Flood risk reduction capacity of resilience measures in the Geul catchment

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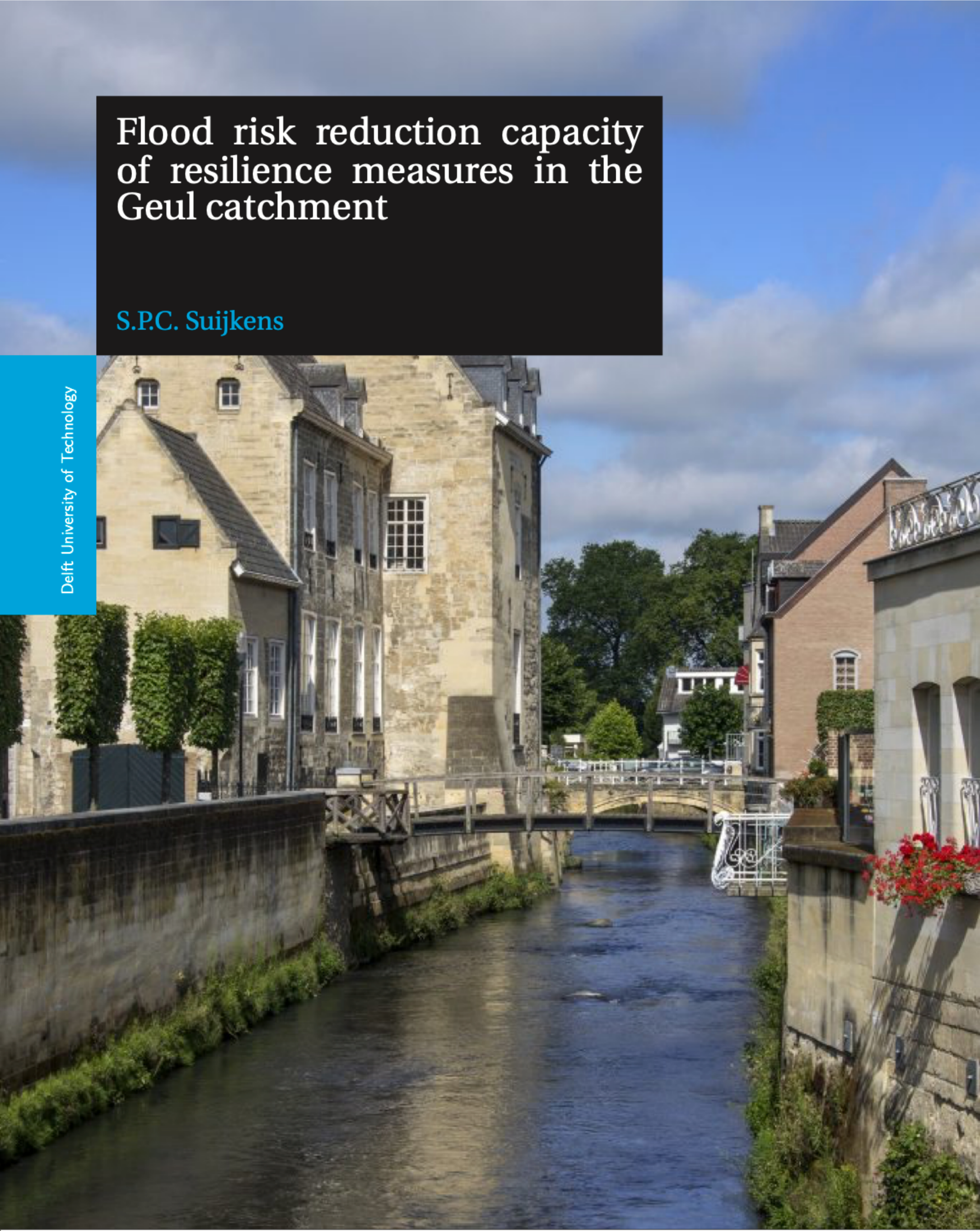

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Flood risk reduction capacity of resilience measures in the Geul catchment

Master Thesis

by

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Abstract

In the summer of 2021 severe flooding occurred in Belgium, Germany and The Netherlands. High damages have been estimated in the Geul catchment, leading up to 250 million euro. Flood risk management in The Netherlands is mostly focussed on reducing the probability of flooding and in lesser extent on damage mitigation. Especially in areas such as the Geul catchment, reducing the probability of flooding through flood defences is difficult to achieve. Also taking climate change and urban development into consideration, it is challenging to meet flood safety standards in the (near) future, as the frequency and intensity of flooding is expected to increase. Under these circumstances a shift is observed in scientific and policy discourses towards a flood risk reduction strategy that includes resilience, in which the capacity to resist, mitigate and recover has a larger role. As a consequence, there is an increasing interest to include private actors in the strategy by promoting private flood mitigation measures. However, it is difficult to quantify the effects of these private measures and little research in The Netherlands has been performed. This thesis investigates which improvements can be made to the flood risk reduction strategy in the Geul catchment, thereby increasing resilience through private flood mitigation measures. Thereto a method to include and asses the effect of the measures in a risk based approach is derived.

An international literature study about flood resilience and society provided two applicable private mitigation measures and their damage reductive effect. Dry-proofing types of measures are defined as measures that prevent water from entering an object and can reduce damages between 60%-100% up to an inundation depth of 1 meter. Wet-proofing measures reduce damages and recovery time, while allowing water inside the object, by flood adapted use or structural measures. The maximum damage reduction is 53% up to an inundation depth of 2 meter. Investigation of the Protection Motivation Theory provided important factors that improve the uptake of these measures, by identifying connections between awareness, preparedness and self-reliance. The two main findings are that the communication strategy should focus on the relative risk reduction effect of private measures and should provide guidance on implementation to motivate private actors to initiate action. Five interviews were used as a reference to these findings. To describe the relative effect of measures, they are modelled in a publicly available risk assessment method (SSM-2017), based on hazard, exposure and vulnerability. The effect of the measures is calculated for two scenarios, that describe at which locations the measures are implemented. In the first scenario, top risk locations are identified and measures are applied. This is representative for high awareness and object specific guidance. The second scenario randomly distributes measures over the flood prone area and represents the current approach without specific guidance. For the modelling of measures and scenarios, an automatic procedure using a Python script is developed, which is applicable in The Netherlands in combination with SSM-2017.

The results show that both dry-proofing and wet-proofing houses and shops are applicable in the Geul catchment. At many locations measures have a positive benefit-cost ratio, indicating it is worthwhile to implement them compared to a situation without measures. More importantly, it is found that high awareness of flood risk or object specific guidance increases the effectiveness and cost-efficiency significantly. For residential objects, an optimum was found to implement measures at the top 40% locations most at risk. The achieved risk reduction was 47% and the benefit-cost ratio 1.3-2.2 for dry-proofing. At this coverage the benefit-cost ratio of measures is a factor 2 higher compared to a situation without specific guidance. Location specific investigation revealed that the inundation depth is the main driver for determining the most effective measure. Wet-proofing is cost-efficient in a smaller number of areas at risk for inundation depths higher than 1 meter. For most areas dry-proofing is more cost-efficient as the expected inundation depths in the catchment are mostly below 1 meter.

The research demonstrates the potential of private measures with a significant reduction of flood risk. Given the limitations to reduce the probability of flooding in the Geul catchment, the measures are highly interesting. The method itself was able to determine the type of measure that was most effective with confidence. However, based on uncertainties in the model, the benefit-cost ratios have to be interpreted carefully. An extension of this research with a higher resolution of input data can address this uncertainty. Current approaches and communication to motivate private measures were found to be ineffective, as they mainly focus on the type of measures and costs instead of the effect and implementation. It is suggested to improve this by explicitly including the before mentioned factors and by making use of social network on the spatial scale of a neighbourhood.

Preface

With this project I have finished my study time at the Delft University of Technology. Since the Bachelor Civil Engineering I have always been interested in the water related topics and courses. During my Bachelor Thesis I was able to develop a global flood risk assessment, which triggered my particular interested towards this subject. During the Master Water Management I was fortunate to participate in two interdisciplinary projects organised by the TU Delft | Delft Deltas, Infrastructures & Mobility Initiative. During these projects, in Japan and Albania, I was able to witness the impact of floods on society and especially the magnitude of the Tsunami in Japan made a large impression. In addition, it emphasized the high contrast in awareness and preparedness regarding flooding between Japan and The Netherlands. After these experiences, the relationship between flood risk and society kept my interest. After the flood event in Limburg in the summer of 2021, I was therefore interested in the possibilities of private measures to prevent flood damages, which resulted in this Master Thesis report. I hope this report can contribute to decrease the impact of flooding in the region.

First of all I want to thank Sweco and the team in De Bilt for the opportunity to work with them on this project, under the supervision of Tom Raadgever. I have appreciated your detailed and thoughtful feedback. Secondly, I want to thank Matthijs Kok for joining my committee. With your knowledge, experience and critical observations I was able to improve my thesis on important topics. Finally I want to thank Erik Mostert to chair my committee. After being my mentor on my very first project in the Bachelor Civil Engineering many years ago, it was a pleasure to finalise my study under your supervision. Thank you for your positive feedback and approachability, not only during the thesis, but also during the complete master programme.

In the last year I also participated in the Delta Futures Lab, where multiple students worked together on topics related to the flooding in Limburg. Thank you Martine for organising the discussions and meetings. Also for enabling contact with the water board Limburg and Deltares. With the help of Kymo Slager I was able to use a flood risk assessment tool. Also Max van Leeuwen provided important information about private measures and allowed me to share my results at the water board. And of course I want to thank my friends and family for the support during my study. Cecilia for your help and encouragement during the thesis. And finally my parents for their endless support and faith.

S.P.C. Suijkens
Delft, September 2022

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1 Introduction

In large area of Germany, Luxembourg, Belgium and in the province of Limburg in The Netherlands, extreme precipitation fell in the summer of 2021. The precipitation caused severe flooding leading up to high damages and mortalities. Estimates for the return period of the rainfall lead up to 1/1000 year and the top discharge of the Meuse river was the highest recorded with an estimate of 3.260 m^3/s (Task Force Factfinding hoogwater, 2021). It could be determined that recent projects on the Meuse river flood defence in Limburg had positive effects, since lower water levels were registered for higher discharges compared to flooding in 1993 & 1995. All primary flood defences withstood the high discharges, nevertheless, still 50,000 inhabitants were evacuated because at several locations the situation was critical along the Meuse. In The Netherlands no mortalities were registered, but mainly damages to property occurred. This damage mostly occurred in flood prone areas along smaller rivers, such as the town of Valkenburg in the Geul catchment. The presence of these extreme conditions in summertime was a complicating factor in the preparedness and initial response. The event was rare for Dutch practice and the Geul catchment received most damages. Compared to the Meuse catchment, there was relatively little warning time and flow velocities were high (Task Force Factfinding hoogwater, 2021).

The events in Limburg led to discussion about current flood risk reduction strategies and safety levels (Kennisportaal Klimaatadaptatie, 2021; Sweco, 2021). The Netherlands has a rich history in managing water and protecting the land against flooding. Around 60% of the country is prone to flooding and the main strategy is to protect the land through flood defences (Ministerie IenW, 2015). In the National Waterplan 2008, the concept of the Multi-Layer Safety (MLS) approach was introduced. The first layer consists of measures to reduce the probability of a flood event. The second layer is focussed on flood damage mitigation. The third layer focusses on measures related to disaster management (Most et al., 2014). Given the lower protection standards in regional water systems and an expected increase in flood events due to climate change, attention for measures to improve the resilience and self-reliance is increasing, which implies an exploration of the second layer of the MLS approach.

Recent studies, such as the STAR-FLOOD project, endorse the importance of a mix of strategies to reduce flood risk. In addition an approach to analyse and improve flood risk reduction strategies is described, as well as the importance of good governance. In the wake of a flood event social awareness and willingness to improve strategies and water systems increase. This forms a good basis and momentum to analyse the current practice and strategies in the Geul catchment.

1.1. Background information

The most recent flood event in Limburg in July 2021 showed flood characteristics that are rare for Dutch water systems, especially in the Geul catchment (figure 1.1). Flooding occurred with relatively short warning time and high flow velocities. In general it can be said that these characteristics have a negative effect on the damages and chances of mortalities.The event triggered public discussion if current flood risk reduction strategies for unprotected smaller rivers in The Netherlands are still sufficient. Also questions emerged about the probability of similar flood events elsewhere, taken into consideration the effects of climate change (Sweco, 2021). The water board Limburg argued that also flooding from regional water systems such as the Geul, should be considered a safety issue and not merely considered as water inconvenience or disturbance (Waterschap Limburg, 2022b).

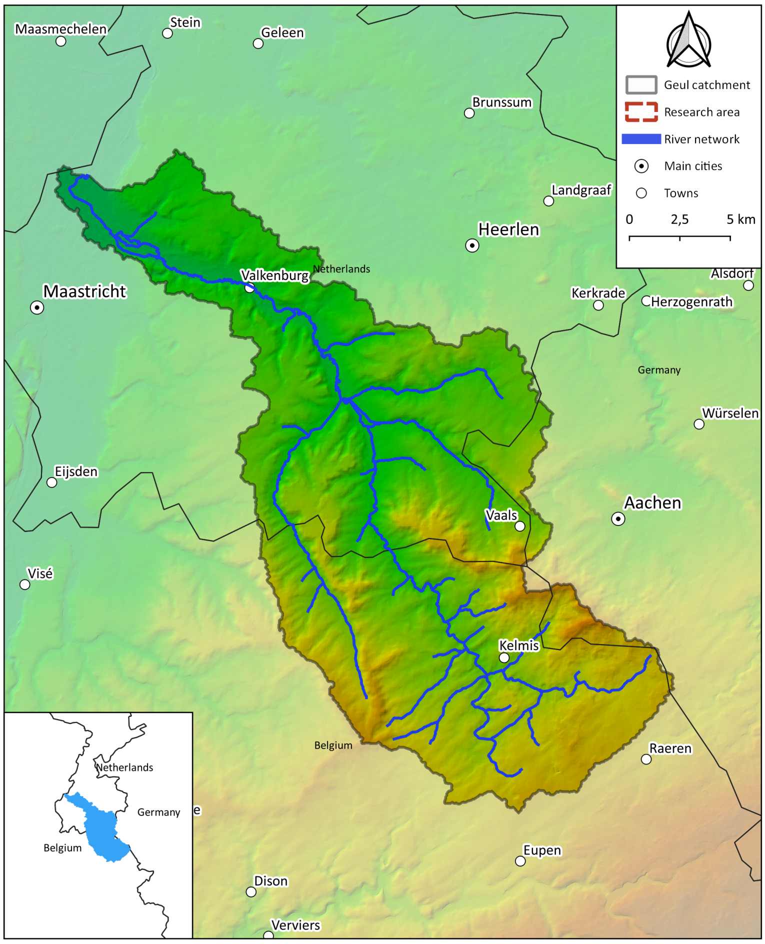


Figure 1.1: Map of the Geul catchment

Despite the formal implementation of a multi-layer safety approach, multiple studies state that measures in the second layer are often not cost-efficient due to the high safety-level of the measures in the first layer (Vreugdenhil, 2018; Kolen et al., 2020; Kolen and Kok, 2011; Kind, 2014a). This holds especially for primary systems and a direct consequence of these high costs is that exchanging measures between the three layers is very limited to reach a similar safety level. In addition, the legal framework does not provide sufficient support for the exchange of measures between layers. For primary flood defences safety levels and assessment methods are legally defined, but for measures in the other layers no legal background exists. This would indicate that within the current legal framework it becomes difficult to prove the principle of equivalence and measures in the second and third layer can therefore only be implemented in addition to the first layer (Kolen and Kok, 2011; te Linde et al., 2018). As a consequence, because of the high cost and lack of clear legal support, the incentive to take adaptive and innovative measures in the second layer is lacking, despite that they can be efficient in specific cases (Kolen et al., 2020), for example in regional systems.

