on the size of the precipitation event. For lower precipitation events ($T < 50$ years, $p > 0.02$), reducing casualties had the highest impact on decreasing the damage costs, followed closely by reducing damage to moveable goods. For each of the seven scenarios, the reduction of casualties consistently had a higher impact on the total cost of damage than the reduction of moveable goods, reducing the total damage costs by approximately 20-25%. At precipitation events with return periods greater than 50 years ($T > 50$ years, $p < 0.02$), reduction of indirect damage had a significant impact, reducing the total cost of damage by up to 50%. The indirect cost of damage indeed contributes significantly to the total cost of damage, as seen in the July 2021 event, where indirect damage was estimated to be half of the total damage [9] [23].

The formulas used in this research only measure the damage costs that are economically quantifiable. There are also damage costs that are intangible, such as emotional damage, [52] which can disrupt daily life for affected residents significantly [9] **LogueEmotionalPennsylvania** [47] [78] [79]. As seen in Figure 7.6, moveable goods do not have the most significant impact on the total cost of damages, reducing the total by only about 10%. However, some of those moveable goods, while inexpensive, are irreplaceable due to the emotional significance of the item, such as: photo albums, home videos, hard drives, financial documents, or random objects with sentimental value [79]. Furthermore, homes or businesses damaged from floods due to lack of preparedness could result in significant disruption of daily life and can cause mental health problems [47] **LogueEmotionalPennsylvania**. These problems can then cause issues in other aspects of life, affecting work performance in adults or academic performance in children **LogueEmotionalPennsylvania**. Although these effects are harder to economically quantify, they can result in monetary damage in business or academic aspects of life.

Although Figure 7.6 implies that saving lives has a significant effect on reducing damage costs, the actual costs saved through the saving of one human life can be argued to be far greater than the calculated valuation of loss of life [71]. It is difficult to quantify the true value of a single life, and the answer varies due to personal values and ethics. The loss of a single life can have a significant impact on society because of the emotional damage caused to friends and family of the person. Even economically, the person contributed to society, and information or skills that the person could provide is now lost. The true value of a human life is difficult to measure, but worthwhile in considering the potential of an effective and trusted FEWS.

# 8 Conclusions

This chapter contains the final answers to the research question and subquestions presented in Chapter 1. The main research question is answered through the answers to the four research questions.

**Research Question 1: What data inputs and boundary conditions are needed to recreate the events of the July 2021 flood in Valkenburg?**

TO create a representative simulation of the July 2021 flood, the final reanalysis precipitation data from KNMI and an additional 2D elevation grid is needed. The final reanalysis product is the only available precipitation data product that contains data representative of the extreme precipitation event that occurred on 13 July 2021. This result produced a discharge that peaked at 140 $m^3/s$ and fluctuated around 120 $m^3/s$. The peak exceeded the expected discharge range by 10 $m^3/s$, which is likely because the HBV rainfall-runoff model is programmed to purposely overestimate the discharge to model a worst-case scenario. The 2D elevation grid is necessary to ensure an accurate water level even after inputting the final reanalysis product. Before inputting the 2D grid, the water level calculated using the final reanalysis product was calculated to be 76.5 m+NAP, which exceeded the expected water level by 6.5 m+NAP. With the 2 elevation grid, the water level was calculated to be 70 m+NAP, which met the expected water level. The presence of a 2D grid increases runtimes of the SOBEK model from a maximum of 2 hours to a maximum of 6 hours, but a quasi-2D model is a possible solution that results in more accurate discharge and water level predictions that are necessary for a working warning system without long runtimes.

**Research Question 2: How does the FEWS react to the following rainfall test cases: summer storm, winter storm, rain after a dry season, and rain after a wet season?**

The peaks in the discharge and water level data simulated by the existing HBV and SOBEK models followed similar peak patterns in both space and time. The simulated discharge and water level peaks occurred at the same time and increased by a similar magnitude. However, the simulated water level data was always offset from available recorded data at Valkenburg Hertenkamp by + 0.5 - 1 m. This behavior was consistent in all four test cases: summer storm, winter storm, rain after dry season, and rain after wet season. Further investigation into other measuring stations using the simulated winter storm data indicated that the simulated data was always either greater or less than the recorded water level data. For example, the simulated water level data was up to 0.5 m greater than recorded data at 11.H.61 - Eyserbeek Eys, but fairly accurate at 10.H.56 - Cottessen.

A theory to this inconsistency across all measuring stations suggests that the difference is due to the presence of hydraulic structures and the difficulty to model the water behavior around these structures as well as changes in land use that could be causing the simulated river behavior to deviate from expectations. This can be improved by calibrating the HBV with more accurate land usage data as well as calibrating the hydraulic structure nodes within the SOBEK model. Because the warning system is designed to warn against flooding, modelling the behavior of the Geul River within the river banks in non-flooding scenarios is not a priority of the system. All four of the scenarios tested did not produce a flood. Therefore, calibration of the HBV and SOBEK models to better model river behavior in non-flooding circumstances is at a lesser priority than designing a quasi-2D model to improve modelling in flood scenarios.

**Research Question 3: What information is necessary for a monitor to trigger a warning to give residents in Valkenburg enough time to evacuate?**

To communicate a warning of a flood that gives the citizens of Valkenburg sufficient time to act, the warning system must use forecasted precipitation data. Analyzing historic real-time precipitation and discharge data indicated that there is not enough time between detection of peaks in either precipitation and discharge and when the discharge peak reaches Meerssen, downstream of the Geul. The required lead time for Valkenburg is 1.5 - 2.5 days in advance of the event. Real-time discharge data at Cottessen, the most upstream point in the Geul, provides notice of a flood less than 12 hours before the flood reaches Meerssen. At the same time, real-time precipitation data provides notice of a possible flood 12 - 24 hours in advance, which is more effective for the warning system than the discharge data, but still not enough for safe evacuation. Neither real-time precipitation data or discharge data meet the required lead time.

Forecasting precipitation data provides a longer lead time for evacuation but reduces accuracy. This is possible up to two weeks in advance, but uncertainty increases the farther into the future the forecast goes. For the July 2021 event, the two-day precipitation forecast detected an anomalous event, while the two-day discharge forecast did not. Although real-time discharge monitoring of the flood waves at Cottessen is a more accurate source of data, the timing of the availability of the data does not allow for enough time to safely evacuate if necessary. Only discharge data within the Netherlands was available for this study, so discharge data from the Geul in Belgium was not studied. Using Belgian discharge data could potentially provide an accurate monitoring data source while also increasing the lead time. Until this is done, relying on forecasted precipitation for warnings gives two days in addition to the 12-24 hours to warn a community and have the community prepare and evacuate safely, if necessary.

**Research Question 4: Under which circumstances is warning and evacuation cost-effective?**

Conducting a cost-benefit analysis on the decision of whether to warn in an event where the chance of extreme damage had a 1% chance of occurring found that delivering a warning to vulnerable people was always economically beneficial, even in the event of a false alarm. The cost-benefit analysis weighed the probability and costs of warning versus not warning for a one-year flood and a hundred-year flood. For the one-year flood, preparation involved movement of goods and it was therefore assumed there was no cost. In the event of a false alarm (warning given but no flood), there is no economic loss. For the 100-year flood, comparing the cost of damage without warning to the cost of damage with warning has found that warning reduces the expected cost of the event by 25%. In the event of a false alarm triggered by the potential 100-year flood, the expected cost of an evacuation with no flood is equal to 10% of the difference between the expected costs of damage with and without warning if the flood would have occurred. Therefore, warning can be considered cost-effective in both scenarios.

Comparison of the costs of damage with and without the FEWS for each of the seven flood scenarios has found investment of the FEWS has the potential to reduce the expected cost of damage per year by more than 50%. For the cost-benefit analysis comparing the cost of investment in the FEWS to the reduction of expected costs over the lifetime of the FEWS, seven scenarios were calculated: one-year, five-year, ten-year, twenty-five-year, fifty-year, hundred-year, and thousand-year floods. The expected damage costs without FEWS and preparation $D_1$ and with FEWS and preparation $D_2$ were calculated for each of the scenarios. Comparing the calculated values of $D_1$ and $D_2$ shows that FEWS is able to reduce the costs of damage per event by more than 50%. Calculating the expected cost per year for both $D_1$ and $D_2$ also shows a reduction in expected cost per year by more than 50%. When comparing the net present value of the costs of investing into FEWS and evacuation to the net present value of the benefits, or the reduction in damage between $D_1$ and $D_2$, it is found that the benefits are nearly 40 times the cost, indicating that investment into FEWS and evacuation is cost-effective.