The general strategy of minimizing the probability of flooding has adverse effects on awareness, preparedness and recovery. The strategy does not explicitly cover these aspects and therefore the resilience of an area is not improved because the consequences if flooding does happen are underexposed (Vreugdenhil, 2018). Concerns are expressed about the ability to adapt water systems in the future to comply with the required safety levels (Dekker et al., 2021). Under the influence of climate change, land subsidence, urbanization, population growth and investments in flood prone areas, the consequences of failure of the first layer will have an increasing negative impact. In addition, residents and business owners affected by flooding face great challenges in the structural recovery and financial settlements. This leads to distressing situations, long recovery time and intangible (in)direct damages as in the current approach little attention is focussed on recovery and financial safety.

Current (publicly available) cost-benefit analyses to asses the feasibility of the multi-layer safety approach are mostly performed for areas protected by primary flood defences. Extensive investigation and cost-benefit analyses for regional water systems are not widely performed. Nevertheless, in the report STOWA 2016-30 it is explained that the concept of multi-layer safety in regional water systems is worthwhile to explore with pilots. A major benefit is that provinces and water boards are working closely together in determining the required safety level and accompanying assessment, hereby not bound by *explicit* national legal requirements. This creates flexibility and a podium to explore alternative strategies. However, a complicating factor is the difficulty to quantitatively assess the effect of flood risk reduction measures in the second layer. Additional expertise on spatial design and resilience measures is needed to adapt this in a risk based approach, including cost, benefits and uncertainty (Kolen and Kok, 2011).

Determining the effect of different strategies in which also the resilience of an area can objectively be measured is difficult. Often resilience is described qualitatively and therefore there remains a gap between economic based risk-assessments and resilience assessments, making a combined evaluation difficult. Resilience of a system to flooding is defined as the ability to prevent flooding, the capacity to cope with the consequences and to recover. This includes the ability to learn and adapt (Raadgever et al., 2016). In this thesis the resilience aspects that focus on the capacity to cope with the consequences of flooding will be the main subject.

1.2. Problem Statement

The water board Limburg faces difficulties to cope with an increase in flood risk. The topography of the area proved to be challenging to adapt the water system and in combination with the strong heterogeneity of flood characteristics, these put the cost-efficiency of preventive measures under pressure. Regional water systems, such as the Geul floodplain, are known for their lower protection standards compared to primary defences, but nevertheless have great potential for high damages. In addition, the protection standards in the Geul floodplain are set at only 1/25 year, which is a quarter of the generally used standard of 1/100 year for urban areas in regional systems in The Netherlands. Due to the aforementioned challenges also that standard is not met in the entire floodplain and some urban locations are estimated at even as low as a 1/10 year flood protection standard.

While efforts are made by the water board to increase the awareness and preparedness amongst residents, little specific guidance is provided at the object level. Especially in the Geul floodplain, with a high damage potential but limited possibility to take preventive measures, it is of importance to increase the resilience of the area through other strategies. To implement these strategies it is essential to gain insights in the effect and cost-efficiency of measures that increase resilience.

Private flood mitigation measures, which can increase the resilience of an area, gain increasing attention and interest, however, current studies in The Netherlands do not describe the quantitative effect of these measures. Therefore there remains a gap between the societal factors that influence resilience and the technical implementation. Currently residents and business owners are stimulated to take private flood mitigation measures themselves and face a difficult decision whether to implement these measures from a economical perspective. This is further complicated by the insurance options and its policy conditions and possible compensation from the government. This leads to a complicated judgement to what extent private actors are responsible for the risks and if measures are a good investment. Nevertheless, the cumulative effect of private measures, observed at the catchment scale, can contribute to flood risk reduction of the area. A quantification of this cumulative effect is useful for the water board Limburg to assess whether the measures can be implemented in their strategy and if they can mitigate flood risk at areas where the required protection standards are difficult to achieve through preventive measures.

1.3. Objective

The main objective of this thesis is to include flood resilience aspects and measures in an economic based risk approach for the Geul floodplain, hereby focussing on private flood mitigation measures. By doing so it will be possible to formulate recommendations to residents, business owners and the waterboard on how and when to improve the resilience of an object or area. In addition a connection between awareness, preparedness, self-reliance and recovery to risk reduction will be identified. The type of measures can be placed within the second layer of the multi-layer safety approach, but only the risk reductive effect of the investigated measures will be determined, without an integral assessment or combination of measures that span all three layers of the multi-layer safety approach.

The thesis will focus on Dutch part of the Geul catchment, but the methodology should be applicable and easily be transferable to other catchments in The Netherlands with unprotected smaller rivers, which are defined as sloping systems that drain freely with the exception of major rivers (primary water systems).

1.4. Research questions

Main question:

> Which improvements to the current flood risk reduction strategy in the Geul catchment can be made, thereby increasing the resilience of the flood prone area, based on lessons learned from the summer 2021 flooding?

Sub-questions:

1. Which general approaches can be used to increase resilience?
2. What is the willingness of residents to adapt?
3. How can resilience be included in the currently used flood risk assessment methods?
4. Which improvements in the strategy can be defined for the Geul floodplain and what are the effects?

1.5. Methodology

At first flood resilience will be investigated in relation to society. A literature study will provide insight into which social factors influence private resilience. In addition, open interviews will be held with residents, business owners and employees of the water board Limburg who have experience with flooding from the Geul river. These findings will be combined with the results of an (international) literature study into the various possibilities to increase the resilience of an area and their effects. This results in a set of potential resilience increasing measures, applicable in the social context of the research area.

The resilience measures that are identified, are quantified in a risk based flood assessment making use of the Slachtoffer en Schademodule 2017 (SSM-2017). The effect of measures applied to the area is investigated on both a floodplain scale and object scale. Based on the gained insights on the effect, cost-benefits and applicability, local advices on a neighbourhood scale are formulated.

1.6. Report structure

The structure of this report is as follows: in chapter 2 the theoretical background of currently used flood risk assessment is explained in more detail. In addition information is presented on the historical perspective and governance structure regarding flood protection in The Netherlands. Finally the summer 2021 flooding event will be described in more detail. In chapter 3 the methods used in the thesis will be explained. In chapter 4 flood risk assessment methods are reviewed and selected. In chapter 5 the set-up of the interviews and results will be given. Also the results of the international literature study on resilience is presented, including the risk reduction effect of measures. In chapter 6 the risk assessment set-up is described in detail and the results are validated and analysed. In chapter 7 the location specific effect of measures will be investigated, based on the gained insights in chapter 5 and 6. In chapter 8 and 9 the discussion and conclusion will be presented. Finally in chapter 10 recommendations are given.

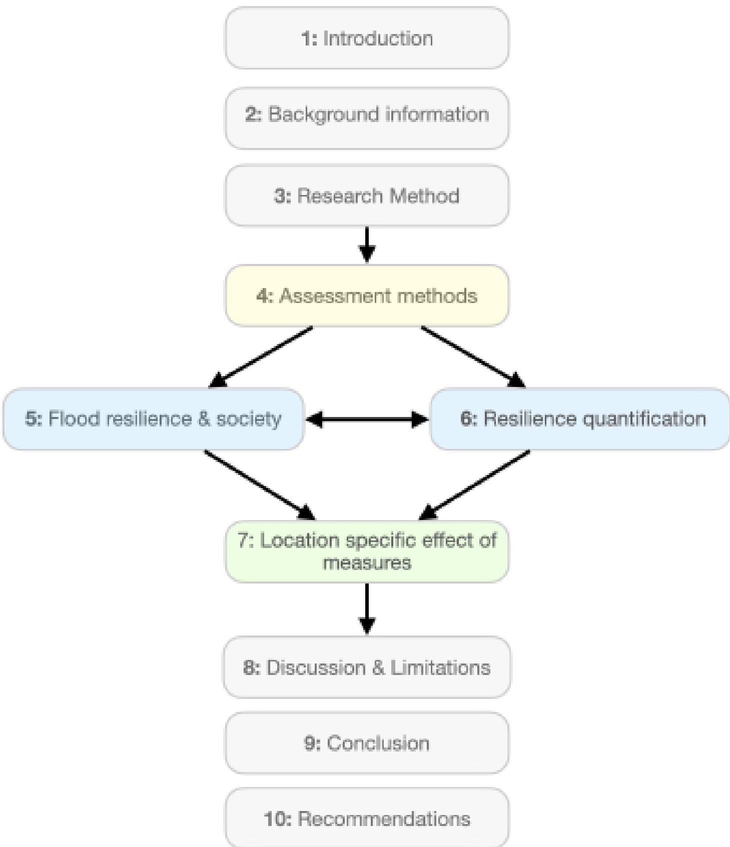


Figure 1.2: Structure of master thesis report

2
Background information

2.1. Historical perspective

The Netherlands has a rich history of flood protection. In several areas in the North the remains of "terpen", which date back to 700 B.C. (Terpen en Wierdenland, 2022) can still be seen: areas of raised land to protect against invading water. Around the year 1000, people started to cultivate the peat grounds in the west where proper drainage was needed and small ditches were constructed. Because of continuous land subsidence, dikes had to be constructed and this marked the beginning of the traditional polder system. Wind mills were placed to pump water to drainage canals with a higher water head and additionally to the river. At first the construction and maintenance of these dikes was performed by local organisations. These organisation form the basis of the current water boards and in 1255 the water board Rijnland was formed, which still exists today. The water boards became responsible for the maintenance and inspection of the dikes and started to collect taxes. On a national level, in 1798 a law was passed in which a central organisation oversaw all water related constructions: "Bureau van den Waterstaat". In 1815 after the French invasion ended, the bureau was transformed into "Rijkswaterstaat" which is the department of Waterways and Public works, as it still exists today. With the development of the department major projects were initiated such as the construction of the Haarlemmermeer polder (Watersnoodmuseum, 2018). In 1927 the water boards were united in the Union of Water Boards to represent them at governmental level (Unie van Waterschappen, 2022b).

In 1916 major flooding occurred and multiple dike breaches were registered. This initiated the Zuiderzee project which led to the closure of the Zuiderzee with an enclosure dam which was finished in 1933. The complete project was finalized in 1970 with the construction of the Zuid-Flevoland polder. The most severe flooding event in modern history happened in 1953 when major parts in the West and especially the province of Zeeland was flooded. In a response the Delta Works were constructed, in which the length of the coastline was reduced from 700 km to 80 km, that consist of five storm surge barriers, two locks and six dams (Rijkswaterstaat, 2022).

After the Zuiderzee project and the Deltaworks (1953-1997), the Deltaplan Large Rivers was formed. The main cause was the high river discharge in 1993 and 1995 which led to flooding of the Meuse in Limburg and other regions. Roughly 1000 km of dikes were reinforced and 100 km was newly constructed. Every twelve years a national control of the safety of the flood defences has to be performed. For some regions the safety level was unsatisfactory and in 2001 the first "high water protection program" was initiated for the period 2001-2006 to address these issues. This was followed by a second program for the period 2006-2015. Parallel to these programs the "Room for the river" program incorporated a strategy to allow for more space, instead of reinforcing flood defences only. Finally the third "high water protection program" is started for the period 2011-2023.

Also smaller rivers caused water disturbance. Mainly caused by their meandering character, during higher flow conditions the discharge capacity is limited (Waterschap Rijn en Ijssel, 2022). Therefore many smaller rivers have been channelised to increase the discharge capacity, thereby disturbing the natural character of the river and surroundings. Currently a "pendulum swing" is described from "from water resources development and control to protection and restoration" (Mostert, 2018). An example is described for the river Dommel in The Netherlands, but also in Limburg several projects are focussing on the restoration of river valleys. This attempts to restore the biodiversity, for example by introducing meandering sections again. An important aspect is that the restoration is performed in such a way that no water disturbance occurs.

2.2. General theory of flood risk and definitions

In literature several definitions of (flood) risk can be found, but often is expressed as the combination of the chance of occurrence of a certain event and the consequences of that event. More specifically it can be described as:

$$\text{Risk} = \text{Hazard x Exposure x Vulnerability} \tag{2.1}$$

Hazard is described as an event that can cause damages and its probability. Exposure refers to resources and infrastructure that are affected by the event. Finally vulnerability refers to what extent the assets are affected and to what extent they are able to provide resistance (Kron, 2002; Merz et al., 2014). An important aspect is the metric that is used to describe the risk. For example loss of life can be expressed in the number of fatalities and is described by Jonkman (2007). Direct damages can be expressed in a monetary value, through the Expected Annual Damage (EAD) with the formal equation (De Bruijn, 2005; Jonkman et al., 2015; Carsell et al., 2004):

$$E[X] = \int_{-\infty}^{\infty} x f_x(x) dx \tag{2.2}$$

With x the random value of annual damage that occurs with probability $f_x(x)$. The procedure to acquire the EAD value is to derive the probability of a certain water level, connect that water level to a damage value and subsequently construct a damage-probability function. The numerical integral of this function is the EAD value. The benefits of measures can be described by the difference in EAD, with and without the implementation of measures.

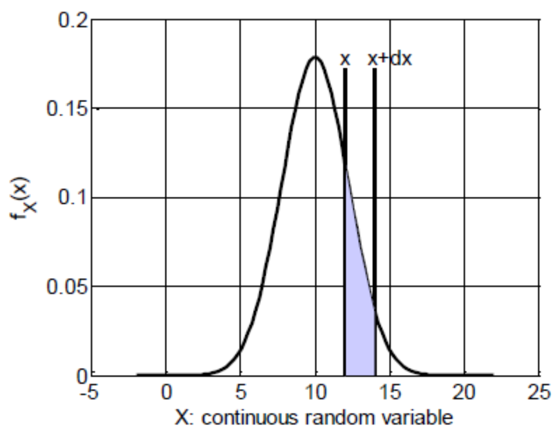


Figure 2.1: Probability density function and visualisation of equation 2.2 (Jonkman et al., 2015)

The benefit of expressing flood risk in a monetary value is the ability to describe the cost-efficient of measures against the risk. This can be explained through the benefit-cost ratio, which for feasible solutions should be greater than one (Mostert, E., 2022). In addition, the benefits of risk reduction over a longer time span can be explained through the Net Present Value (NPV), as described by equation 2.3 (Mostert, E., 2022).

$$NPV = \sum_{i=1}^{T} \frac{C_i}{(1+r)^t} \tag{2.3}$$

With:

- C_i is the cost in year i [€]
- r is the discount rate
- T is the reference period in years

The economic, damage based assessments are often of major importance to determine required safety levels. However, focussing only on economic metrics is limited and a sustainable solution has to include environmental and social aspects as well (Miguez et al., 2018). It is difficult to express the more qualitative resilience assessments in objective and/or monetary values and therefore there often remains a gap between both assessment, making an clear integral evaluation difficult. These issues are confirmed in the literature study of Morrison et al. (2017), in which 258 articles regarding governance and flooding & resilience & adaptation are investigated. It is herein concluded that the integration of the social-ecological complexity is lacking in flood risk management.