**How can the flood early warning system (FEWS) designed for the Geul River be assessed and improved based on the UNDRR criteria for an effective warning system?**

Analysis of the existing FEWS for the Geul River has revealed several points of improvement. Analysis of real-time historic data indicated that real-time monitoring of precipitation and discharge does not provide enough time between detection and event to effectively warn and evacuate Valkenburg. The knowledge component of the Geul FEWS is recommended to remain reliant on forecasted precipitation data collected by third parties unless the data collection methods of discharge data improve. The monitoring component of the FEWS was assessed by running various water level and discharge simulations and comparing the results to known data. These runs included the simulation of the July 2021 flood event and four non-flooding events demonstrating various temperature and catchment conditions: The monitoring component of the FEWS must be improved with the inclusion of a 2D or quasi-2D grid to accurately model potential water levels in flooding scenarios, which is crucial in disaster planning and assessment for Valkenburg. The SOBEK model and possibly the HBV model must be recalibrated to accurately model the behavior of water caused by hydraulic structures present within the Geul FEWS. This will lead to more accurate modelling of the river behavior in non-flooding situations and reduce the chances of a false alarm. Improvement of the monitoring component of the FEWS will in turn improve the accuracy of warnings communicated to Valkenburg as well as the preparedness of the overall system to warn Valkenburg of future floods. Cost-benefit analyses indicate that these improvements lead to economic benefit in warning during individual events by 25% as well as the reduction of expected yearly damage costs by 50%.

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# A

# Estimation of Boundaries for Expected Discharge and Water Level for July 2021 Simulations

## A.1. Discharge Boundary Assumptions

The lower boundary for the estimation of the discharge in Valkenburg was determined by the Expertise Waterveiligheid Rapport, which estimated 100 m$^3$/s flowed through Valkenburg in the Geul River.

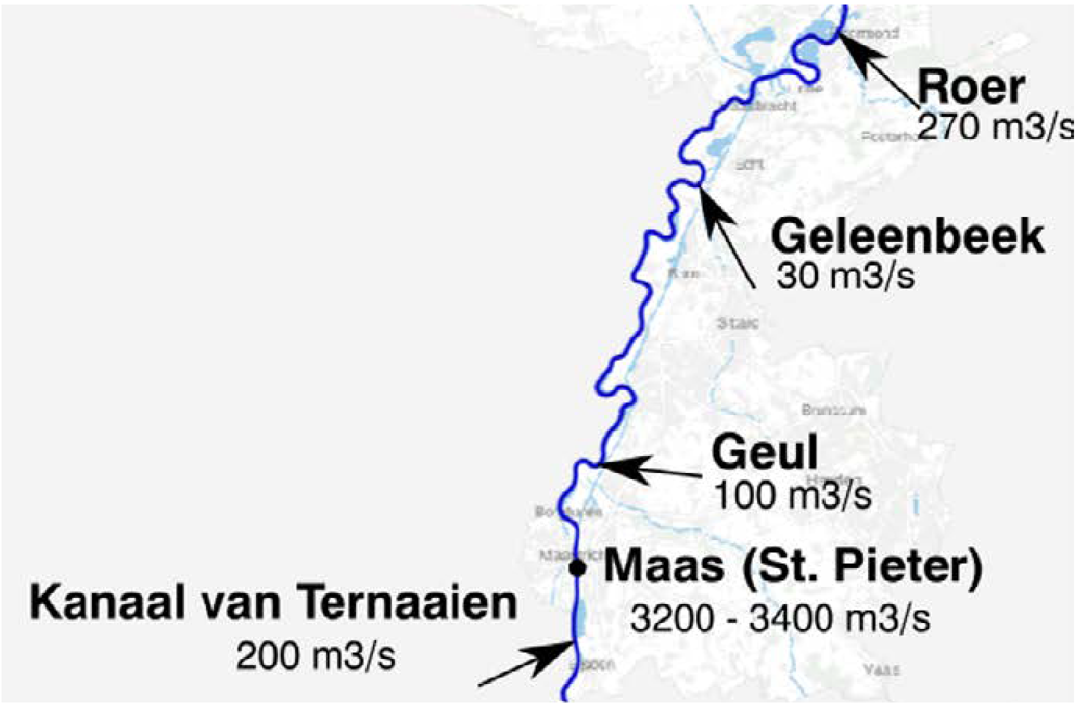


**Figure A.1:** Comparison of HBV research results to Deltares research results [13]

The discharge that flowed through Valkenburg during the July 2021 event was calculated by Deltares in 2022 [13]. Their results estimated approximately 130 m$^3$/s at the peak. The results of the Deltares discharge were used as the upper boundary of the estimated discharge range.

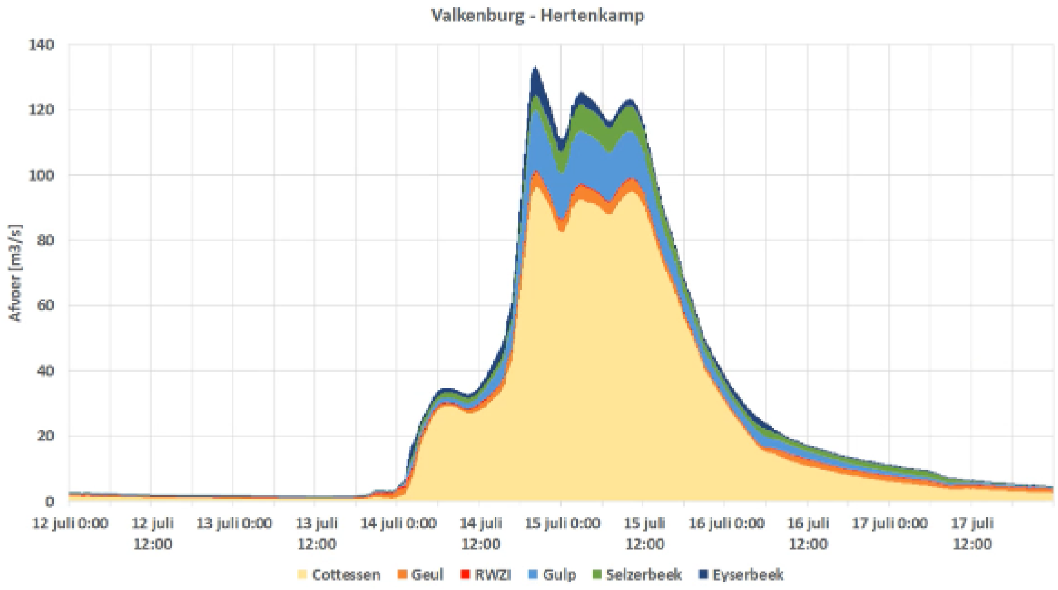


**Figure A.2:** Comparison of HBV research results to Deltares research results [13]

## A.2. Water Level Boundary Assumptions

The expected water level to which the results are compared was found using topographic data for the Geul catchment. The recorded flood extents (see Figure 2.7) were traced over a topographic map of Valkenburg in Figure A.3 to estimate the expected water level reached during the July 2021 foods to which the SOBEK run results can be compared.

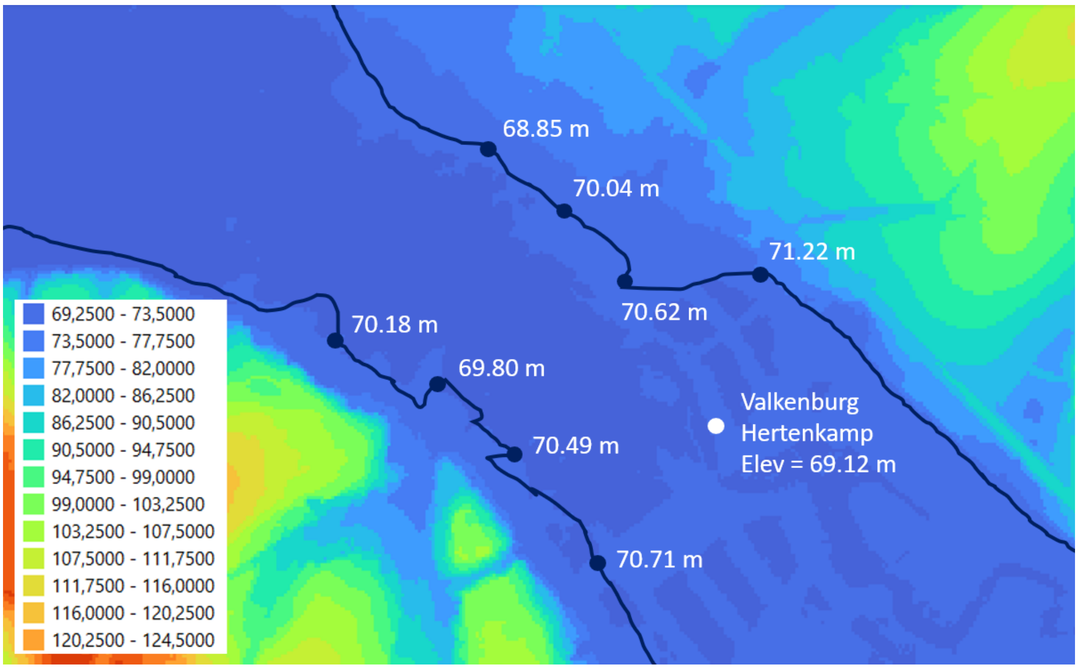


**Figure A.3:** Topographic map of Valkenburg with flood extents observed from the July 2021 event outlined in black [9]

Using this method, it was found that the Hertenkamp measuring station is located at an elevation of 69.12 m and the water level during the flood reached areas with elevations ranging from 68 - 71.2 m+NAP. Therefore, a water level ranging from 70 - 71 m+NAP, or a 1 - 2 m increase, was expected from the SOBEK run.