To express damages it is important to distinguish different types of damage. First and the most visible one is *direct tangible* damage. It is damage as a result of direct contact with water and expressible in a monetary value, for example damage to buildings and other infrastructure. Damages outside of the flood prone area and/or business or production losses, are *indirect tangible* damages. Intangible damages are usually difficult to express in a monetary value. *Direct intangible* damage is for example loss of life or the negative effect on the ecosystem. An example of *indirect intangible* damage is (psychological) trauma. (Merz et al., 2010; Jongman et al., 2012).

In the research of White et al. (2018) a shift is described from "flood defences" only to manage risks towards "Flood Risk Management" (FRM). Within the concept of FRM, flood resilience and resistance measures play an increasingly important role. The definition of resilience is flexible, but can be described as: "measures that may allow ingress but create the conditions for a quicker recovery of individuals, communities and buildings."(White et al., 2018) or that resilience "is directly associated with the capacity or ability of individuals, groups, or communities to cope with the adverse effects of a hazard." (Gotangco et al., 2016). Resistance on the other hand can be defined as "structural" resilience and is then explained as the ability to resist hazards. At a property scale resistance measures are therefore seen as measures that aim to refrain water from entering the building (dry-proofing). Whereas resilience measures mainly limit damage and improve recovery time (wet-proofing) (White et al., 2018). In the STAR-FLOOD research another aspect of resilience is explained as the ability to learn and adapt (Raadgever et al., 2016). It must be noted that although a distinction can be made, a certain interaction between the types of measures can occur, where for example resistance measures increase the resilience.

2.3. Governance in The Netherlands

Several governmental agencies are responsible for flood risk and water management on a national and regional level. In addition throughout the years numerous policies and guidelines have been written to adapt to new developments. In this section a brief overview of the governmental actors is presented.

The main governmental institute responsible for water management and flood protection is the Ministry of Infrastructure and Water Management. The ministry defines a National Waterplan in which the national and regional strategic water policies are described. Based on the results of the Deltaprogram safety, new safety standards and assessment methods for primary flood defences were included in the National Waterplan. As of 1 January 2017 these regulations are incorporated in the national Water Act and are therefore mandatory (STOWA, 2022). Finally, Directive 2007/60/EC of the European Parliament was published on 6 November 2007 and describes the assessment and management of flood risk for all member states.

The management of the national waters (large rivers, canals, North Sea, IJssel lake, Waddenzee) and a limited number of flood defences lies with "Rijkswaterstaat". The management of other waters is determined by provincial ordinance and is usually a water board (Mostert, E., 2019). Rijkswaterstaat and the water boards are responsible for the maintenance, inspection and where necessary improvement of the flood defences. Safety levels for regional water systems are determined by the provincial executive. Usually based on a cost-benefit analysis the level is defined as a return period of non-exceedance and in addition the provincial executive determines which defences have to be included. The water boards compose a management plan in which it is described how these standards will be implemented and enforced. It must be noted that the judicial status of the provincial safety levels can be interpreted as an "best efforts obligation" and not an obligation of result (Ministerie IenW, 2022). The determination of regional safety levels have to comply with the general principles of good administration and the national Water Act describes the necessity to establish a safety standard and accompanying management plan. Contrary to primary flood defences, no explicit protocol for the determination and assessment is described. However, for urban areas usually the safety level is determined at 1/100 year for regional water systems (Ministerie IenW, 2022; Mostert, E., 2019).

As described in section 2.1, the origin of the water boards lies more than 1000 years ago. They originated in the low lying parts of the country in the West. For Limburg the first water board was formed in 1866 and later fused to the current water board Limburg. Initially there was no need for a water board, as most agricultural areas were located on high grounds. A higher demand of agricultural areas and the starting industralisation gave incentive to the construction of a water board. Flooding in these areas of the smaller rivers was accepted, as it also deposited fertile soil on the land (Waterschap Limburg, 2022c).

The water boards are considered a public entity with an executive committee and a general board. The general board consists of representatives of several categories, such as inhabitants and farmers (Mostert, E., 2019). These representatives are voted upon by public election. The executive committee consists of a chairman (or "dijkgraaf") and is appointed by the Crown for 6 years. In 1953 The Netherlands had around 2650 water boards, which through abolition and fusion was reduced to 21 as of 2022 (Overheid.nl, 2022). The status of the water boards has been subject to public debate. Currently there is discussion about the democratic position of the secured or reserved seats, that are directly appointed instead of being voted upon. In May 2022 the house of representatives approved a new initiative that reduces the number of secured seats (Unie van Waterschappen, 2022a). The water boards have a major role in the "water review" (*dutch: watertoets*). The water review is a process which ensures that water management goals are explicitly incorporated in any spatial plans (Mostert, E., 2019). It consists of five phases and it was found that mostly in the determination of "destination plans" the role of water can be a decisive factor.

Despite this governance structure and relatively high safety levels (primary defences), flooding does occur. For flood events it is complicated if any party can be held responsible for occurring damages. For many years insurance companies only covered water damage due to direct or indirect precipitation. As of 2020 multiple insurance companies included coverage for damages due to the failure of regional flood defences for private contracts. For damages due to failure of primary flood defences only one company provides coverage. In general coverage for these flood events are difficult to insure because of the cumulative risk. For damages that can not be insured, a "safety net" provided by the government can be activated through a Disaster Compensation Act. If the national government rules an event as a disaster, the act can be activated. Under specific conditions damages that were not insurable, not recoverable and not avoidable will be paid by the government. Those affected have to personally apply for compensation and within 13 weeks a decision will be made about the claim and after gratification another 6 weeks apply for the payment to be completed. In a worst case scenario it could therefore take 19 weeks before repairs can be started which negatively influence the recovery capacity of an area. It must be noted that in case of the 2021 flooding the government was generous since the possibility of insurance was relatively new and not many residents made use of the option. For future events it is expected that the Disaster Compensation Act will be handled more strictly and no compensation will be given if insurance is determined to be possible.

2.3.1. Current Flood risk assessments in The Netherlands

In section 2.3 new safety standards for primary flood defences are mentioned. In Most and te Nijenhuis (2019) and Slootjes and Most (2016) the main concept of the standards are described and it is explained that the incentive for the new standards is the increase of economic value in flood prone areas. Two goals were leading in the creation of the standards:

- Basic safety level for everyone behind a primary flood defence, with a protection level of 10^{-5}/year, indicating the chance of death for an individual by flooding each year. It is expressed through the Local Individual Risk, which is defined as the product of the chance of flooding, the percentage of people that don't evacuate and the mortality rate.
- The implementation of extra safety for areas with high group risk. The main purpose is to decrease the societal impact of flooding.

It is a risk-based approach, taking into consideration the probability of flooding based on the probability of failure of a dike section. For the failure probability several failure mechanisms are considered, which fall out of the scope of this thesis. A social cost-benefit analysis is used to determine the optimal protection level, which is dependent on the economic damage of a flood event and the cost to reduce the chance of flooding. Hydrodynamic flood simulations (Sobek 2D) are used based on the project "Veiligheid Nederland in Kaart" and they form the basis to calculate the direct and indirect damages due to flooding. These damages are calculated with a damages and fatalities model, HIS-SSM (Slootjes and Most, 2016). The safety level is finally determined as the most critical demand from the assessment between basic safety and economic feasibility.

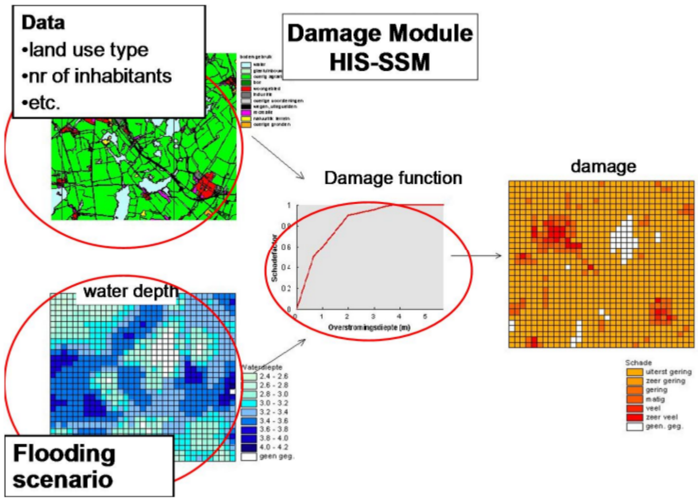


Figure 2.2: Outline of HIS-SSM assessment method (De Bruijn et al., 2015)

For regional water systems the assessments are organised in a different manner. The most important difference of the standards is that for regional systems they are based on a chance of exceedance instead of a chance of flooding because of failure of the defence. In 2000 the committee "Waterbeheer 21ste eeuw" advised on national standards for regional water systems, which were later translated to standards based on land use and expected damages (table 2.1). These standards indicate the acceptance of the occurrence of inundation from surface water. Alternatively a Ground Level Criterion (*dutch: maailveldcriterium*) can be used, which is defined as the percentage of water that can be inundated without a bottleneck (Dekker et al., 2021). After the introduction of the Water Act, standards are incorporated in the Provincial Ordinance and define the efforts of the water boards. To avoid divergence of the assessment methods, in 2011 advices were made on a standard approach to assess regional defences, while it must be noted it is allowed for water boards to use other methods. The general workflow of the method is to first set-up a hydrological and hydrodynamic model for the area. Then after a statistical analysis of precipitation, accompanying water levels are calculated which are translated into inundation maps. These inundation maps are compared with a standard map based on table 2.1. Based on this comparison areas in the regional water system that do not comply are identified.

Table 2.1: Overview inundation standards regional water systems (Dekker et al., 2021)

Land use	**Standard [year]**	**Ground level Criterion [%]**
Grassland	1/10	5
Agriculture	1/25	1
High quality agriculture & Horticulture	1/50	1
Residential area	1/100	-

2.3.2. Multi-layer safety approach

In the introduction of chapter 1 and section 1.1, the concept of multi-layer safety (figure 2.3) was introduced and the general problems that are faced with the implementation. In this section more detail is given about the three layers:

- Layer 1: consists of measures to reduce the probability of a flood event. In The Netherlands this is mainly implemented by dikes and storm surge barriers. For the majority of the cases this is the most cost-efficient measure (Kind, 2014a).
- Layer 2: is focussed on flood risk mitigation through for example spatial design and adaptation.
- Layer 3: focusses on measures to improve disaster management, for example evacuation and preparedness.

In general it can be stated that for areas with high inundation depths, measures in the first layer are more economically feasible. In areas with lower inundation depths or very localised high risk areas, measures in the second layer can become attractive. The difficulties in exchanging measures between the layers have been addressed in section 1.1 and the study of te Linde et al. (2018) further investigates the possibilities in primary systems. A smart combination is defined as the possibility to take measures in the second and third layer to (partially) replace measures in the first layer. In such a combination the safety level of the first layer can be lowered, but the overall safety level will remain similar. Main findings are that when the determining factor of the safety level of a dike is because of the social cost-benefit analysis, smart combinations are not feasible. For areas where the Local Individual Risk (LIR) was leading, possibilities exist. Also this research finds that determining and proving that the safety level is maintained through measures in the second or third layer is a difficult task. Experts in the field are generally positive, but agencies that are responsible to prove and maintain the safety are less open to the idea of smart combinations. Especially measures in the third layer, that increase the evacuation fraction, seem to have low support by the Safety Regions. It is concluded that support for a smart combination can be achieved when the idea is formed bottom-up. Specific areas are mentioned as option for smart combinations, for example where improving the dike has no local support, is not possible due to spatial problems or where measures in the first layer disturb the current cityscape. A remark about the latter is that this is an important aspect in Valkenburg.

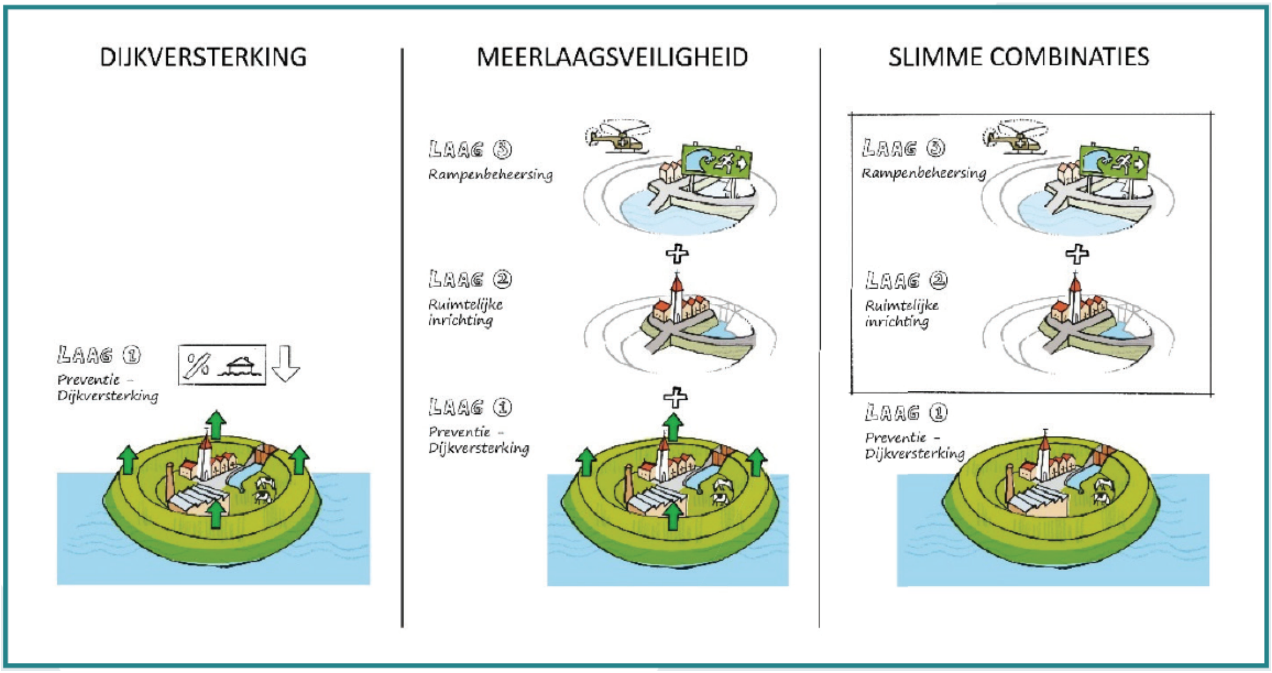


Figure 2.3: Multi-layer safety concept. *English: Strengthening dikes, Multi-layer safety, Smart combinations. (te Linde et al., 2018)*

2.4. Geul catchment research area

The Geul catchment is approximately 340 km^2 and the river has a length of 58km. For The Netherlands the river has a steep slope, with a elevation difference of 250m (Van Heeringen et al., 2022). North of the village Gulp the slope decreases before it reaches the confluence with the Meuse river. The origin lies in Belgium and especially in The Netherlands the river flows through a incised valley. The total catchment is located for 42% in Belgium, 6% in Germany and 52% in The Netherlands (Klein, 2022). The main river has several tributaries, of which the most important one are the Gulp, Eyserbeek and Selzerbeek. The Dutch part of the catchment is shown in figure 2.4.