# B

# Rainfiles and Results for Flood Extent Map

## B.1. Results of Discharge Runs in Winter versus Summer

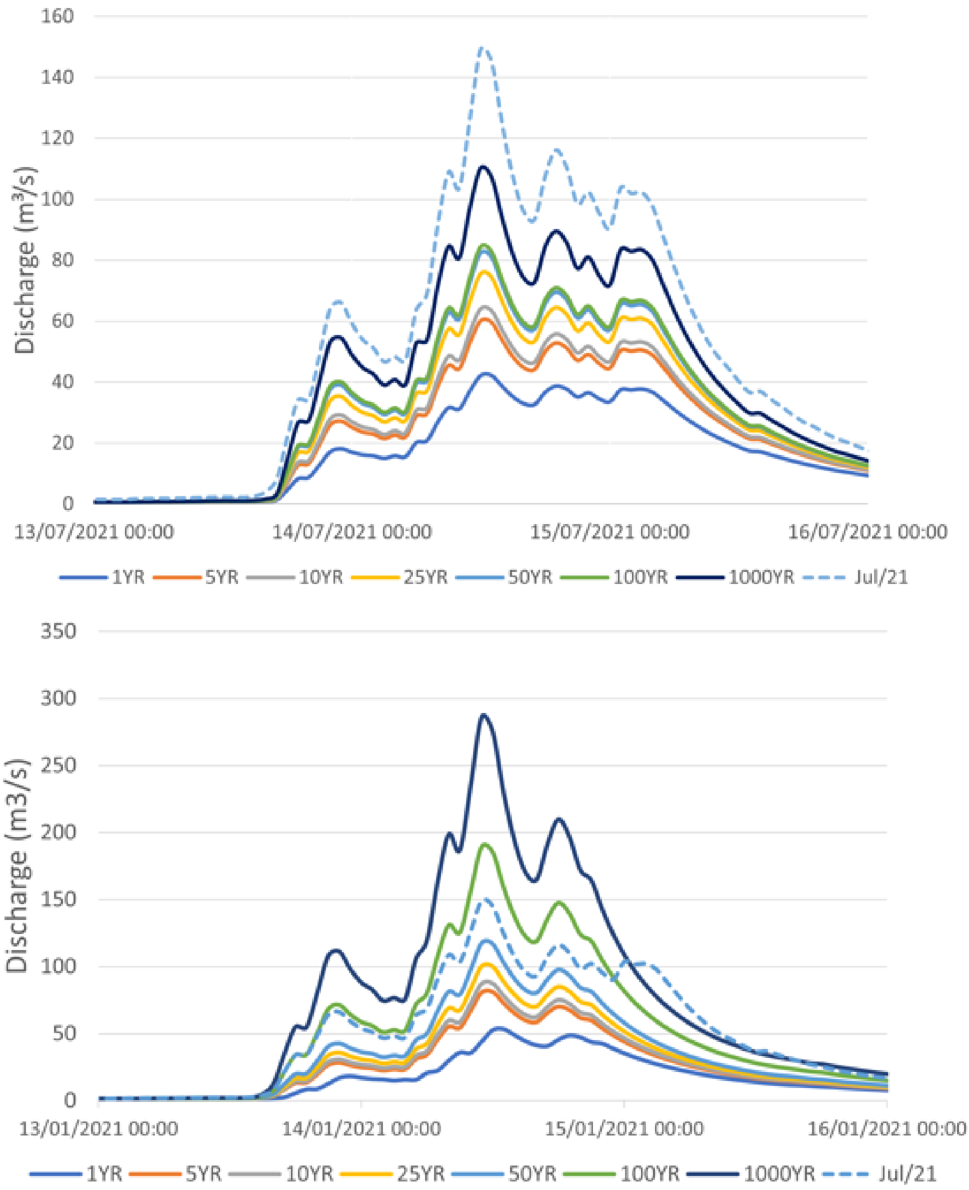


**Figure B.1:** Comparison of summer discharge (top) and winter discharge (bottom) results of the same precipitation files listed in Table 6.1

The winter discharge is much higher than the summer discharge. Every inputted precipitation file resulted in a winter discharge amount that was around double the resulting summer discharge for the same file. Furthermore, the summer discharge stays elevated longer than the winter discharge, peaking four times while the winter discharge only peaks three. It is likely that the reason the summer discharge behaves this way because the friction in the floodplains is higher, as vegetation is more present in the summer than in the winter.

## B.2. Simulation Examples for Flood Extent Map

The individual water depth files for each of the seven scenarios in Chapter 6 are shown in Figures B.2 to B.8. Each of these files was created by inputting the precipitation data listed in Table 6.1 into SOBEK. SOBEK program outputted several files, including water velocity and water level, shown in this Appendix. These files were inputted into SSM2017 to calculate the damages with and without evacuation in Chapter 7.


**Figure B.2:** Individual water depth results for one-year precipitation event used to create the flood extent map for Valkenburg

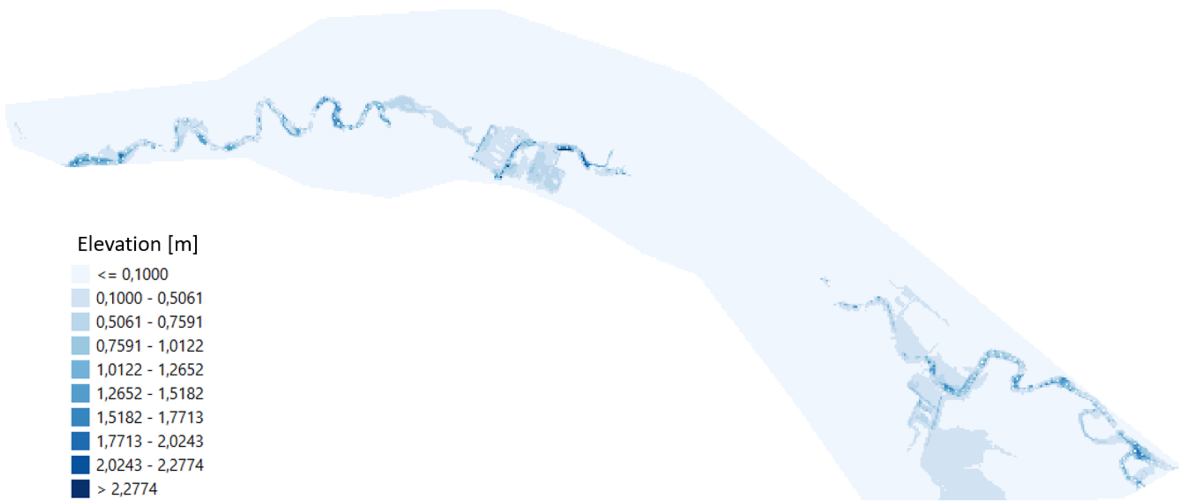


**Figure B.3:** Individual water depth results for five-year precipitation event used to create the flood extent map for Valkenburg


**Figure B.4:** Individual water depth results for ten-year precipitation event used to create the flood extent map for Valkenburg

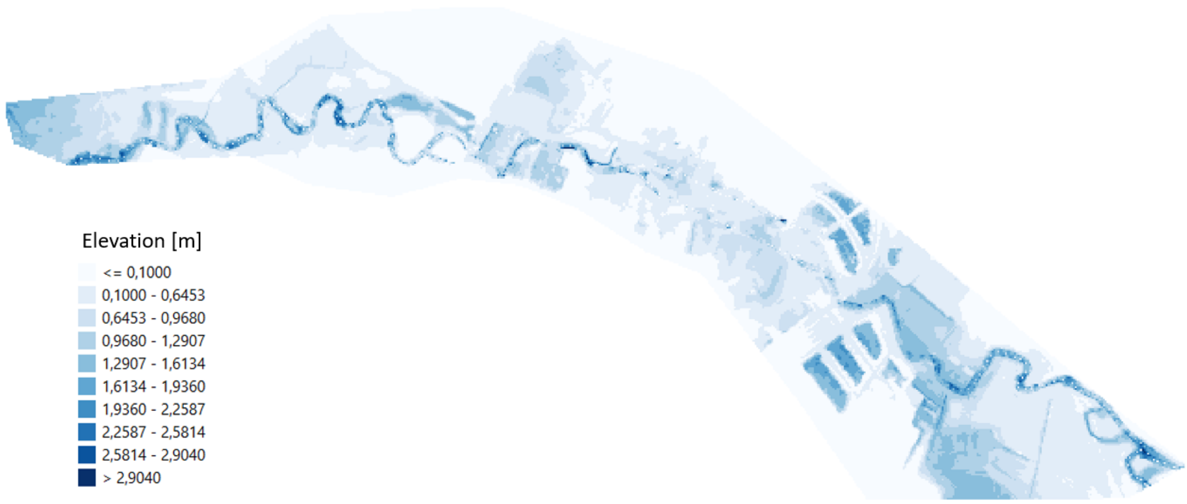


**Figure B.5:** Individual water depth results for twenty-five-year precipitation event used to create the flood extent map for Valkenburg