Rainfall in the area reaches a fast run-off through the steep hills in the area. In the past decade several projects were initiated to restore the natural character of the river, thereby re-introducing the meandering character. However, in most villages the Geul is channelized and this acts as a bottleneck for water discharge. Several rain water buffers have been constructed in the valleys of the tributaries and more upstream in the catchment to delay the high water peak. Nevertheless, the current standards for urban areas in the regional water system are not met. In Valkenburg for a T=25 year event, up to 15cm of inundation is predicted (Van Heeringen et al., 2022). These inundation events occur under the influence of heave rainfall over a time span of multiple days.

The largest town in the area is Valkenburg with 16,365 inhabitants. The number of residential objects is 8,309, of which 39% are rental houses. With 91% of the houses built before 1990, the objects are relatively old (Kadastrale kaart, 2022). The Geul flows past several other villages before it reaches Valkenburg: Partij, Wijlre and Schin op Geul. Other larger villages upstream in the catchment are Gulpen, Eys and Simpelveld. Downstream of Valkenburg are Meerssen and Bunde located. Near Bunde the Geul flows through a culvert underneath the Julianacanal. After the culvert it reaches the Meuse.

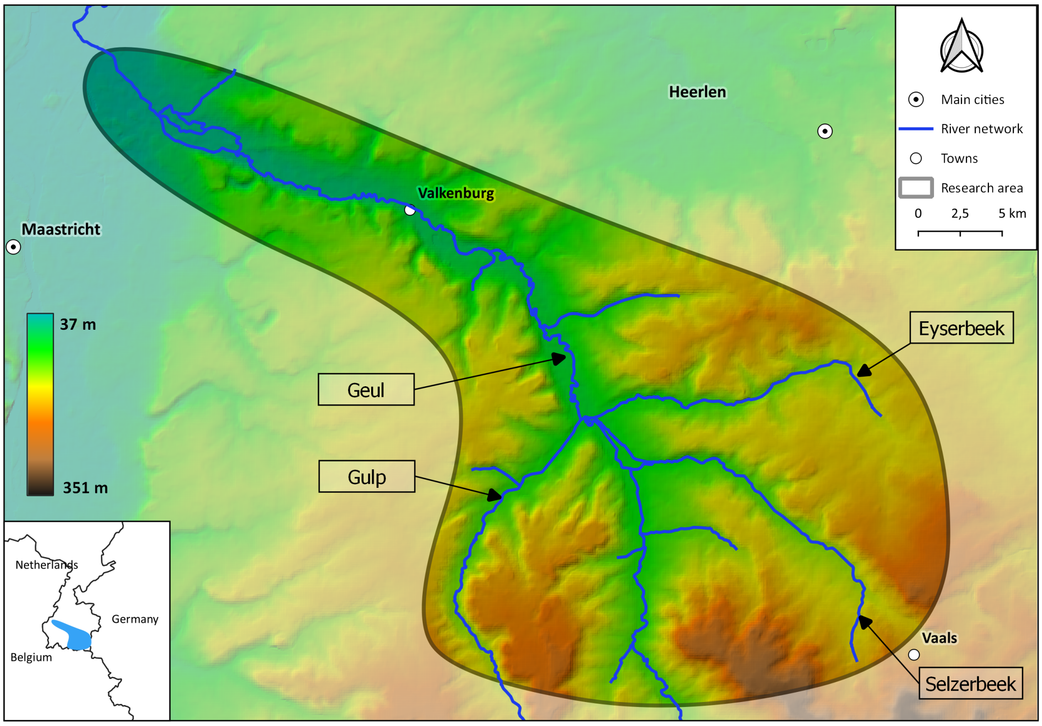


Figure 2.4: Map of the Dutch part of the Geul catchment

2.5. Summer 2021 flooding event

The Task Force Factfinding hoogwater (2021), hereafter referred to as Factfinding, is a consortium of universities and (knowledge) institutes led by the TU Delft and Deltares that investigated the 2021 flooding and this section provides a brief overview of their findings.

On July the 13th and 14th extreme precipitation was registered in the German Eiffel, Belgian Ardennes and in the south of Limburg. The main driver of this precipitation was the presence of a "cold pit", which is a cold air bubble high in the atmosphere. Under these circumstances it becomes possible to attract moist air from other regions and a lot of energy is available to generate precipitation. In this specific case most moist air was attracted from the Baltic region, which suffered a heat wave in the weeks before the high precipitation event. In the south of Limburg 158-182mm precipitation was measured for a 48-hour period and it is estimated that the frequency of occurrence is in the order of 1/1000 year. However, if taken into consideration that the precipitation occurred in the summer, a Gumbel-distribution shows return periods of up to 1/10.000 year in Limburg and 1/100.000 year in the Belgian Ardennes. A remark must be made that for these return periods the uncertainty of the estimation is relatively large, given the small area and fact that the current data series is roughly 100 years. Based on the precipitation, attempts were made to predict river discharges. For the Geul catchment an HBV-model coupled to a Sobek model exists, but was not active during the flooding. Since it was estimated that for this precipitation event the model would not perform accurately it was decided to not use it to predict discharges for the Geul river.

After the event the maximum discharge in the Meuse river was estimated at 3.260 m^3/s. For the smaller Geul and Roer river, the discharges were 100 m^3/s and 270 m^3/s respectively. An overview of all peak discharges in Limburg is given in figure 2.5. The peak discharge of the Geul into the Meuse coincided with the peak discharge in the Meuse, which caused additional problems in the most downstream end of the Geul. For the Geul, water levels are in the order of decimetres to 1 meter higher than the inundation maps made by the water board Limburg for T=100 year. Since no inundation maps for higher return periods are constructed, the exact chance of the occurring water level can not be determined precisely. The city of Valkenburg lies in the Geul floodplain and is known for it's historic views and tourism industry and the presence of the river is of major importance for the city. However, the dense urban area in close proximity to the river increased flood risk and efforts to reduce this risk are costly. For the city of Valkenburg a safety level of 1/25 years was determined, based on a (social) cost-benefit analysis, taken into consideration the mentioned factors. According to this analysis the flood event in Valkenburg should therefore be seen as the expertly accepted risk, however, given the responses by residents and the municipality that might be controversial. In addition, it is therefore questionable to what extent the strategy complies with legitimacy as explained in the STAR-FLOOD project. In the project legitimacy is described as the social acceptance of the input, process and output of flood risk management and governance (Raadgever et al., 2016). Similar findings are expressed by Dekker et al. (2021) who state that the interface of public responsibility and residual risk for stakeholders is not always transparent. Most water boards do not define which climate scenarios are taken into consideration and to what reference situation assessments are being performed, which causes uncertainty about local inundation depths, residual risks and responsibilities of the water board (Dekker et al., 2021).

The flooding led to high damages, but luckily in The Netherlands no mortalities. The flood characteristics show that there was a significant risk of mortalities: high flow velocities, inundation depth above 1.5m and a fast inundation rate.

Especially along the smaller rivers and mostly the Geul, high damages occurred. Inundation depth, time of arrival and flow velocities were determining factors. Large differences are observed between buildings and in addition there is wide variation in the recovery time, mainly based on the drying capacity of the construction. This induced large differences in direct and indirect damages, for example some business expected to open after 6 months of the flooding while others opened within days. Flooding of this magnitude is rare for the summer season which made people less prepared and had a negative impact on damages. A first estimate was made making use of the Standard Method Damages and Victims 2017 (Task Force Factfinding hoogwater, 2021) for direct tangible damages, supplemented with estimates for business losses (indirect tangible). The calculated damages are in a range of 350-600 million euro for all affected areas (figure 2.6), but estimates from other agencies go up to 1.8 billion euro.

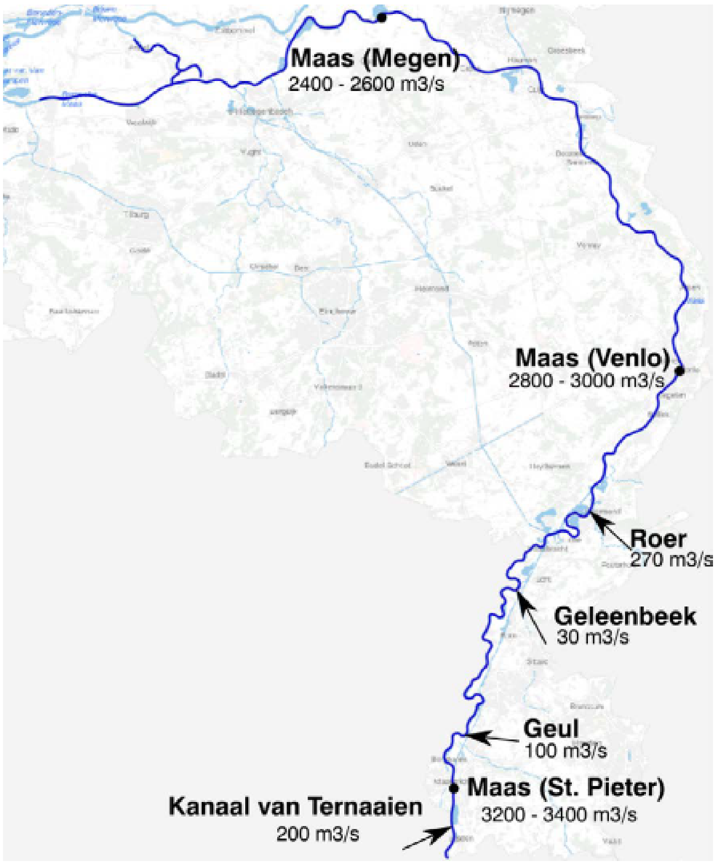


Figure 2.5: Overview of discharges for rivers in Limburg (Task Force Factfinding hoogwater, 2021)

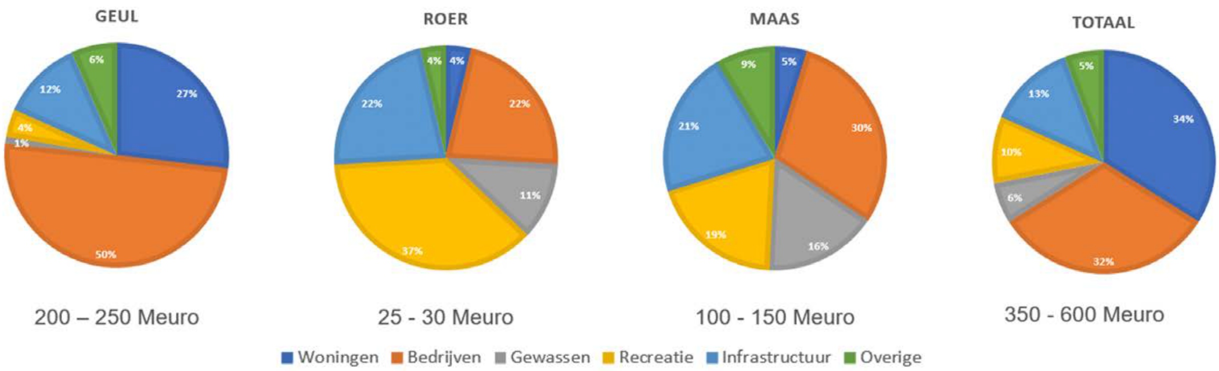


Figure 2.6: Overview of damage estimates for different catchments (Task Force Factfinding hoogwater, 2021)

3 Method

In this chapter the methods that are used to answer the research questions are explained. Section 3.1 describes the literature study into the general approaches of resilience to answer sub-question 1. The willingness of residents to adapt, sub-question 2, is answered by the combination of the literature study and interviews described in section 3.2. The methods to include and quantify flood risk and the effect of measures, thereby answering sub-question 3, are discussed in section 3.3 & 3.4. Finally, the method for sub-question 4, determining improvements for the area, is discussed in section 3.5.

3.1. Literature study on improvement of resilience

To propose measures and strategies to reduce flood risk and increase resilience, it is first important to investigate the current state of development on an international scale. In addition, a clear definition of resilience, besides the more general concepts described in chapter 1, has to be defined for the context of this thesis. In chapter 1, a short elucidation was provided on the history of Dutch flood defences and strategies. From this it can be derived that the majority is focussed on polder systems, river dikes and storm surge barriers. The majority of the damages in the 2021 flooding occurred in a completely different setting, namely a small river without dikes in a fast responding hilly area. These settings, also including low protection standards, can be found in numerous locations worldwide. International investigation through a literature study will provide valuable information and new insights in current flood protection approaches and definitions of resilience. This provides the answer to sub-question 1.

An important aspect to improve resilience is the willingness and ability of those affected to adapt. A complex interaction between flood protection technologies and society has occurred for more than thousand years, in which the determination of the public-private divide of flood risk management is an ongoing process. Any proposed measure or strategy can not be treated separately from the social context and the dependencies between stakeholders needs to be recognized (Mostert et al., 2008). A widely used method to investigate the viewpoints of residents regarding flooding is a survey research and analysis. The answers can be analysed to derive topics as received damages, preparedness, implementation of measures and motivations to undertake these measures. The complete process from survey construction, testing, sending, collecting answers and analysis, takes too much time for the time frame of this master thesis research. Therefore any existing surveys are reviewed, and any international research is related to the Dutch context. In addition, general theories and principles that describe the willingness of residents to adapt are investigated and related to the to be followed strategy. This partially answers sub-question 2. Currently survey research at the VU Amsterdam is ongoing in Limburg, but the results have not yet been published. Therefore, alternatively five interviews are held and analysed to create insight about the current state of awareness and willingness to take measures, more specifically in the Geul catchment.

3.2. Interview set-up

As mentioned in section 3.1, investigation into the stakeholders is of importance to formulate measures or a strategy for the area. To investigate the social context and stakeholders, interviews with residents and business owners are held in the flood affected area.

Interviews can be held according to different principles. Open interviews can be used “to obtain facts, subjective perceptions, emotions and values in combination with background information of interviewees” (Mostert, E., 2022). It can be used to obtain quantitative and qualitative information about the research topic and can be applied with a low number of participants. In the research set-up it is important to consider the access there is to interviewees, how introductions are made and also which persons are selected to be interviewed. Dependant on the research questions it might be necessary to interview people from different demographic groups to obtain an unbiased result. The interview setup can be structured, semi-structured or unstructured. The benefit of unstructured interviews is that priorities of the participants emerge through the interview and new (unforeseen) topics and questions might arise. A downside is that deviations from the research topic might also occur, making the interview less relevant. Structured interviews with pre-determined questions have the benefit that the interview will stay on topic, but leave less room for flexibility. A semi-structured interview is guided by subjects but the exact questions are less defined, leaving space for the interviewee to express priorities while still maintaining close to the research topic. The interviewer must be careful not to steer the outcome of the interview by the line of questioning. The use of open and neutral questions is therefore important. Language wise the questions should be phrased towards the knowledge of the interviewee without the use of jargon. Especially after interviews with “professionals” it is important to send a written report of the interview for approval. In general a good introduction guide as well as a human research ethics work plan must be established to minimize and mitigate any risks for the interviewee’s as much as possible. A downside of the research method is the intensive time it can take to conduct and process the interviews.