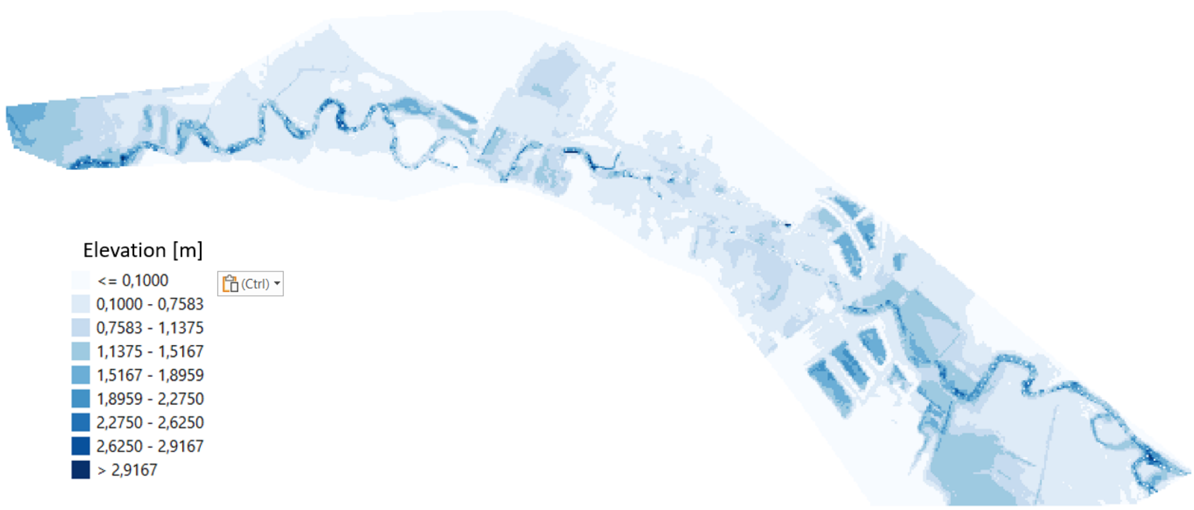


**Figure B.6:** Individual water depth results for fifty-year precipitation event used to create the flood extent map for Valkenburg

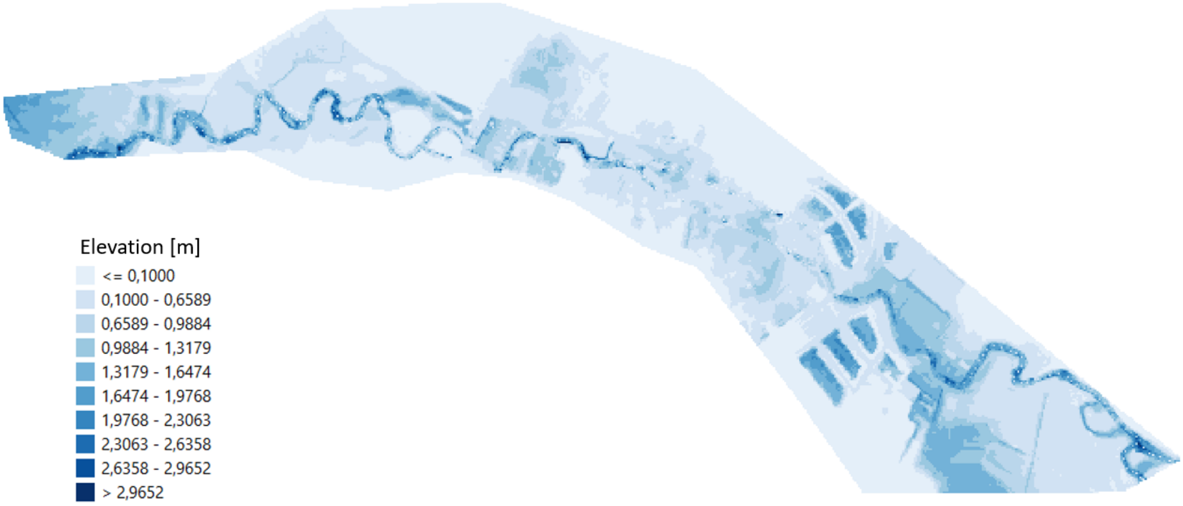


**Figure B.7:** Individual water depth results for hundred-year precipitation event used to create the flood extent map for Valkenburg

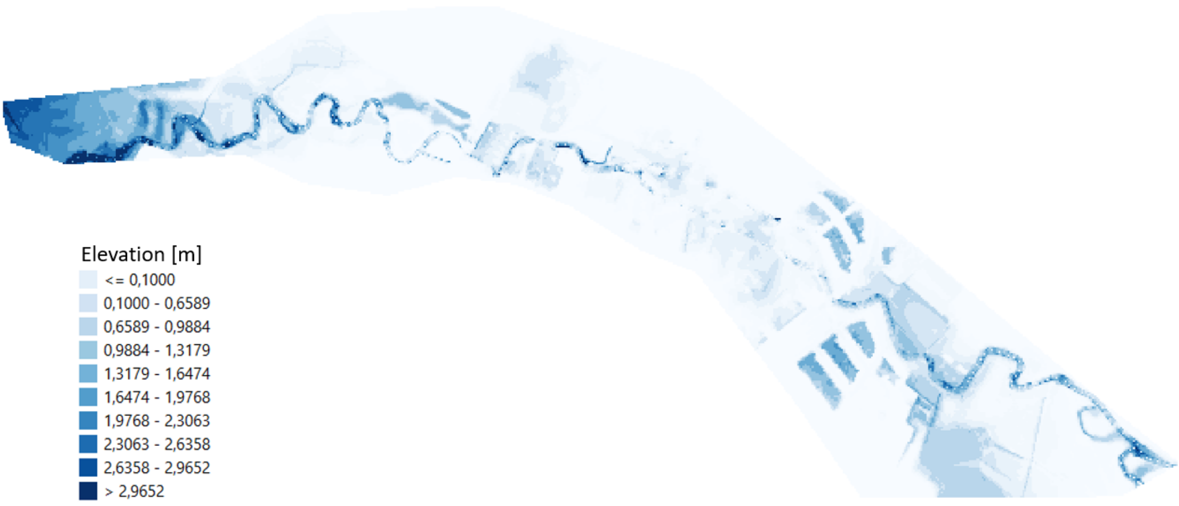


**Figure B.8:** Individual water depth results for thousand-year precipitation event used to create the flood extent map for Valkenburg

# C

# Calculations for Cost-Benefit Analysis

## C.1. Calculation Equations used by SSM2017 Regionaal

| Categorie | Directe schade | Schadefunctie | Maximale schade |
|---|---|---|---|
| | | | Direct |
| Bedrijven | | | in € / $m^2$ |
| Bijeenkomst | x | Winkel | 168 |
| Gezondheidszorg | x | Kantoor | 1974 |
| Industrie | x | Industrie | 1565 |
| Kantoor | x | Kantoor | 1283 |
| Onderwijs | x | Kantoor | 993 |
| Sport | x | Industrie | 102 |
| Winkel | x | Winkel | 1508 |
| Woningen | | | in € / $m^2$ en **€ / object** |
| Eengezinswoningen – opstal | x | Eengezinswoningen - opstal | 1000 |
| Eengezinswoningen – inboedel | x | Eengezinswoningen - inboedel | **70000** |
| Begane grond app. – opstal | x | Begane grond - opstal | 1000 |
| Begane grond app. – inboedel | x | Begane grond - inboedel | **70000** |
| Eerste verdieping app. – opstal | x | Eerste verdieping – opstal | 1000 |
| Eerste verdieping app. – inboedel | x | Eerste verdieping – inboedel | **70000** |
| Hogere verdieping app. – opstal | x | Hogere verdieping – opstal | 1000 |
| Hogere verdieping app. – inboedel | x | Hogere verdieping – inboedel | **70000** |
| Infrastructuur | | | in € / m |
| Rijkswegen | x | Infrastructuur | 1770 |
| Autowegen | x | Infrastructuur | 1200 |
| Overige wegen | x | Infrastructuur | 327 |
| Spoorwegen (non-electrisch) | x | Infrastructuur | 1350 |
| Spoorwegen (electrisch) | x | Infrastructuur | 5400 |
| Overig landgebruik | | | in € / $m^2$ en **€ / object** |
| Landbouw | x | Landbouw | 1,83 |
| Glastuinbouw | x | Landbouw | 49 |
| Stedelijk gebied | x | Infrastructuur | 59,65 |
| Extensieve recreatie | x | Landbouw | 10,79 |
| Intensieve recreatie | x | Landbouw | 13,29 |
| Vliegvelden | x | Landbouw | 146 |
| Vervoermiddelen | x | Auto | 7942 |
| Gemalen | x | Gemalen | **911600** |
| Zuiveringsinstallaties | x | Zuiveringsinstallatie | **1.324 m** |
| Inwoners | | | |
| Slachtoffers | x | Slachtoffers | nvt |

**Figure C.1:** Table included in the user manual of the SSM2017 Regionaal explaining the formula used to calculate damage

## C.2. SSM2017 Results

The individual SSM results for each of the seven scenarios are included from Figures C.2 to C.8. The SSM results for the data pertaining to the July 2021 flooding simulation is shown in Figure C.9. In each SSM result, the objects that counted as moveable goods ($D_{Mov}$) are highlighted in yellow.

2022-04-12 22:15:12.342052 methode: SSM2017 Regionaal

**Totaal schade** 180 euro(x1000)
**Totaal slachtoffers*** 0 personen
**Totaal getroffenen** 6 personen
*ZONDER evacuatie

| Categorie naam | Schade [euro(x1000)] | No. objecten | Eenheid |
|---|---|---|---|
| Bedrijven: Bijeenkomst | 0 | 0 | m2 |
| Bedrijven: Gezondheidszorg | 0 | 0 | m2 |
| Bedrijven: Industrie | 0 | 0 | m2 |
| Bedrijven: Kantoor | 0 | 0 | m2 |
| Bedrijven: Onderwijs | 0 | 0 | m2 |
| Bedrijven: Sport | 0 | 0 | m2 |
| Bedrijven: Winkel | 0 | 0 | m2 |
| Infrastructuur: Autowegen | 0 | 0 | m |
| Infrastructuur: Overige wegen | 2 | 223 | m |
| Infrastructuur: Rijkswegen | 0 | 0 | m |
| Infrastructuur: Spoorwegen (electrisch) | 0 | 0 | m |
| Infrastructuur: Spoorwegen (non-electrisch) | 0 | 0 | m |
| Overige: Extensieve recreatie | 68 | 27000 | m2 |
| Overige: Gemalen | 0 | 0 | objecten |
| Overige: Glastuinbouw | 0 | 0 | m2 |
| Overige: Intensieve recreatie | 27 | 7725 | m2 |
| Overige: Landbouw | 45 | 71080 | m2 |
| Overige: Stedelijk gebied | 3 | 475 | m2 |
| Overige: Vervoermiddelen | 1 | 2 | objecten |
| Overige: Vliegvelden | 0 | 0 | m2 |
| Overige: Zuiveringsinstallaties | 0 | 0 | objecten |
| Speciaal: Drinkwaterlocaties | 0 | 0 | objecten |
| Speciaal: IPPC-bedrijven | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ander opbject | 0 | 0 | objecten |
| Speciaal: Kwetsbaar hotel / pension | 0 | 0 | objecten |
| Speciaal: Kwetsbaar kantoor / bedrijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar publieksgebouw | 0 | 0 | objecten |
| Speciaal: Kwetsbaar woonverblijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ziekenhuis / tehuis | 0 | 0 | objecten |
| Speciaal: Kwetsbare onderwijsinstelling | 0 | 0 | objecten |
| Speciaal: Natura2000 gebieden | 0 | 54220 | m2 |
| Speciaal: Rijksmonumenten | 0 | 0 | objecten |
| Speciaal: Zwemwaterlocaties | 0 | 0 | objecten |
| Woningen: Begane grond appartementen (inboedel) | 0 | 0 | objects |
| Woningen: Begane grond appartementen (opstal) | 0 | 0 | m2 |
| Woningen: Eengezinswoningen (inboedel) | 29 | 3 | objecten |
| Woningen: Eengezinswoningen (opstal) | 5 | 816 | m2 |
| Woningen: Eerste verdieping appartementen (inboedel) | 0 | 0 | objecten |
| Woningen: Eerste verdieping appartementen (opstal) | 0 | 0 | m2 |
| Woningen: Hogere verdieping appartementen (inboedel) | 0 | 0 | objecten |
| Woningen: Hogere verdieping appartementen (opstal) | 0 | 0 | m2 |
| **Totaal** | **180** | | |

| Categorie naam | Getroffenen | Eenheid |
|---|---|---|
| Getroffenen | 6 | personen |
| Getroffenen: eengezinswoningen | 6 | personen |
| Getroffenen: hoogbouw | 0 | personen |
| Getroffenen: laagbouw | 0 | personen |
| Getroffenen: middenbouw | 0 | personen |

**Figure C.2:** SSM2017 calculation results of 1-year flood inputs

| | |
|---|---|
| 2022-04-09 02:13:20.456403 | methode: SSM2017 Regionaal |

| | | |
|---|---|---|
| **Totaal schade** | 180 | euro(x1000) |
| **Totaal slachtoffers*** | 0 | personen |
| **Totaal getroffenen** | 6 | personen |
| *ZONDER evacuatie | | |

| **Categorie naam** | **Schade [euro(x1000)]** | **No. objecten** | **Eenheid** |
|---|---|---|---|
| Bedrijven: Bijeenkomst | 0 | 0 | m2 |
| Bedrijven: Gezondheidszorg | 0 | 0 | m2 |
| Bedrijven: Industrie | 0 | 0 | m2 |
| Bedrijven: Kantoor | 0 | 0 | m2 |
| Bedrijven: Onderwijs | 0 | 0 | m2 |
| Bedrijven: Sport | 0 | 0 | m2 |
| Bedrijven: Winkel | 0 | 0 | m2 |
| Infrastructuur: Autowegen | 0 | 0 | m |
| Infrastructuur: Overige wegen | 2 | 223 | m |
| Infrastructuur: Rijkswegen | 0 | 0 | m |
| Infrastructuur: Spoorwegen (electrisch) | 0 | 0 | m |
| Infrastructuur: Spoorwegen (non-electrisch) | 0 | 0 | m |
| Overige: Extensieve recreatie | 68 | 27000 | m2 |
| Overige: Gemalen | 0 | 0 | objecten |
| Overige: Glastuinbouw | 0 | 0 | m2 |
| Overige: Intensieve recreatie | 27 | 7725 | m2 |
| Overige: Landbouw | 45 | 71080 | m2 |
| Overige: Stedelijk gebied | 3 | 475 | m2 |
| Overige: Vervoermiddelen | 1 | 2 | objecten |
| Overige: Vliegvelden | 0 | 0 | m2 |
| Overige: Zuiveringsinstallaties | 0 | 0 | objecten |
| Speciaal: Drinkwaterlocaties | 0 | 0 | objecten |
| Speciaal: IPPC-bedrijven | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ander opbject | 0 | 0 | objecten |
| Speciaal: Kwetsbaar hotel / pension | 0 | 0 | objecten |
| Speciaal: Kwetsbaar kantoor / bedrijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar publieksgebouw | 0 | 0 | objecten |
| Speciaal: Kwetsbaar woonverblijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ziekenhuis / tehuis | 0 | 0 | objecten |
| Speciaal: Kwetsbare onderwijsinstelling | 0 | 0 | objecten |
| Speciaal: Natura2000 gebieden | 0 | 54220 | m2 |
| Speciaal: Rijksmonumenten | 0 | 0 | objecten |
| Speciaal: Zwemwaterlocaties | 0 | 0 | objecten |
| Woningen: Begane grond appartementen (inboedel) | 0 | 0 | objects |
| Woningen: Begane grond appartementen (opstal) | 0 | 0 | m2 |
| Woningen: Eengezinswoningen (inboedel) | 29 | 3 | objecten |
| Woningen: Eengezinswoningen (opstal) | 5 | 816 | m2 |
| Woningen: Eerste verdieping appartementen (inboedel) | 0 | 0 | objecten |
| Woningen: Eerste verdieping appartementen (opstal) | 0 | 0 | m2 |
| Woningen: Hogere verdieping appartementen (inboedel) | 0 | 0 | objecten |
| Woningen: Hogere verdieping appartementen (opstal) | 0 | 0 | m2 |
| **Totaal** | **180** | | |

| **Categorie naam** | **Getroffenen** | **Eenheid** |
|---|---|---|
| Getroffenen | 6 | personen |
| Getroffenen: eengezinswoningen | 6 | personen |
| Getroffenen: hoogbouw | 0 | personen |
| Getroffenen: laagbouw | 0 | personen |
| Getroffenen: middenbouw | 0 | personen |

**Figure C.3:** SSM2017 calculation results of 5-year flood inputs

| | |
|---|---|
| 2022-04-13 15:33:31.722623 | methode: SSM2017 Regionaal |

| | | |
|---|---|---|
| **Totaal schade** | 4900 | euro(x1000) |
| **Totaal slachtoffers*** | 0 | personen |
| **Totaal getroffenen** | 308 | personen |
| *ZONDER evacuatie | | |