In this research a semi-structured interview approach is constructed. Subjects and type of questions are based on a survey constructed by W. Botzen, S. Duijndam, H. de Moel and P. Robinson (Institute for Environmental Studies, VU Amsterdam). An overview of the subjects and example questions can be found in Appendix A. In addition the research is submitted with the Human Ethics Research Committee (HREC) of the Delft University of Technology. For approval by the HREC a data management plan, risk assessment and mitigation plan and an informed consent form have to be submitted. The consent form can be found in Appendix A. The number of interviewees is not sufficient to make substantiated statements for the whole area. Therefore the interviews are complementary to the literature study and act as an indication and reference, together providing the answer to sub-question 2.

3.3. Quantification of damage and flood risk

To answer sub-question 3, first a suitable flood risk assessment method needs to be derived. Several flood damage assessments are being used in The Netherlands, of which the HIS-SSM model and the Waterschadeschatter (WSS) are the two most widely used (Lendering et al., 2015). Both methods are unit-loss models that describe a certain damage per object. Based on the probability of the damages calculated with these methods, risk can be calculated as defined in section 2.2. HIS-SSM was used in the derivation of safety levels for primary defences and is in the meantime updated to the current Schade- en Slachtoffer Module 2017 (SSM-2017) (Slager and Wagenaar, 2017). For regional systems mostly the WSS is used.

Both methods estimate damages to constructions (direct tangible) and production losses (indirect tangible), but SSM-2017 assumes that indirect damages are negligible in regional systems because of the short duration and limited area of the flooding (Slager and Wagenaar, 2017). Note that in contrast to most literature, by the the definitions used in SSM-2017, business losses are considered direct damages and indirect damages are only referred to as damages outside of the flood prone area . SSM-2017 does calculates the loss of life potential of a flooding event (direct intangible) behind primary and regional defences. The WSS does not include loss of life, because it is assumed that flooding in regional systems can not provide sufficiently enough inundation depth to be of lethal risk.

A first step is to thoroughly analyse both methods to decide which of the two methods will be used to describe damages in the Geul catchment. A first overview of the methods for regional water systems is given in table 3.1 and the evaluation is reported in chapter 4. Relatively high uncertainty of damage estimates are expected for lower inundation depths. Therefore after the initial damage and risk estimate, an in-depth review and validation will be performed, making use of reported damages and expert judgement, which is reported in section 6.2.

Table 3.1: Overview damage assessment SSM-2017 and WSS for regional water systems

Type of damage	SSM-2017	WSS
Direct tangible	Yes, low accuracy	Yes, up to 0.3m
Direct intangible	no	yes
Indirect tangible	yes, loss of life	no
Indirect intangible	no	no

3.4. Modelling of measures

The main challenge is to quantify the impact of measures that improve the resilience of an area. These capacities are more difficult to express in a monetary value. Nevertheless, a certain standard has to be derived to meaningfully identify and compare measures. Several studies have tried to assess the resilience of a flood prone area with indicators and metrics (Gotangco et al., 2016; Miguez and Veról, 2017; Bozza et al., 2015; Verschuur et al., 2017). However, most of them fail to connect the qualitative assessment of resilience into an economic decision context as was explained in section 2.2.

In this research it is proposed to derive a method in which resilience aspects are connected to their effect on risk reduction. Therefore resilience measures should be translated to the three input variables of the damage assessment: hazard, exposure and vulnerability. The resilience measures should represent awareness, preparedness and self-reliance. The literature study in chapter 5 will provide the to be investigated measures. Together with the selected flood risk assessment method this defines the answer to sub-question 3.

For each input variable it will be described how a connection can be made: the *hazard* can be adjusted, corresponding with measures that either influence the water system itself. The *exposure* can be adjusted to represent any measures that have an influence on the spatial location of objects and urban landscape design. Finally the *vulnerability* can be influenced by changes in the depth-damage function, as the shape and steepness are characteristic for the occurring damages.

3.5. Improvement of current strategy and recommendations

With the risk assessment method described in section 3.3, the total cumulative effect of each investigated measure for the Geul floodplain will be calculated. This is performed by modelling the implementation of measures in the selected flood risk assessment method. Two implementation scenarios are assessed and the differences are explained. One scenario is representative for high awareness amongst residents and/or high transparency and a guiding role of local government. The other scenario is representative for low awareness amongst residents and little transparency about specific risks at the object scale by local governments. Based on these insights the measures are reviewed on a neighbourhood scale to formulate advises, which answers sub-question 4.

The key parameter to assess the feasibility of measures is the benefit-cost ratio (BCR). With the decrease in expected annual damage as the benefits of a measure, the BCR can be calculated over the total time span in which the measure is effective. The Net Present Value (equation 2.3) is used to compare the cumulative reduction over the years so it can be compared with the investment cost directly. The BCR is reviewed at a neighbourhood scale again and forms the basis for a strategy decision that improves resilience. Any differences between neighbourhoods will be investigated and based on that, general principles of the feasibility of the measures are formulated. With these principles advises to residents and business owners can be made.

4

Investigation of flood risk assessment methods

In section 3.3, SSM-2017 and WSS were introduced as two of the main flood damage and risk assessment methods. In this chapter a selection out of the two will be made. The selected method is then further explained in detail.

4.1. Selection of method

SSM-2017 was used to derive safety standards for primary systems and is most suitable for high inundation depths. The method can be used for regional systems, but a high resolution of input data and proper interpretation of the results is necessary because of the high uncertainty at low inundation depths. For regional systems mostly WSS is used, which is applicable for inundation depths up to 0.3m. For higher inundation depths, adaptions to the used damage functions have to be made (Lendering et al., 2015)

Both methods are in their essence a unit-loss method, in which for each unit the damage (loss) is calculated. For each unit a Depth-Damage Function (DDF) is used, based on the category of the unit, that describes the ratio of the maximum possible damage that occurs as a function of the water depth. It is therefore important to select a DDF that is operable within the inundation depths that occur in the area. An analysis of the flooding in Valkenburg by Van Heeringen et al. (2022) presents a maximum inundation depth of approximately 1.25 meters. For this inundation depth the DDF of the Waterschadeschatter is considered not to be accurate and SSM-2017 is favourable. However, significant areas with smaller inundation depths in the order of 10-50cm are expected as well, for which SSM-2017 is not accurate. This indicates that regardless of the selected method, a critical analysis and validation must be made as both methods are not explicitly suitable for the occurring inundation depths. This is further emphasized in the research of Jongman et al. (2012) in which several European flood damages models are compared, as well as a sensitivity analysis of depth-damage functions. One of the conclusions being: "uncertainty in depth–damage functions leads to a larger relative spread of model outcomes in study areas with low inundation depths" (Jongman et al., 2012). For an even inundated area of 50cm this uncertainty could theoretically become a factor 40-50 and it was found that for inundation depths higher than 80cm this uncertainty decreases. For the specific case studies that were investigated the uncertainty at low depth lead to a factor 4-11 difference. In addition, the "frequency histogram of inundation depths" can be useful as an indication for the performance of the assessment in terms of uncertainty. The research of Jongman et al. (2012) implicates that especially with the flood characteristics in the Geul catchment high uncertainties are expected and the regional characteristics have to be accounted for in the model.

Another factor to consider in the used approach is the adaptability of the model in such a way that measures can be implemented. WSS is an online tool where hazard maps can be uploaded. Damage and risk calculations are performed in a cloud based calculation tool, of which only the output can be assessed by the user. WSS therefore offers no possibility to model any measures and is not feasible for the purpose of this thesis. On the contrary, SSM-2017 is a locally installed program and depth-damage functions and exposure maps are accessible. Despite this more open access, the program contains a built in security which does not allow calculations when any of the files are adjusted.

In the core SSM-2017 is a shell built around the open source Flood Impact Assessment Tool (FIAT) from Deltares (Slager et al., 2016). Therefore FIAT was requested from Deltares and SSM-2017 is reproduced in FIAT. To verify the operability, the damage for the flooding in 2021 is calculated with both the official SSM-2017 program and the reproduced version in FIAT. Both programs produce the same outcome and thereby the set-up of FIAT is verified. A major benefit of using FIAT instead of the original SSM-2017 program is the built in risk calculation function. With SSM-2017 only damages can be calculated and a damage-probability curve has to be calculated by hand and integrated to obtain the EAD. Especially when the risk reduction effect of measures has to be quantified, this leads to a tedious process and workflow. With FIAT the damages for inundation maps for several return periods can be calculated in one run and the risk is calculated directly based on those inputs. Given the model possibilities of SSM-2017 reproduced in FIAT, it is decided to use this assessment method. WSS is not feasible for the purposes of this study, but can act as a reference to verify the plausibility of outcomes.

4.2. Details of SSM-2017

In earlier versions of SSM-2017 (HIS-SSM) residential damages were 60-75% of the total damages (De Bruijn et al., 2015) and are therefore of special interest to evaluate. The functions for the family homes and ground floor apartments are shown in figure 4.1. For family homes a separate function is used for structure and content damages. The family home content DDF is based on the 1953 flooding in The Netherlands and combined with the damage function of Penning and Rowsell in the first two meters. The DDF for contents is based on Penning-Rowsell (2005) in the first two meters and after that reaches the maximum damage potential relatively fast. This is based on the 1953 flooding again, where for inundation depths above 2.5 meter houses collapsed (De Bruijn et al., 2015). Given the 1953 flooding was caused by a storm surge, the damage function for higher inundation depths must be used with care, as it is expected that with the current structural state of houses and other flood characteristics a collapse is less likely. For apartments no distinction is made between the two categories and an averaged function is used.

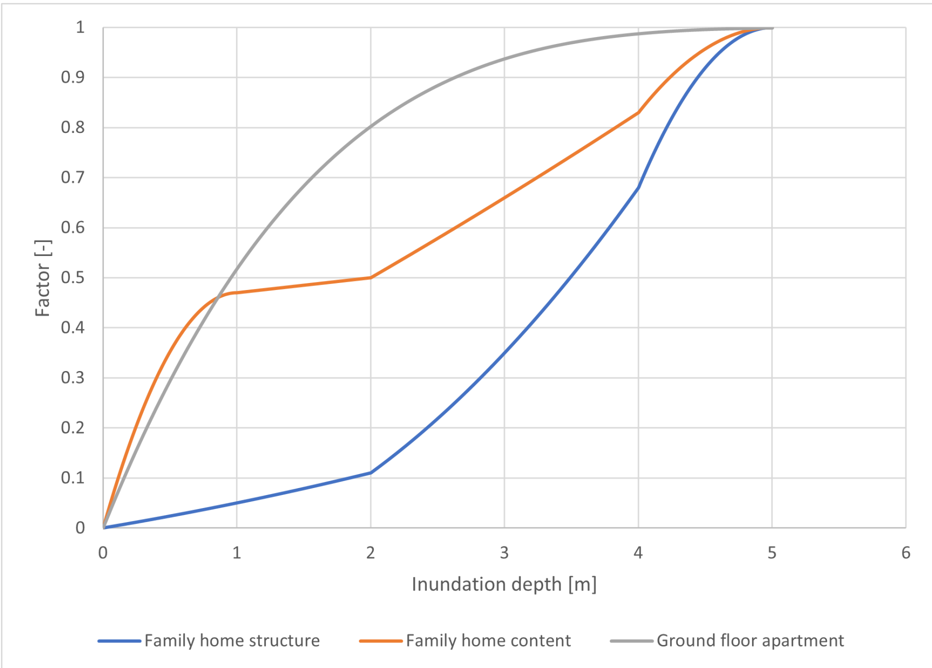


Figure 4.1: Residential depth-damage functions SSM-2017 (De Bruijn et al., 2015)

The DDF is used in combination with a maximum damage potential per land use category. The formal equation in SSM-2017 for the calculation of damages is described by Slager and Wagenaar (2017) in equation 4.1.

$$S = \sum_{i=1}^{n} (\alpha_i n_i SN_i + (1-\alpha_i)SB_i)\beta_i ID(1-SF_i)M_i \tag{4.1}$$

with:

α_i = direct damage factor in category i
β_i = damage factor company disruption in category i
n_i = number of units in category i
SN_i = maximum nett damage per unit in category i
SB_i = maximum gross damage per unit in category i
ID = 1 yr; maximum duration of company disruption of affected object
SF_i = substitution factor of category i
M_i = multiplier for indirect damages for i

The damage factor α_i & β_i are derived from the corresponding depth-damage function for the investigated category, where the factor can be read for the occurring inundation depth. The categories can be in the unit of square meters, number of objects or meters. For each category maximum damage values are derived and for each category the unit and direct and indirect damages are listed in table 4.1.

For regional systems SSM-2017 assumes that damages due to company disruptions and disruptions of residential functions is negligible due to the limited extent and inundation depth for regional flooding (Slager and Wagenaar, 2017). Given the known disruptions in Valkenburg, this assumption is highly doubtful and requires specific attention in the analysis and conclusions. In equation 4.1 therefore only the first part is used that describes direct damages. Since loss of life is not within the scope of this thesis, these functions are not described.

Two approaches can be followed in the definition of maximum damage. The first is based on the total value of the object, including parts that are not susceptible to flooding. The second is based on the maximum potential damage, and the values have to be adjusted to only include parts of the object which reasonably take part in damage generation (De Bruijn et al., 2015). In SSM-2017 the values are based on the maximum potential damage.

For the *commercial group* five steps are described by De Bruijn et al. (2015) to calculate the maximum damages per category. Instead of using the replacement value of capital goods, the actual value is used in the method. It is explained that using the replacement value will lead to an overestimation of damages, since "capital goods will be replaced by better replacements" (De Bruijn et al., 2015). The first and second step are to assess the monetary value of capital goods and of stock. In the third step a "susceptibility" factor is used to derive the part of the capital good that is susceptible to flooding. In the fourth step that part or factor is multiplied with the monetary values from step 1 to derive the maximum damage per capital good, specified for each commercial category. Finally in the fifth step all the types of capital goods are summed to obtain the maximum damage potential for each commercial category.

For the *residential group* the content damage is based on reconstruction costs per square meters of living space. Some research uses the GDP per capita to represent differences between regions (Huizinga, 2007), but within the spatial scale of The Netherlands no significant differences were found in the reconstruction cost. Therefore SSM-2017 uses the same price level for all regions of the Netherlands. The Statline database from the Central Bureau for Statistics (CBS) is used to determine the reconstruction cost per cubic meter, which were found to be €260/m^3 at the price level of 2011. To convert this to reconstruction cost per square meter, the following procedure is followed:

1. The average living space of all houses built in 2009-2012 is calculated.
2. The average construction costs of all houses built in 2009-2012 is determined.
3. The cost per square meter are derived by dividing the average construction costs by the averaged areas, corrected for inflation up to 2011.
4. The average construction cost are found to be €1017/m^2 with a range of €900-€1100/m^2. The value is used in SSM-2017 is set at €1000/m^2.