| **Categorie naam** | **Schade [euro(x1000)]** | **No. objecten** | **Eenheid** |
|---|---|---|---|
| Bedrijven: Bijeenkomst | 470 | 18490 | m2 |
| Bedrijven: Gezondheidszorg | 23 | 125 | m2 |
| Bedrijven: Industrie | 270 | 1830 | m2 |
| Bedrijven: Kantoor | 240 | 2002 | m2 |
| Bedrijven: Onderwijs | 0 | 0 | m2 |
| Bedrijven: Sport | 3 | 138 | m2 |
| Bedrijven: Winkel | 1700 | 5099 | m2 |
| Infrastructuur: Autowegen | 0 | 0 | m |
| Infrastructuur: Overige wegen | 22 | 950 | m |
| Infrastructuur: Rijkswegen | 0 | 0 | m |
| Infrastructuur: Spoorwegen (electrisch) | 0 | 0 | m |
| Infrastructuur: Spoorwegen (non-electrisch) | 0 | 0 | m |
| Overige: Extensieve recreatie | 250 | 55300 | m2 |
| Overige: Gemalen | 0 | 0 | objecten |
| Overige: Glastuinbouw | 0 | 0 | m2 |
| Overige: Intensieve recreatie | 270 | 71500 | m2 |
| Overige: Landbouw | 110 | 163400 | m2 |
| Overige: Stedelijk gebied | 180 | 38620 | m2 |
| Overige: Vervoermiddelen | 81 | 129 | objecten |
| Overige: Vliegvelden | 0 | 0 | m2 |
| Overige: Zuiveringsinstallaties | 0 | 0 | objecten |
| Speciaal: Drinkwaterlocaties | 0 | 0 | objecten |
| Speciaal: IPPC-bedrijven | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ander opbject | 0 | 0 | objecten |
| Speciaal: Kwetsbaar hotel / pension | 0 | 0 | objecten |
| Speciaal: Kwetsbaar kantoor / bedrijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar publieksgebouw | 0 | 0 | objecten |
| Speciaal: Kwetsbaar woonverblijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ziekenhuis / tehuis | 0 | 0 | objecten |
| Speciaal: Kwetsbare onderwijsinstelling | 0 | 0 | objecten |
| Speciaal: Natura2000 gebieden | 0 | 100800 | m2 |
| Speciaal: Rijksmonumenten | 0 | 7 | objecten |
| Speciaal: Zwemwaterlocaties | 0 | 0 | objecten |
| Woningen: Begane grond appartementen (inboedel) | 260 | 39 | objects |
| Woningen: Begane grond appartementen (opstal) | 440 | 4000 | m2 |
| Woningen: Eengezinswoningen (inboedel) | 510 | 48 | objecten |
| Woningen: Eengezinswoningen (opstal) | 90 | 9983 | m2 |
| Woningen: Eerste verdieping appartementen (inboedel) | 0 | 28 | objecten |
| Woningen: Eerste verdieping appartementen (opstal) | 0 | 2663 | m2 |
| Woningen: Hogere verdieping appartementen (inboedel) | 0 | 14 | objecten |
| Woningen: Hogere verdieping appartementen (opstal) | 0 | 2129 | m2 |
| **Totaal** | **4900** | | |

| **Categorie naam** | **Getroffenen** | **Eenheid** |
|---|---|---|
| Getroffenen | 308 | personen |
| Getroffenen: eengezinswoningen | 114 | personen |
| Getroffenen: hoogbouw | 33 | personen |
| Getroffenen: laagbouw | 93 | personen |
| Getroffenen: middenbouw | 67 | personen |

**Figure C.4:** SSM2017 calculation results of 10-year flood inputs

2022-04-10 20:08:31.002671 methode: SSM2017 Regionaal

| | | |
|---|---|---|
| **Totaal schade** | 33000 | euro(x1000) |
| **Totaal slachtoffers*** | 2 | personen |
| **Totaal getroffenen** | 1465 | personen |
| *ZONDER evacuatie | | |

| **Categorie naam** | **Schade [euro(x1000)]** | **No. objecten** | **Eenheid** |
|---|---|---|---|
| Bedrijven: Bijeenkomst | 2100 | 36030 | m2 |
| Bedrijven: Gezondheidszorg | 750 | 2195 | m2 |
| Bedrijven: Industrie | 1600 | 6065 | m2 |
| Bedrijven: Kantoor | 1200 | 5639 | m2 |
| Bedrijven: Onderwijs | 79 | 1231 | m2 |
| Bedrijven: Sport | 16 | 862 | m2 |
| Bedrijven: Winkel | 6400 | 12890 | m2 |
| Infrastructuur: Autowegen | 0 | 0 | m |
| Infrastructuur: Overige wegen | 200 | 3009 | m |
| Infrastructuur: Rijkswegen | 0 | 0 | m |
| Infrastructuur: Spoorwegen (electrisch) | 0 | 0 | m |
| Infrastructuur: Spoorwegen (non-electrisch) | 0 | 0 | m |
| Overige: Extensieve recreatie | 550 | 108900 | m2 |
| Overige: Gemalen | 0 | 0 | objecten |
| Overige: Glastuinbouw | 0 | 0 | m2 |
| Overige: Intensieve recreatie | 660 | 110300 | m2 |
| Overige: Landbouw | 280 | 319200 | m2 |
| Overige: Stedelijk gebied | 3200 | 199200 | m2 |
| Overige: Vervoermiddelen | 2000 | 615 | objecten |
| Overige: Vliegvelden | 0 | 0 | m2 |
| Overige: Zuiveringsinstallaties | 0 | 0 | objecten |
| Speciaal: Drinkwaterlocaties | 0 | 0 | objecten |
| Speciaal: IPPC-bedrijven | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ander opbject | 0 | 0 | objecten |
| Speciaal: Kwetsbaar hotel / pension | 0 | 0 | objecten |
| Speciaal: Kwetsbaar kantoor / bedrijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar publieksgebouw | 0 | 0 | objecten |
| Speciaal: Kwetsbaar woonverblijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ziekenhuis / tehuis | 0 | 0 | objecten |
| Speciaal: Kwetsbare onderwijsinstelling | 0 | 0 | objecten |
| Speciaal: Natura2000 gebieden | 0 | 150200 | m2 |
| Speciaal: Rijksmonumenten | 0 | 12 | objecten |
| Speciaal: Zwemwaterlocaties | 0 | 0 | objecten |
| Woningen: Begane grond appartementen (inboedel) | 3000 | 129 | objects |
| Woningen: Begane grond appartementen (opstal) | 4300 | 13400 | m2 |
| Woningen: Eengezinswoningen (inboedel) | 5900 | 274 | objecten |
| Woningen: Eengezinswoningen (opstal) | 1100 | 43740 | m2 |
| Woningen: Eerste verdieping appartementen (inboedel) | 0 | 130 | objecten |
| Woningen: Eerste verdieping appartementen (opstal) | 0 | 12000 | m2 |
| Woningen: Hogere verdieping appartementen (inboedel) | 0 | 78 | objecten |
| Woningen: Hogere verdieping appartementen (opstal) | 0 | 8115 | m2 |
| **Totaal** | **33000** | | |

| **Categorie naam** | **Getroffenen** | **Eenheid** |
|---|---|---|
| Getroffenen | 1464 | personen |
| Getroffenen aankomsttijd < 24 uur | 0 | personen |
| Getroffenen 24 uur <= aankomsttijd <= 48 uur | 0 | personen |
| Getroffenen aankomsttijd > 48 uur | 1451 | personen |
| Getroffenen: eengezinswoningen | 656 | personen |
| Getroffenen: hoogbouw | 187 | personen |
| Getroffenen: laagbouw | 309 | personen |
| Getroffenen: middenbouw | 312 | personen |

**Figure C.5:** SSM2017 calculation results of 25-year flood inputs

| | | | |
|---|---|---|---|
| 2022-04-13 20:56:22.409671 | methode: SSM2017 Regionaal | | |
| **Totaal schade** | 36000 | euro(x1000) | |
| **Totaal slachtoffers*** | 2 | personen | |
| **Totaal getroffenen** | 1503 | personen | |
| *ZONDER evacuatie | | | |

| **Categorie naam** | **Schade [euro(x1000)]** | **No. objecten** | **Eenheid** |
|---|---|---|---|
| Bedrijven: Bijeenkomst | 2300 | 37310 | m2 |
| Bedrijven: Gezondheidszorg | 840 | 4713 | m2 |
| Bedrijven: Industrie | 1800 | 6065 | m2 |
| Bedrijven: Kantoor | 1400 | 5639 | m2 |
| Bedrijven: Onderwijs | 97 | 1231 | m2 |
| Bedrijven: Sport | 18 | 862 | m2 |
| Bedrijven: Winkel | 6900 | 13320 | m2 |
| Infrastructuur: Autowegen | 0 | 0 | m |
| Infrastructuur: Overige wegen | 230 | 3183 | m |
| Infrastructuur: Rijkswegen | 0 | 0 | m |
| Infrastructuur: Spoorwegen (electrisch) | 0 | 0 | m |
| Infrastructuur: Spoorwegen (non-electrisch) | 0 | 0 | m |
| Overige: Extensieve recreatie | 590 | 110600 | m2 |
| Overige: Gemalen | 0 | 0 | objecten |
| Overige: Glastuinbouw | 0 | 0 | m2 |
| Overige: Intensieve recreatie | 700 | 112000 | m2 |
| Overige: Landbouw | 300 | 324600 | m2 |
| Overige: Stedelijk gebied | 3500 | 206800 | m2 |
| Overige: Vervoermiddelen | 2200 | 631 | objecten |
| Overige: Vliegvelden | 0 | 0 | m2 |
| Overige: Zuiveringsinstallaties | 0 | 0 | objecten |
| Speciaal: Drinkwaterlocaties | 0 | 0 | objecten |
| Speciaal: IPPC-bedrijven | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ander opbject | 0 | 0 | objecten |
| Speciaal: Kwetsbaar hotel / pension | 0 | 0 | objecten |
| Speciaal: Kwetsbaar kantoor / bedrijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar publieksgebouw | 0 | 0 | objecten |
| Speciaal: Kwetsbaar woonverblijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ziekenhuis / tehuis | 0 | 0 | objecten |
| Speciaal: Kwetsbare onderwijsinstelling | 0 | 0 | objecten |
| Speciaal: Natura2000 gebieden | 0 | 150600 | m2 |
| Speciaal: Rijksmonumenten | 0 | 12 | objecten |
| Speciaal: Zwemwaterlocaties | 0 | 0 | objecten |
| Woningen: Begane grond appartementen (inboedel) | 3200 | 132 | objects |
| Woningen: Begane grond appartementen (opstal) | 4600 | 13600 | m2 |
| Woningen: Eengezinswoningen (inboedel) | 6300 | 285 | objecten |
| Woningen: Eengezinswoningen (opstal) | 1200 | 45860 | m2 |
| Woningen: Eerste verdieping appartementen (inboedel) | 0 | 132 | objecten |
| Woningen: Eerste verdieping appartementen (opstal) | 0 | 12120 | m2 |
| Woningen: Hogere verdieping appartementen (inboedel) | 0 | 78 | objecten |
| Woningen: Hogere verdieping appartementen (opstal) | 0 | 8115 | m2 |
| **Totaal** | **36000** | | |

| **Categorie naam** | **Getroffenen** | **Eenheid** |
|---|---|---|
| Getroffenen | 1503 | personen |
| Getroffenen aankomsttijd < 24 uur | 0 | personen |
| Getroffenen 24 uur <= aankomsttijd <= 48 uur | 0 | personen |
| Getroffenen aankomsttijd > 48 uur | 1484 | personen |
| Getroffenen: eengezinswoningen | 682 | personen |
| Getroffenen: hoogbouw | 187 | personen |
| Getroffenen: laagbouw | 316 | personen |
| Getroffenen: middenbouw | 316 | personen |