Table 4.1: Overview maximum potential damage values SSM-2017 (price level 2021) (Slager and Wagenaar, 2017)

	Unit	Direct damage [€]	Disruption gross [€]	Disruption nett [€]
Commercial				
Gathering	m^2	198	171	156
Health care	m^2	2,325	1.326	1,243
Industry	m^2	1,763	952	825
Offices	m^2	1,511	1.304	1,110
Education	m^2	1,169	216	191
Sport	m^2	120	64	54
Shops	m^2	1,776	394	325
Residential				
Family home - structure	m^2	1,178		
Family home - content	object	82,460	12,567	
Ground floor apartment - structure	m^2	1,1780		
Ground floor apartment - content	object	82,460	12,567	
First floor apartment -structure	m^2	1,178		
First floor apartment -content	object	82,460	12,567	
Higher floor apartment - structure	m^2	1,178		
Higher floor apartment - content	object	82,460	12,567	
Infrastructure				
Highway	m	2,085		
Regional roads	m	1,413		
Other roads	m	385		
Railway electrified	m	1,590		
Railway non-electrified	m	6,361		
Other				
Agriculture	m^2	2		
Horticulture	m^2	57		
Urban area	m^2	70		
Extensive recreation	m^2	13		
Intensive recreation	m^2	16		
Airports	m^2	172		
Cars	object	9,355		
Pumping station	object	1,073,865		
Sewage treatment plant	object	15,596,720		

The value of €1000/m^2 is expected to give a small overestimation since also parts of the construction that do not need replacement of reconstruction after flooding are included (De Bruijn et al., 2015). For contents a fixed value of €70.000/object is used based on insurance data. This price level dates from the year 2000 and after review by De Bruijn et al. (2015) no adjustment to this value was deemed necessary.

Similar to the uncertainty in the DDF, Jongman et al. (2012) described the uncertainty of the used maximum damage value for two specific case studies. An increasing range of the model outcome was found for larger inundation areas under the influence of different maximum damage values. It was therefore concluded that the inundation extent is the main driver for damage value uncertainty. When compared with the uncertainty in the DDF, it becomes apparent that the DDF uncertainty is significantly higher and the most dominant factor for uncertainty in the damage assessment. Given these findings for relatively low uncertainty that is introduced by the maximum damage values and apparent constant value of contents, the value of €70,000/object is maintained.

It is arguable if this value should be corrected for inflation to match the price level of 2021, since contents are usually insured for daily values and not the replacement value. However, often floors are considered to be contents by the insurance companies. In specific cases wallpaper and paintwork is also considered content. For these types of damages insurances usually cover repair or replacement costs. Since damages to walls and floors have a large share in the total damages, it is chosen to correct the content value for inflation, thereby accepting an overestimation for damages to "loose inventory". The inflation between 2011 and 2021 is 17.8% (CBS, 2022) and therefore the value of €1000/m^2 is corrected to €1178/m^2 within this thesis and €70.000/m^2 to €82.481/m^2. For all other categories the same correction for inflation of 17.8% is assumed as well.

4.3. Hazard and exposure data

For the Geul catchment a HBV model is currently in place coupled to a SOBEK-model. The output of this model can give inundation maps for return periods up to 100 years (Vermulst, 2014). Since the inundation event of July 2021 was estimated above a 1/100 year event (Van Heeringen et al., 2022), this model output does not give a complete and robust indication of the possible risks in the area. Furthermore these models are often not publicly available which makes transferability of the method to other areas difficult. Another inundation map is provided by Deltares, which simulates the flooding event of Juli 2021 itself. With one event map it is not possible to construct a damage-probability curve, however, this map is used to validate the initial damage assessment when compared to reported damages.

The Water Management Center Netherlands (WMCN) created a product which contains probabilistic inundation maps for The Netherlands. The dataset is referred to as the National Information system Water and Flooding (*Dutch: Landelijk Informatiesysteem Water en Overstromingen (LIWO)*). In module D, inundation from the regional water system, inundation for the Geul floodplain can be downloaded. The available return periods are 1/10, 1/100 and 1/1000 year. An important side note is that the map shows areas that are expected to inundate within the given return periods, but the areas in the map do not necessarily inundate at the same time. In this thesis the LIWO inundation maps are used to construct the damage-probability curve and determine the expected annual damage. A major benefit of the inundation maps from LIWO is the nationwide coverage and therefore good transferability of the method to other regions. The dataset is constructed and validated in 2014 and is the most current public available probabilistic inundation map. An example is given in figure 4.2 where the area between Valkenburg and Schin op Geul is shown for T=100 year.

Exposure data is used from the damages and fatalities model (SSM-2017). For residential and commercial areas the Base administration Addresses and Buildings (BAG) is the source of the data. It contains information about objects such as geometry, areas, location and function. An example of the functions for commercial objects are offices, healthcare, education, shops, etc. For residential areas the area and geometry are listed and two types of homes are distinguished: family homes and apartments (ground floor, first floor, second floor). Furthermore roads are derived from the National Road database and other land use categories are assigned making use of the Central Bureau for Statistics' database for land use. In total 41 types of exposure data are identified and grouped in 5 classes (table 4.1).

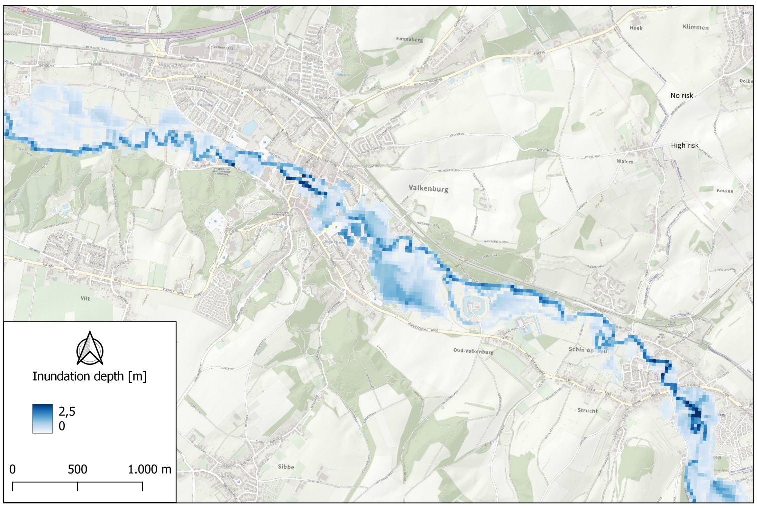


Figure 4.2: Inundation map for Valkenburg and Schin op Geul area (LIWO, 2022)

5

Flood resilience & Society

In this chapter applicable private flood mitigation measures will be identified that increase resilience. The effect of these measures and how they can be connected to the flood risk assessment in chapter 4 is described. Thereto first the concept of resilience is further investigated and it is reviewed what methods exist to describe resilience. In addition, social factors are derived that influence the implementation of private measures. The chapter is concluded with a summary of the selected measures and their effects.

5.1. Resilience concepts

A more detailed overview of the concept of resilience is needed to properly identify applicable measures. An extensive literature research is performed by McClymont et al. (2020) in which 596 peer reviewed papers were screened to review how the concept of resilience in FRM is treated. The outline of this section is based on the identifications made in their study and subsequent additional review of mentioned literature. McClymont et al. (2020) states that uncertainty related to climate change forms an important incentive to include resilience aspects in FRM and three types of resilience are identified. First *engineering resilience* is mentioned as "the ability of a system to bounce-back to a previous state and is associated with the emergency recovery stage of a shock event." Secondly *systems resilience* is referred to as "maintaining system function in the event of a disturbance". An important difference with engineering resilience is that a system has interacting parts to maintain functionality. And third "the ability to withstand, recover from, and reorganise in response to crisis" is described as *complex adaptive systems resilience* (McClymont et al., 2020). Only 15% of the investigated papers by McClymont et al. (2020) include all three types of resilience, while the majority (55%) focusses on engineering or systems resilience or a combination of the two. Furthermore in literature a distinction can be seen between resistance and resilience, however, also many authors included resistance as an integral part of resilience. For example Liao (2014) is an author that makes a distinction and claims that a flood resistant approach has adverse effects on long-term flood resilience, since flood knowledge acquired by exposure to events decreases. Awareness and preparedness is claimed to be generally low by those that are protected by flood barriers. These findings are shared by Odemerho (2015) who states that direct personal experience is of major importance to motivate individual and community action. Authors with a similar point of view often assess flood risk on a large spatial scale, while others that include resistance in resilience, assess flood risk on a neighbourhood or object scale. In the STAR-FLOOD research, resilience is defined for the whole system as the capability to prevent, adapt and recover, thus explicitly include resistance in the definition.

McClymont et al. (2020) summarizes important conclusions from the literature review, one of them being that the concept of resilience needs to be converted into an "operational framework" and that the concept "emerged as a result of a paradigm shift within flood risk management". They found that a disconnect between human and natural systems has occurred and Marcus and Colding (2011) even mention "environmental generational amnesia" within city dwellers. This is representative for the knowledge gap that exists in integrating and understanding, in this case, flood risk in urban planning. Furthermore it is identified that in Western countries society is highly dependant on governmental action in flood risk management, with little intention to undertake private actions. However, private property-level flood resilience measures have an increasing large interest in flood risk management and it is important to investigate methods that describe the implementation. The confidence of private actors in their ability to implement measures and trust in the positive effects of these measures play a large role in the incentive to undertake action.

5.2. Resilience assessment methods

Before resilience measures are connected to the flood risk assessment from chapter 4, first the currently used assessment approaches are investigated.

In general two assessment approaches for resilience in flood risk management are described: quantitative approaches and qualitative approaches. The quantitative approaches can be numerical-based or semi-quantitative. A widely used example of a quantitative approach is the use of hydrodynamic modelling to simulate the effect of flooding on the surroundings. Semi-quantitative approaches often use indicators as a measure of resilience and quantify how these indicators change for different simulations. McClymont et al. (2020) found qualitative approaches to be dominant to determine the level of resilience. The most used techniques to assess resilience are interviews and conceptual frameworks. Based on the dominance of qualitative approaches McClymont et al. (2020) concludes that "flood resilience is less expert-driven and technocratic than previous flood risk management strategies", with a current shift to the viewpoints of those affected by flooding.

Furthermore different spatial and temporal scales of the assessment methods are distinguished and their connection to either a social or technical perspective. McClymont et al. (2020) found that most methods in flood risk management were physical based and "social science techniques were used for stakeholder engagement". From a national to household scale a shift between social or technical perspectives can be observed. At a household scale most literature focusses on the technical methods and capabilities to increase property resilience. In lesser extent the connection between awareness and risk perception and resilience are described. Moving to a community scale more qualitative methods are used to describe resilience and social aspects have a larger role. At a city-scale a mixture of social and technical methods can be seen as well as the unfolding of strategic methods. On a national scale these strategic perspectives are dominant to describe resilience and emphasize the importance of governance structures. Finally the temporal scale of resilience is less defined in literature and is mostly used to quantify recovery. De Bruijn (2004) found that recovery is difficult to quantify due to the high variability in a system.

5.3. Method to connect resilience to risk assessment

As described in section 3.3, a monetary based risk assessment is proposed to describe flood risk. A technical based, quantitative perspective of resilience is therefore the most feasible to connect to the risk assessment. From the research of McClymont et al. (2020) it is found that this corresponds with technical measures at the household scale. It is found that at an object and/or household scale the main methods to increase resilience are dry-proofing, wet-proofing and flood-adapted use. Viewed at the household scale, dry-proofing is seen as a resistance measure, withstanding flood water. Dry-proofing measures could for example include placement of sand bags, mobile barriers, flood resistant doors and automatic barriers. Wet-proofing is seen as a measure to mitigate and reduce damages, decrease recovery time, while allowing water to enter the object during a flood event. By the definition of STAR-FLOOD, both type of measures can be seen as resilience improving. Dry-proofing and wet-proofing, hereafter combined named as flood-proofing, can be done for both existing buildings and to be developed buildings, whereas the latter is less expensive and is highly interesting for future development. Also for renovating projects coupling flood-proofing measures can form economic feasible options and can be placed under the "building back better" philosophy.

To express the flood risk reduction capacity of the flood-proofing measures, the effects on damages due to flooding have to be quantified. Gersonius et al. (2008) states that in The Netherlands no data on the effect of private household measures is available and since then no additional studies have been identified to cover this gap. Therefore any findings from other countries should be identified and evaluated if use in a Dutch setting is applicable. Several studies investigated the damage reduction capacity of flood-proofing by conducting large surveys and interviews in areas affected by flooding. Kreibich et al. (2005) investigated the effect of measures by questioning 1248 households that were affected by the 2002 flooding of The Elbe river. Kreibich et al. (2005) concluded that precautionary measures were mainly effective in areas prone to frequent and small flooding events in terms of inundation depth, but still reduced damages for larger flood events. However, during the Elbe flooding many barriers overtopped leading to damages. Kreibich et al. (2005) therefore found that for larger flooding events wet-proofing measures were more effective, where damages to content was reduced to 53%. In addition households that fully relied on barriers were prone to flood risk with little redundancy, since a false sense of security is created by barriers for areas with a significant possibility of high inundation depths. The research was followed by a study focussing on economic motivation and benefit-cost ratios of the different measures in Kreibich et al. (2011). It is shown that large investments, such as the construction of a sealed cellar, are only economically efficient if the frequency of flooding of the building is high (Kreibich et al., 2011). In the German context smaller investments such as oil tank protection are found to be very economically efficient and also remain with a positive benefit-cost ratio for areas that are less prone to frequent flooding.

Poussin et al. (2012) investigated the effects of flood-proofing in the Meuse floodplain in Limburg, The Netherlands. This quantitative investigation relies on the damage reduction potential derived from literature studies. For dry-proofing, Poussin et al. (2012) found a damage reduction potential of 60%-100% per house up to 1 meter inundation depth, based on the report of ICPR (2002). The limit of 1 meter is due to the risk of overtopping and constructive failure because of water pressure differences (Aerts, 2018). The dry-proof measures include "sandbags, coffer dams and panels on doors and windows" (Poussin et al., 2012). For wet-proofing measures all "semi-structural and non-structural measures are considered that adapt the exterior, interior or use of a house to reduce damages due to flooding" (Poussin, 2012). The damage reduction that Poussin et al. (2012) identified is 36%-53% for structural assets and 48%-53% for household contents. This damage reduction is based on before mentioned research of Kreibich et al. (2005). Above 2 meter of inundation depth the damage reduction potential is found to be negligent and is set at 0%. Furthermore, for dry-proofing temporary and permanent measures are distinguished (Gersonius et al., 2008). Permanent measures include injected walls, non-return valves, sealing of brick openings and flood resistant doors. Temporary measures are mostly related to temporary barriers for doors and sandbags.