**Figure C.6:** SSM2017 calculation results of 50-year flood inputs

| | |
|---|---|
| 2022-04-11 00:46:47.145160 | methode: SSM2017 Regionaal |

| | | |
|---|---|---|
| **Totaal schade** | 37000 | euro(x1000) |
| **Totaal slachtoffers*** | 2 | personen |
| **Totaal getroffenen** | 1511 | personen |
| *ZONDER evacuatie | | |

| **Categorie naam** | **Schade [euro(x1000)]** | **No. objecten** | **Eenheid** |
|---|---|---|---|
| Bedrijven: Bijeenkomst | 2300 | 37310 | m2 |
| Bedrijven: Gezondheidszorg | 910 | 4713 | m2 |
| Bedrijven: Industrie | 1800 | 6065 | m2 |
| Bedrijven: Kantoor | 1400 | 5639 | m2 |
| Bedrijven: Onderwijs | 100 | 1231 | m2 |
| Bedrijven: Sport | 18 | 862 | m2 |
| Bedrijven: Winkel | 7000 | 13320 | m2 |
| Infrastructuur: Autowegen | 0 | 0 | m |
| Infrastructuur: Overige wegen | 240 | 3194 | m |
| Infrastructuur: Rijkswegen | 0 | 0 | m |
| Infrastructuur: Spoorwegen (electrisch) | 0 | 0 | m |
| Infrastructuur: Spoorwegen (non-electrisch) | 0 | 0 | m |
| Overige: Extensieve recreatie | 600 | 111000 | m2 |
| Overige: Gemalen | 0 | 0 | objecten |
| Overige: Glastuinbouw | 0 | 0 | m2 |
| Overige: Intensieve recreatie | 710 | 112400 | m2 |
| Overige: Landbouw | 300 | 326800 | m2 |
| Overige: Stedelijk gebied | 3600 | 208900 | m2 |
| Overige: Vervoermiddelen | 2200 | 634 | objecten |
| Overige: Vliegvelden | 0 | 0 | m2 |
| Overige: Zuiveringsinstallaties | 0 | 0 | objecten |
| Speciaal: Drinkwaterlocaties | 0 | 0 | objecten |
| Speciaal: IPPC-bedrijven | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ander opbject | 0 | 0 | objecten |
| Speciaal: Kwetsbaar hotel / pension | 0 | 0 | objecten |
| Speciaal: Kwetsbaar kantoor / bedrijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar publieksgebouw | 0 | 0 | objecten |
| Speciaal: Kwetsbaar woonverblijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ziekenhuis / tehuis | 0 | 0 | objecten |
| Speciaal: Kwetsbare onderwijsinstelling | 0 | 0 | objecten |
| Speciaal: Natura2000 gebieden | 0 | 150800 | m2 |
| Speciaal: Rijksmonumenten | 0 | 12 | objecten |
| Speciaal: Zwemwaterlocaties | 0 | 0 | objecten |
| Woningen: Begane grond appartementen (inboedel) | 3200 | 133 | objects |
| Woningen: Begane grond appartementen (opstal) | 4700 | 13650 | m2 |
| Woningen: Eengezinswoningen (inboedel) | 6400 | 286 | objecten |
| Woningen: Eengezinswoningen (opstal) | 1200 | 46010 | m2 |
| Woningen: Eerste verdieping appartementen (inboedel) | 0 | 133 | objecten |
| Woningen: Eerste verdieping appartementen (opstal) | 0 | 12160 | m2 |
| Woningen: Hogere verdieping appartementen (inboedel) | 0 | 78 | objecten |
| Woningen: Hogere verdieping appartementen (opstal) | 0 | 8115 | m2 |
| **Totaal** | **37000** | | |

| **Categorie naam** | **Getroffenen** | **Eenheid** |
|---|---|---|
| Getroffenen | 1510 | personen |
| Getroffenen aankomsttijd < 24 uur | 0 | personen |
| Getroffenen 24 uur <= aankomsttijd <= 48 uur | 0 | personen |
| Getroffenen aankomsttijd > 48 uur | 1501 | personen |
| Getroffenen: eengezinswoningen | 685 | personen |
| Getroffenen: hoogbouw | 187 | personen |
| Getroffenen: laagbouw | 318 | personen |
| Getroffenen: middenbouw | 319 | personen |

**Figure C.7:** SSM2017 calculation results of 100-year flood inputs

2022-04-09 19:12:55.987565 methode: SSM2017 Regionaal

| | | |
|---|---|---|
| **Totaal schade** | 44000 | euro(x1000) |
| **Totaal slachtoffers*** | 3 | personen |
| **Totaal getroffenen** | 2002 | personen |
| *ZONDER evacuatie | | |

| **Categorie naam** | **Schade [euro(x1000)]** | **No. objecten** | **Eenheid** |
|---|---|---|---|
| Bedrijven: Bijeenkomst | 2700 | 37730 | m2 |
| Bedrijven: Gezondheidszorg | 1300 | 4713 | m2 |
| Bedrijven: Industrie | 2300 | 6065 | m2 |
| Bedrijven: Kantoor | 1600 | 5639 | m2 |
| Bedrijven: Onderwijs | 160 | 1231 | m2 |
| Bedrijven: Sport | 22 | 862 | m2 |
| Bedrijven: Winkel | 8300 | 14800 | m2 |
| Infrastructuur: Autowegen | 0 | 0 | m |
| Infrastructuur: Overige wegen | 330 | 3455 | m |
| Infrastructuur: Rijkswegen | 0 | 0 | m |
| Infrastructuur: Spoorwegen (electrisch) | 0 | 0 | m |
| Infrastructuur: Spoorwegen (non-electrisch) | 0 | 0 | m |
| Overige: Extensieve recreatie | 740 | 113200 | m2 |
| Overige: Gemalen | 0 | 0 | objecten |
| Overige: Glastuinbouw | 0 | 0 | m2 |
| Overige: Intensieve recreatie | 800 | 114400 | m2 |
| Overige: Landbouw | 390 | 342100 | m2 |
| Overige: Stedelijk gebied | 4300 | 232500 | m2 |
| Overige: Vervoermiddelen | 2700 | 840 | objecten |
| Overige: Vliegvelden | 0 | 0 | m2 |
| Overige: Zuiveringsinstallaties | 0 | 0 | objecten |
| Speciaal: Drinkwaterlocaties | 0 | 0 | objecten |
| Speciaal: IPPC-bedrijven | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ander opbject | 0 | 0 | objecten |
| Speciaal: Kwetsbaar hotel / pension | 0 | 0 | objecten |
| Speciaal: Kwetsbaar kantoor / bedrijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar publieksgebouw | 0 | 0 | objecten |
| Speciaal: Kwetsbaar woonverblijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ziekenhuis / tehuis | 0 | 0 | objecten |
| Speciaal: Kwetsbare onderwijsinstelling | 0 | 0 | objecten |
| Speciaal: Natura2000 gebieden | 0 | 152000 | m2 |
| Speciaal: Rijksmonumenten | 0 | 13 | objecten |
| Speciaal: Zwemwaterlocaties | 0 | 0 | objecten |
| Woningen: Begane grond appartementen (inboedel) | 3900 | 177 | objects |
| Woningen: Begane grond appartementen (opstal) | 5500 | 16040 | m2 |
| Woningen: Eengezinswoningen (inboedel) | 7400 | 323 | objecten |
| Woningen: Eengezinswoningen (opstal) | 1500 | 51120 | m2 |
| Woningen: Eerste verdieping appartementen (inboedel) | 0 | 253 | objecten |
| Woningen: Eerste verdieping appartementen (opstal) | 0 | 17280 | m2 |
| Woningen: Hogere verdieping appartementen (inboedel) | 0 | 82 | objecten |
| Woningen: Hogere verdieping appartementen (opstal) | 0 | 8865 | m2 |
| **Totaal** | **44000** | | |

| **Categorie naam** | **Getroffenen** | **Eenheid** |
|---|---|---|
| Getroffenen | 2002 | personen |
| Getroffenen aankomsttijd < 24 uur | 0 | personen |
| Getroffenen 24 uur <= aankomsttijd <= 48 uur | 0 | personen |
| Getroffenen aankomsttijd > 48 uur | 1976 | personen |
| Getroffenen: eengezinswoningen | 773 | personen |
| Getroffenen: eengezinswoningen aankomsttijd < 24 uur | 0 | personen |
| Getroffenen: eengezinswoningen 24 uur <= aankomsttijd <= 48 uur | 0 | personen |
| Getroffenen: eengezinswoningen aankomsttijd > 48 uur | 759 | personen |
| Getroffenen: hoogbouw | 196 | personen |
| Getroffenen: laagbouw | 424 | personen |