5.4. Background of survey studies

This section will provide detailed information about the procedures that are performed to extract damage reduction factors, as mentioned in section 5.3, from surveys. The damage reduction potential of measures is difficult to quantify due to its variability and lack of extensive research. In the research of Poussin et al. (2015) an investigation into this quantification is performed by an analysis of data from a survey of French households in three different regions. The survey set-up is described in Poussin et al. (2013). Specific questions about flood damage and any property-level measures were assessed. Two main findings were that the effect of measures is very dependent on the region and flood characteristics, and that the cost-efficiency is mainly defined by the flooding probability.

In the studies of Kreibich et al. (2005) and Poussin et al. (2012, 2015) the damage ratio of buildings is determined by dividing the occurred damage by the market value of the house or contents. The survey of Poussin et al. (2013) was sent to 8201 households and had 885 respondents, of which 530 had a history of flooding. The sample was found to be “approximately” representative, with small deviations. However, since the main purpose of the research was to identify the damage reduction effect of structural measures, it was concluded that the deviations in the sample would not have an effect on that outcome. Interaction variables that can influence the flood damage have been identified by Poussin et al. (2014) by ordinary least square regression models and are: flood characteristics, building characteristics and the presence of mitigation measures. The Pearson coefficient, which describes the correlation between two variables, is used to assess if measures have to be excluded from the results. Measures with a high Pearson coefficient with the interaction variables indicate high correlation, which can lead to “multi-collinearity” (Poussin et al., 2014). In addition measures can be excluded because of a low number of respondents that implemented those. The mean damage ratios for households that implemented or did not implement flood protection measures are compared with each other. To determine the significance of the differences the non-parametric Mann-Whitney U test is used. A formula describing the damage ratio with the damage (Y) and the value of the home (a) is defined in eq 5.1.

$$\begin{aligned} Y/a = {} & \beta_0 + \beta_1 \times X_1 + \beta_2 \times X_2 + \beta_3 \times X_1 \times X_2 + \beta_4 \times Z_1 + \beta_5 \times Z_1 \times X_1 + \beta_6 \times Z_1 \times X_2 \\ & + \beta_7 \times Z_2 + \beta_8 \times Z_2 \times X_1 + \beta_9 \times Z_2 \times X_2 + \beta_1 0 \times Z_3 + \beta_1 1 \times Z_3 \times X_1 + \beta_{12} \times Z_3 \times X_2 \\ & + \ldots + \beta_n \times Z_n + \beta_n \times Z_n \times X_1 + \beta_n \times Z_n \times X_2 + \epsilon \end{aligned} \tag{5.1}$$

The equation is used to determine the effect of measures independent of possible other measures implemented. β_0 is a constant, all other β are coefficients from the linear regression, Z corresponds with the mitigation measures, X_1 is the water height and X_2 is the distance to the source of the flood. In the analysis one Z value is changed between 0-1 while the others are fixed at their average value. By doing so the independent effect of the measure on the Y/a ratio is determined. An important finding is that damage is higher for residents with similar inundation depth, but with close proximity to the source of flooding. Finally wet-proofing the ground floor did not significantly reduce damages in the overall sample (all regions together), but raising power sockets was more effective.

After these findings Poussin et al. (2015) focussed on the differences between the sub-regions. Here it was found that wet-proofing the ground floor actually did significantly reduces damages in the Ardennes and the Var, but not in the West region. It is concluded that out of the 11 measures that are investigated, some are effective in all regions, but in general large differences between the three regions can be observed, mainly driven by differences in water depth.

Kreibich et al. (2005) interviewed 1248 households after the 2002 flooding of the Elbe river through a computer telephone interview. In terms of flood characteristics two areas are distinguished, where one area suffered flash floods and the other area flooding due to a slowly rising river. All streets that were flooded were obtained and out of those households a sample was taken. Also Kreibich et al. (2005) compared damage reduction of specific measures by comparing damages of households. Households with a specific measure implemented are compared with households without that specific measures, not taking into consideration the presence of any other measures in place. In addition, also significance is tested with the Mann-Whitney U test. For three groups of data related to household parameters the Kruskal-Wallis H test is used, which is an extension of the Mann-Whitney U test, allowing to compare more than two groups (Laerd statistics, 2022). A major difference between Kreibich et al. (2005) and Poussin et al. (2014) is that the latter isolates the effect of measures and thus provides a more detailed view of the effects. In addition, any relations between measures and the hazard itself are excluded with the calculation of the Pearson coefficient.

5.4.1. Relation of international surveys to Dutch households

Three studies are identified in which surveys where conducted in The Netherlands related to flooding. Botzen et al. (2009) investigated the willingness of residents (N=509) to undertake four different private measures, in exchange for a discount on flood insurance. The investigated measures were: placement of sand bags, replacement of floor with a tile floor, move appliances to higher floors and move boilers to a higher floor. 68% of the respondents was willing to invest in sand bags and 20% was willing to install a tile floor. In addition, the expected avoided damages are estimated, mostly based on the ICPR (2002) report for dry-proofing and Kreibich et al. (2005) for wet-proofing. The study did not provide insights on the actual stage of measure implementation and no new damage reduction factors are used or identified. Botzen and Van den Bergh (2012) again conducted a survey (N= 1000) with the focus on the need of flood insurance in The Netherland for homeowners. Also in this paper no additional details about the current state of measure implementation and damage reduction was identified. In the survey (N=516) held by Zaalberg et al. (2009) the focus was more related to what extent residents were affected by flooding and coping responses are identified.

Based on the literature review, research outside of the Netherlands has to be applied to the Geul catchment, in the absence of more local investigations about the effect of measures. Similarly to the uncertainty that is created when transferring depth-damage functions from one region to another, uncertainty is introduced when damage reduction factors are transferred between countries. However, some general remarks about the effect of measures can be made. Two papers that describe damage reduction factors, making use of surveys have now been identified in section 5.3. Focussing on the presence and effect of damage mitigation measures, in France major differences between regions are observed, with flood characteristics as the main factor. Therefore it is expected that any differences or similarities between countries in the effectiveness of household measures are dominated by the flood characteristics and in lesser extent by country boundaries or building characteristics.

Regarding the current state of measure implementation it is difficult to derive this quantitatively for The Netherlands. In France 228 households out of the 885 had measures installed, corresponding to a ratio of 0.26. In Germany similarly the ratio is 0.33. Using equation 5.2 a test-statistic of 3.59 is calculated, which indicates a significant difference (>1.96) between French and German households focussed on the number of residents that took measures, with a confidence interval of 95%. It is likely that Dutch households would also have a significant difference with these implementation ratios.

$$
\begin{aligned}
SE &= \sqrt{(p*(1-p))*(\frac{1}{n_1}\frac{1}{n_2}} \\
t &= \frac{p_1 - p_2}{SE}
\end{aligned} \tag{5.2}
$$

with:

SE = Standard error
p = pooled sample proportion
p_1 = proportion group 1
p_2 = proportion group 2
n_1 = sample size group 1
n_2 = sample size group 2

A method to describe, qualitatively, the difference between countries is based on the theory of cultural dimensions by Geert Hofstede (Hofstede insights, 2022). The theory consist of six dimensions:

1. Power distance
2. Individualism vs Collectivism
3. Masculinity
4. Uncertainty avoidance
5. Long term orientation
6. Indulgence

Noll et al. (2020) uses the six dimensions to explain difference in mitigation measures between countries. Three dimensions were found to have a significant relationship with previous flood experience and implementation of private mitigation measures: power distance, individualism and uncertainty avoidance. Power distance relates to what extent less powerful people in society accept that power "is distributed unequally" (Hofstede insights, 2022). Individualism refers to how autonomous individuals are and how strong (predefined) relationships with other individuals are. Uncertainty avoidance refers to how societies deal with unknown situations or the future. Societies that score high on this dimensions often have strong beliefs and strict rules and codes (Noll et al., 2020).

A negative relationship is identified between countries that score high on individualism and households that take private mitigation measures. Furthermore a high score for power distance had a positive relationship with the uptake of measures. Finally flood experience led to relatively less new implementations in countries with high uncertainty avoidance. The Netherlands scores as one of the most individualist countries and higher than Germany and France. This would indicate less implementation of measures in The Netherlands. In addition France scores high with 68 on power distance and thereby has an expected higher implementation of measures compared to Germany, although these findings are not represented in the before mentioned sample of the surveys. Based on the societal dimensions of Hofstede a lower implementation of measures in The Netherlands is suggested compared to France and in lesser extent compared to Germany.

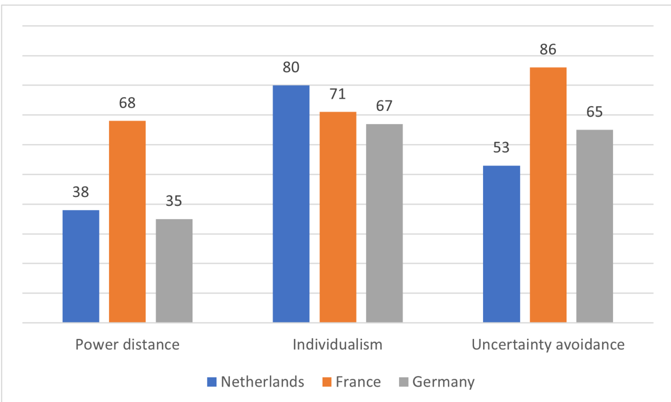


Figure 5.1: Country comparison societal dimensions Hofstede (Hofstede insights, 2022)

5.5. Social factors influencing private resilience

For a strategy including private flood mitigation measures to be successful, it is necessary to motivate private actors to implement them. To achieve the desired level of implementation, the communication towards private actors is therefore an important part of the strategy. In this section a method is described that identifies important factors that influence the motivation of private actors.

An increasingly used theory to describe human behaviour in flood risk is the Protection Motivation Theory (PMT). An explanation of the theory and its relevance will be described. In addition, the link between human behaviour, flood resilience and structural measures can be made using the theory.

Haer et al. (2017) explains that human behaviour is often a constant parameter in flood risk assessments. Excluding the "interaction and feedback loops" between human behaviour and for example object vulnerability could lead to a "misinterpretation of flood risk" (Haer et al., 2017). A shift is observed in Flood Risk Management towards a more risk-based approach, increasingly including private household measures in an integrated manner (Bubeck et al., 2012, 2013). However, in the literature review of Bubeck et al. (2012) no empirical evidence or theory "between individual flood risk perceptions and mitigation behaviour" could be observed. This indicates that risk communication alone is not a decisive factor to motivate private household measures. The PMT is used to derive which factors are of importance and what this means for a strategy that intends to include household measures.

The Flood Protection Theory is a framework that predicts how people respond under the influence of a threat (Oakley et al., 2020). The framework is schematized in figure 5.2 and consist of two stages or "main cognitive processes" (Bubeck et al., 2018). Threat appraisal is referred to as the perceived vulnerability and severity of consequences. Whenever the threat appraisal is high enough the coping appraisal can be triggered. Coping appraisal is the combination of three factors. Response efficacy refers to the perceived effect of an action or measure. Self efficacy is related to how a individual judges its own ability to implement a measure. Finally the response cost refer to the expected cost of measures. Within the PMT, cost also include "the time and emotional effort needed to implement a measure" (Bubeck et al., 2018). For an individual to take action, both the threat and coping appraisal need to be high. Only a high threat appraisal does not necessarily result in action, but could lead to fatalism, denial, or wishful thinking (Festinger, 1957; Bubeck et al., 2018).

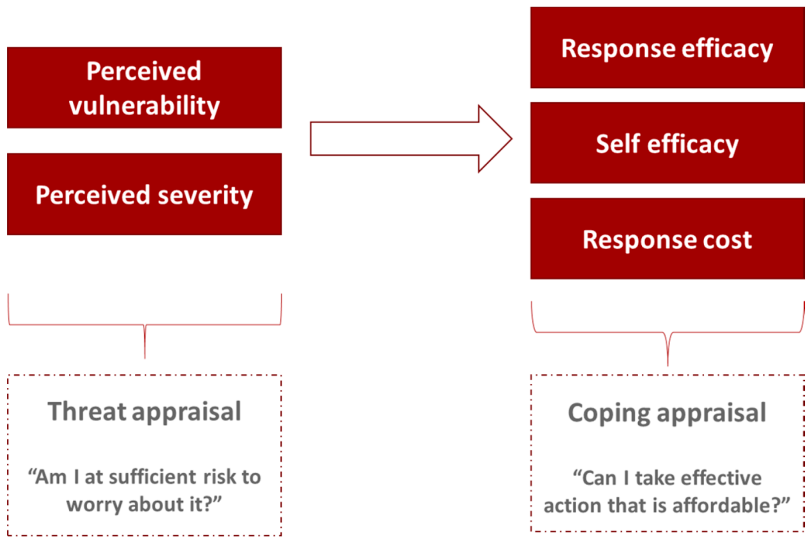


Figure 5.2: Visualization of Protection Motivation Theory (Oakley et al., 2020)

As flood risk perception is an apparent weak predictor of mitigation, Bubeck et al. (2012) also investigated other indicators based on 16 survey studies. Flood experience was the most significant factor found in all studies, with a positive trend between experience and protective behaviour. Also the emotional connection towards protective actions are investigated. It was found that fear and worrying about flooding have an influence on how risk is perceived and consequently had a positive influence on implementing mitigation measures. Surprisingly, for knowledge about floods and protection little positive links were found. In the research of Botzen et al. (2009) a negative correlation between knowledge and the willingness to take protective measures was seen. Also it might be expected that financial means has a strong influence on the ability to implement measures, however, no evidence was found for that by Bubeck et al. (2012). It was found that response cost were not a factor for mitigation measures such as adapted building use, flood barriers or flood insurance. However, for permanent structural measures an influence of income was seen, as these type of measures are expensive. This means that time and effort are not expected to be a complicating factor for protective behaviour. Botzen et al. (2009) found only a weak correlation between income and the need for flood insurance. Finally a factor that could hinder the implementation of measures is the presence of "government compensation" or "the perceived responsibility of the government" (Bubeck et al., 2012; Botzen et al., 2009).

Several conclusions are found from various studies using the PMT. Oakley et al. (2020) suggest that communication of the "relative efficacy of products and approaches" to mitigate flood risk would increase the uptake of household measures. This is in line with findings of Bubeck et al. (2012) who concludes to focus more on the risk reductive potential of mitigation measures and clear guidance regarding the implementation. In addition, subsidies are proposed to reduce the response cost and thereby increase the coping appraisal. Bubeck et al. (2018) concludes that the "social environment and observational learning" can have a positive influence on coping appraisal. Therefore risk communication should make use of these social networks.

Based on these findings, the modelling of measures and the reporting of the results will focus on the relative effect of the investigated measures. Furthermore a cost-benefit analysis can provide valuable information about the effectiveness of the response cost. The current communication strategy of the water board Limburg does not comply with the outcomes of the protection motivation theory. Private measures are currently encouraged through an information folder and it is up to the resident or business owner to judge and evaluate if the measures are effective. Therefore also qualitative recommendations will be formulated for the water board.

5.6. Local interview reports Geul

An in-depth interview is performed with a resident in the flood prone area, heavily affected by the event in July 2021. Another in-depth interview is performed with two business owners in one of the most severely affected areas in the Geul floodplain. Secondly two residents are briefly interviewed about their experiences and opinion on private mitigation measures. Finally contact with employees of the waterboard is concisely reported. For privacy reasons no exact location or identifiable information is provided. The goal of the interview reports is to obtain a more tangible view on the events and circumstances last year, as well as the personal experiences of those affected. Any relation to the investigated literature is identified.