**Figure C.8:** SSM2017 calculation results of 1000-year flood inputs

| | |
|---|---|
| 2022-03-22 11:49:35.856459 | methode: SSM2017 Regionaal |

| | | |
|---|---|---|
| **Totaal schade** | 48000 | euro(x1000) |
| **Totaal slachtoffers*** | 3 | personen |
| **Totaal getroffenen** | 2143 | personen |
| *ZONDER evacuatie | | |

| **Categorie naam** | **Schade [euro(x1000)]** | **No. objecten** | **Eenheid** |
|---|---|---|---|
| Bedrijven: Bijeenkomst | 2800 | 39050 | m2 |
| Bedrijven: Gezondheidszorg | 1400 | 4713 | m2 |
| Bedrijven: Industrie | 2400 | 6065 | m2 |
| Bedrijven: Kantoor | 1700 | 5639 | m2 |
| Bedrijven: Onderwijs | 180 | 1231 | m2 |
| Bedrijven: Sport | 24 | 862 | m2 |
| Bedrijven: Winkel | 9100 | 15210 | m2 |
| Infrastructuur: Autowegen | 0 | 0 | m |
| Infrastructuur: Overige wegen | 400 | 3599 | m |
| Infrastructuur: Rijkswegen | 0 | 0 | m |
| Infrastructuur: Spoorwegen (electrisch) | 0 | 0 | m |
| Infrastructuur: Spoorwegen (non-electrisch) | 0 | 0 | m |
| Overige: Extensieve recreatie | 820 | 113800 | m2 |
| Overige: Gemalen | 0 | 0 | objecten |
| Overige: Glastuinbouw | 0 | 0 | m2 |
| Overige: Intensieve recreatie | 830 | 114800 | m2 |
| Overige: Landbouw | 450 | 352200 | m2 |
| Overige: Stedelijk gebied | 4700 | 243800 | m2 |
| Overige: Vervoermiddelen | 3100 | 900 | objecten |
| Overige: Vliegvelden | 0 | 0 | m2 |
| Overige: Zuiveringsinstallaties | 0 | 0 | objecten |
| Speciaal: Drinkwaterlocaties | 0 | 0 | objecten |
| Speciaal: IPPC-bedrijven | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ander opbject | 0 | 0 | objecten |
| Speciaal: Kwetsbaar hotel / pension | 0 | 0 | objecten |
| Speciaal: Kwetsbaar kantoor / bedrijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar publieksgebouw | 0 | 0 | objecten |
| Speciaal: Kwetsbaar woonverblijf | 0 | 0 | objecten |
| Speciaal: Kwetsbaar ziekenhuis / tehuis | 0 | 0 | objecten |
| Speciaal: Kwetsbare onderwijsinstelling | 0 | 0 | objecten |
| Speciaal: Natura2000 gebieden | 0 | 152300 | m2 |
| Speciaal: Rijksmonumenten | 0 | 13 | objecten |
| Speciaal: Zwemwaterlocaties | 0 | 0 | objecten |
| Woningen: Begane grond appartementen (inboedel) | 4400 | 191 | objects |
| Woningen: Begane grond appartementen (opstal) | 6300 | 17440 | m2 |
| Woningen: Eengezinswoningen (inboedel) | 7800 | 337 | objecten |
| Woningen: Eengezinswoningen (opstal) | 1600 | 52430 | m2 |
| Woningen: Eerste verdieping appartementen (inboedel) | 0 | 272 | objecten |
| Woningen: Eerste verdieping appartementen (opstal) | 0 | 18960 | m2 |

| **Categorie naam** | **Getroffenen** | **Eenheid** | objecten |
|---|---|---|---|
| Getroffenen | 2143 | personen | m2 |
| Getroffenen aankomsttijd < 24 uur | 0 | personen | |
| Getroffenen 24 uur <= aankomsttijd <= 48 uur | 0 | personen | |
| Getroffenen aankomsttijd > 48 uur | 2122 | personen | |
| Getroffenen: eengezinswoningen | 806 | personen | |
| Getroffenen: eengezinswoningen aankomsttijd < 24 uur | 0 | personen | |
| Getroffenen: eengezinswoningen 24 uur <= aankomsttijd <= 48 uur | 0 | personen | |
| Getroffenen: eengezinswoningen aankomsttijd > 48 uur | 790 | personen | |
| Getroffenen: hoogbouw | 225 | personen | |
| Getroffenen: laagbouw | 458 | personen | |
| Getroffenen: middenbouw | 652 | personen | |

**Figure C.9:** SSM2017 calculation results of the July 2021 event flood inputs

## C.3. Calculation of Area under Damage Curves

Figure 7.3 is redrawn for the damage curves with and without FEWS to show the rectangles (A,B,C,D,E,F) and the triangles (a,b,c,d,e,f) that were used to calculate the total expected damages.

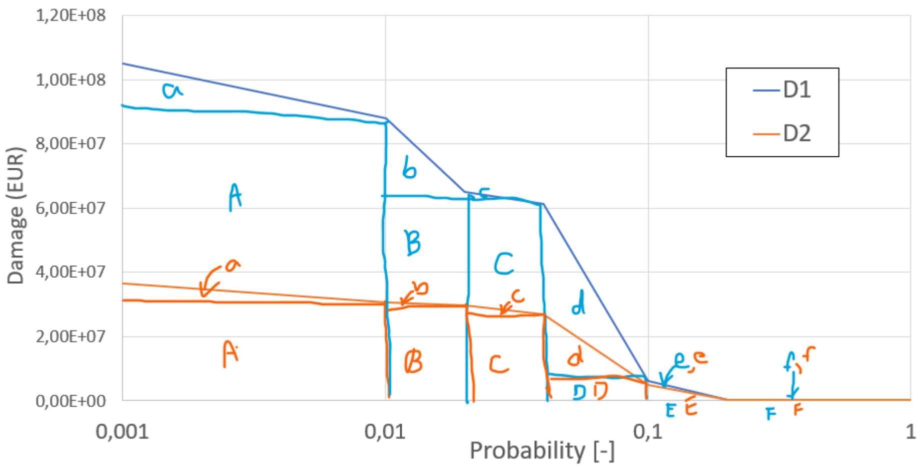


**Figure C.10:** Schematic of simplistic area-under-curve calculation for total expected damages

$$E(D_{A,B,C...}) = D_{1000-year}(p_{100-year} - p_{1000-year}) + D_{100-year}(p_{50-year} - p_{100-year}) + ... + D_{5-year}(p_{1-year} - p_{5-year}) \tag{C.1}$$

$$E(D_{a,b,c...}) = \frac{1}{2}(D_{1000-year} - D_{100-year})(p_{100-year} - p_{1000-year}) + \frac{1}{2}(D_{100-year} - D_{50-year})(p_{50-year} - p_{100-year}) + ... + \frac{1}{2}(D_{5-year} - D_{1-year})(p_{1-year} - p_{5-year}) \tag{C.2}$$

$$D_{expected} = D_{A,B,C...} + D_{a,b,c...} \tag{C.3}$$

Using Equations C.1 - C.3 and Figure C.10, the total expected damage is calculated. The calculations and results are summarized in Table C.1.

| Shape | $D_1$ | $D_2$ | Shape | $D_1$ | $D_2$ |
|---|---|---|---|---|---|
| A | € 9.46 $\times 10^5$ | € 3.27 $\times 10^5$ | a | € 7.70 $\times 10^4$ | € 2.63 $\times 10^4$ |
| B | € 8.80 $\times 10^5$ | € 3.02 $\times 10^5$ | b | € 1.15 $\times 10^5$ | € 5.28 $\times 10^3$ |
| C | € 1.30 $\times 10^6$ | € 5.75 $\times 10^5$ | c | € 3.80 $\times 10^4$ | € 2.69 $\times 10^4$ |
| D | € 3.68 $\times 10^6$ | € 1.5 $\times 10^6$ | d | € 1.66 $\times 10^6$ | € 6.09 $\times 10^5$ |
| E | € 6.16 $\times 10^5$ | € 4.37 $\times 10^5$ | e | € 2.97 $\times 10^5$ | € 2.11 $\times 10^5$ |
| F | € 1.76 $\times 10^5$ | € 8.18 $\times 10^4$ | f | € 0 | € 0 |
| Total | € 7.6 $\times 10^6$ | € 3.23 $\times 10^6$ | | € 7.6 $\times 10^6$ | € 8.79 $\times 10^5$ |

**Table C.1:** Calculations of rectangular areas under $D_1$ and $D_2$ curves using Figure C.10 and Equation C.1.