5.6.1. Interview with resident

The interviewed resident is a home owner and first resident of the building built in 1975. In 1973 the area was assigned with a residential function and construction started. The municipality prescribed a small elevation of the land to cope with any water disturbance from the nearby Geul river. In 1984 the first flooding occurred and the pavement was flushed out and water entered the basement through the driveway. The resident decided to remove and fill up the driveway down into the basement, to prevent a reoccurrence. In the next flood event in 1987 the basement flooded again despite the filled driveway. After this event the resident took additional measures and also elevated a section of the building. Based on the general advices for water infiltration, the down-spouts were disconnected from the sewer system. To enable proper drainage of the land an infiltration tube was installed. This tube was directed through a ground retaining wall of the filled up driveway. The resident showed a very informed and proactive attitude and consistently responded to flooding events. Already in 1983 a report was made to the municipality that a speed bump in the street caused water to accumulate. Because of traffic safety reasons the municipality insisted on retaining the speed bump. Appeals went up to the Council of State (*Dutch: Raad van State*), but ruled against the residents. In the following years no significant inundation occurred. Because of other activities to a nearby bridge over the Geul, which was raised, it was assumed that this had a positive effect on the flooding frequency in the street. However, during the event in 2021 the street did inundate again. The speed bump caused accumulation of water again and for several houses the inundation lasted a day longer because of that.

In July 2021 a large part of the garden was completely flushed out, where originally the driveway into the basement was present. Most probably the infiltration tube created a preferential flow path and a scour hole was formed. The basement flooded again and also the ground floor inundated. The wooden floor had to be replaced, as well as household contents in the basement and large appliances. The kitchen cabinets could be maintained after drying. The resident was not warned for the flood event and in a relatively late stage sand bags were made available. These had to be collected in a central depot several kilometres away. Given the weight of these bags the resident was physically not able to collect and place them and was dependent on others for placement. The bags were placed at the front door in combination with sheets. A staircase leading down to a door of the basement was also sealed with sand bags. The sand bags at the front door did not retain the water, while the sand bags at the basement entry were flushed away. At the residents' neighbours, a barrier collapsed under the water pressure and also high damages occurred.

The resident indicated that the recovery phase took long and at the time of the interview, 9 months after the event, the new floor had just been placed. Other than that all furniture on the ground floor consisted of camping equipment. Also the financial settlements took long and it was often unclear what was covered by which organization or fund. Despite all funding, still damages were not fully covered. The event itself, but mainly the aftermath and recovery phase had a large impact on the resident. This can be categorised as intangible indirect damages and the recollection of the event was still emotional.

When asked more specifically about private flood mitigation measures, the resident showed a positive and open attitude towards the possibilities. He already followed advices and instead of a wooden floor, had a tile floor placed after the event. Dry-proofing measures such as placement of barriers are in consideration. Concerns are being expressed about the abilities to successfully seal all openings. The flooding at this object occurred from both the front as the back facade of the building. The resident was impressed by the force of the water and doubts his own personal abilities to dry-proof. The benefits versus the costs of measures were not directly a decisive factor in the implementation. The main fear of the resident is that the event reoccurs and the whole aftermath process has to be dealt with again. Prevention is therefore of more importance than the exact benefit-cost ratio of measures. This is an example of intangible damages that can't be quantified, but have a major role in decision making. Although the resident shows high participation in taking measures, the viewpoint remains that the water board is the main responsible party to prevent a future event through changes in the water system or larger structural measures. Despite the active presence of the water board and resident participation in their plans, the pace and nature of proposed solutions are unsatisfactory for the resident.

In another area, the neighbourhood Neerhem in Valkenburg, a short conversation took place with a resident. Despite the close proximity to the Geul, low inundation depths occurred around the object and no water entered the building. One block behind this object lies one of the most heavily affected streets, which is an example of the high spatial variability of damages. Asked about flood mitigation measures the residents showed a subdued attitude. The viewpoint was that it is impossible to prevent against such extreme events, so in the residents opinion there's little gained by measures or even worrying. Although eventually the resident did acknowledge that some (emotional) valuable contents are not stored in the basement, but at higher floors for safekeeping. This is an example of flood adapted use and indicates awareness and preparedness. Asked about responsible parties for undertaking measures the resident had a less outspoken opinion and argued that also for the water board the 2021 event was too extreme.

5.6.2. Interview with business owner

Two business owners in the hospitality sector were interviewed. In 2015 the object was bought and reconstructed to suit the needs of the owners. During this process contact was established with the water board where they were told about a 1/100 year standard and reassured. Partly based on this the object was acquired. It is located directly at the Geul river, with only 5 meters in between. During the reconstruction the wall in the back, facing the Geul, was opened. A terrace was constructed near the river with direct access from the building through a common area and kitchen. In addition a wellness room was constructed at the ground floor. The owners were warned by neighbours about the risks, but decided to continue nevertheless given the added value to the business.

During the event in 2021 the water levels increased fast and there was no time for any preventive measures inside the object itself. An effort to prevent damages was made by the placement of sand bags. Still the ground floor was flooded with a water level of 1.15m. The owners estimate that the sand bags only had some effect on the amount of sediment that entered and subsequently made the cleaning process somewhat easier.

After the event the business was closed for 9 months. The insurance company interpreted the flooding as flooding from rainwater and most of the damages were covered. In addition a governmental fund, a business risk insurance and a (unrelated to the flooding) Covid-19 fund provided sufficient means to cover the recovery period. The owners estimate that for any future event the financial settlements through the insurance company might be more difficult.

The owners where aware of the brochure from the water board Limburg and studied the measures. They decided to invest into wet-proofing. Given the close proximity to the Geul and building characteristics there is little confidence in the ability to dry-proof. Instead the whole ground floor is made of tiles up to a water level of 1.30m. All fixed contents, like kitchen cabinets, are made of water resistant materials. Kitchen appliances are modular so they can easily be removed. Furniture that could not be made waterproof is placed on (hidden) wheels. An elevator is present in the building that can accommodate all movable furniture. The owners have good contacts in the village and an action and evacuation plan is made with help of others. They estimate that 24 hours of warning time is needed to fully prepare the ground floor for a flood event. Currently there is no clear decision model or criteria when to start preparations and evacuate the object. Although the structural measures seem very effective, there remains a risk in the human factor during the decision making. An unnecessary evacuation is costly and time consuming, as also clients have to be reimbursed. In contrary when the decision is made too late still damages occur. However, even during a late decision to evacuate and prepare, there will always be a damage reducing effect of the permanent structural measures.

The benefits versus the costs were not a factor in the decision to wet-proof the ground floor. The main objective was to prevent a long business disruption. After a new event they aim to be operational again within three weeks. It must be noted that a relative short time ago, in 2015, major investment were made to the building. With the current knowledge it would have been more beneficial to include the wet-proofing from the start, as the additional cost to wet-proof would have been less. This is an example of flood knowledge and experience or the lack thereof, which influences decision making.

5.6.3. Notes from meetings

Several meetings took place with the water board Limburg, focussed on their "Water in Balance" program. The program initially consisted of 4 "buttons" and is recently updated with two additional buttons.

Water in Balance program:

1 **Rural area:**
Farmers are being asked to retain 10mm additional water on their land to prevent fast run-off.

2 **Urban area:**
Municipalities and residents are motivated to find solutions to better infiltrate water.

3 **Water system stream(valleys):**
The water board initiates programs to reshape the valleys and retain more water, for example through buffers.

4 **Private flood protection measures:**
A brochure is provided to residents with 17 measures to prevent or reduce damages when flooding occurs.

5 **Spatial adaptation:**
Creating more room for the rivers and assessing if current and future land use meets the demands for water safety.

6 **International cooperation:**
Contact is established with neighbouring countries to improve cooperation in the prevention of flooding.

For button 4 a project is currently undergoing in the Mechelderbeek valley. In the south of Limburg roughly 1000 houses are identified on a location that does not meet with current standards for water disturbance. In the valley of the Mechelderbeek around 75 houses are located at such a location. It is difficult to achieve the standards in this area and therefore the water board shifted the focus from prevention to mitigation. It is investigated if dry-proofing the mentioned houses can be a solution to cope with water problems in the area. In this case the measures would be funded by the water board and have to be maintained by the residents. In the current phase there's still uncertainty about the legal possibilities and validity of providing such measures. In addition, also within the water board there is little knowledge about the efficacy and effectiveness. Wet-proofing measures are not considered in the project.

The initiatives are received mixed by the residents. There's hesitation towards measures at the household level and essentially allow flooding, while the initial responsibility lies with the water board to prevent flooding in the first place. With wet-proofing these arguments are stronger, since in those cases water would even enter the houses itself. Although the attention for flood damage mitigation measures is a positive contribution to increase the resilience of the area, it is a slow process before concise steps are being made.

5.7. Summary of chosen resilience assessment method

For this thesis the damage reduction factors as used by Poussin et al. (2012) are being used for the risk reduction quantification of measures at property level, an overview is given in table 5.1. For dry-proofing a relatively large range of 40% is found. Given the introduced uncertainty when these factors are applied in a different location, it is decided to explicitly describe the full range for the remainder of the thesis. An average damage reduction factor will make the uncertainty less visible.

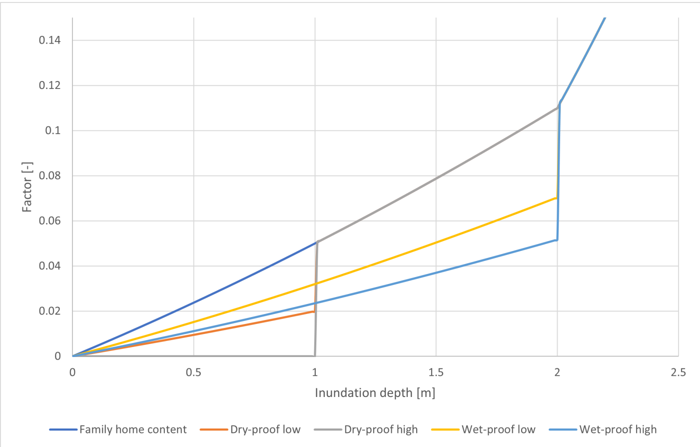
Later research by Poussin et al. (2013, 2014, 2015) provided additional knowledge about differences between regions and the methods to derive damage reduction factors, but no conclusive new reduction factors were obtained compared to Poussin et al. (2012) and (Kreibich et al., 2005). The later work mainly focussed on the significance of individual measures and in lesser extent on reduction factors. Based on the characteristics the findings from the Ardennes are expected to be relevant for the Geul catchment. Here it was seen that wet-proofing the ground floor had a relatively high reduction effect on damages. This endorses the decision to include wet-proofing in the method.

Resistance in the definition of resilience solves issues with the spatial scale of measures. On a neighbourhood scale dry-proofing can be considered as a mitigation measure, where water is allowed into the area and the vulnerability is decreased. If dry-proofing is assessed on the object scale, it can be considered as a resistance measure without decrease the vulnerability of the house contents.

Table 5.1: Overview of damage reduction factors

Measure	Reduction	Use range
Dry-proof	60%-100%	up to 1m
Wet-proof structure	36%-53%	up to 2m
Wet-proof content	48%-53%	up to 2m

The depth-damage function (DDF) for each considered land-use is multiplied with the reduction factors from table 5.1. Given the wide range of the effect of measures, for the remainder of the thesis a low bound and high bound will be used. This generates a new DDF corresponding with each measure and this can be used to model the effect of measures and simulate the risk reduction. All functions and measures are found in figure 5.3.



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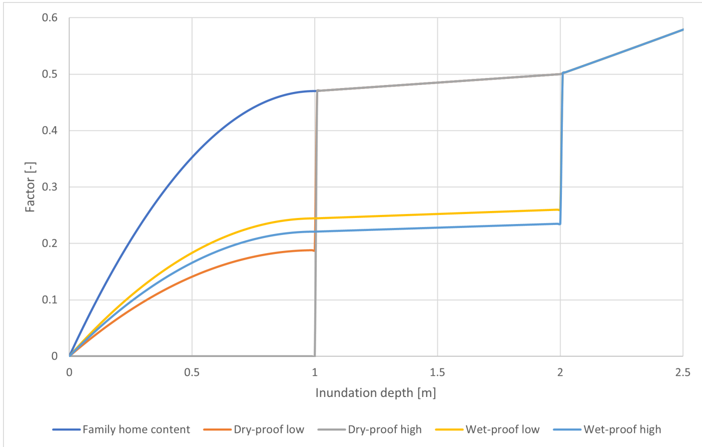

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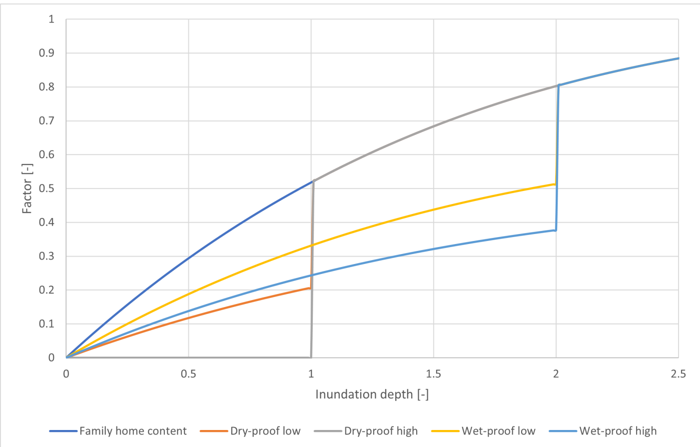

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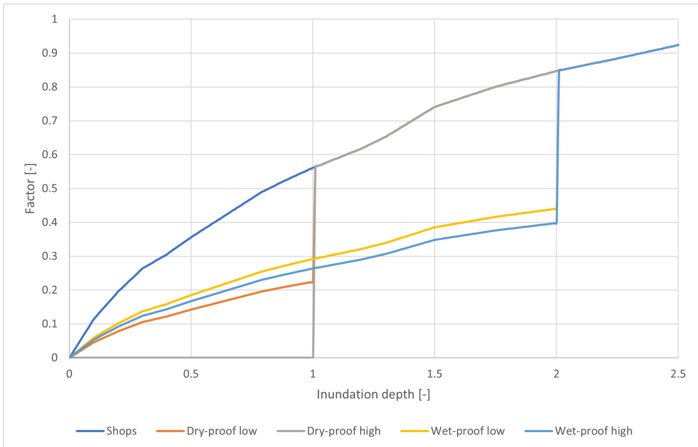


(d)

Figure 5.3: Overview of depth-damage functions including measures.
(a) Residential structure. (b) Residential content. (c) Ground floor apartment. (d) Commercial: shops.

6

Quantification of flood risk the Geul & Resilience measures

Based on the method described in chapter 4, the effect of private measures on flood risk is described in this chapter. Two scenarios are investigated and compared with the expected annual damage without any measures present. The analysis performed in this chapter and acquired insights form the basis for a proposal for a strategy in the Geul floodplain.

An overview and reading guide of the chapter is given in figure 6.1.

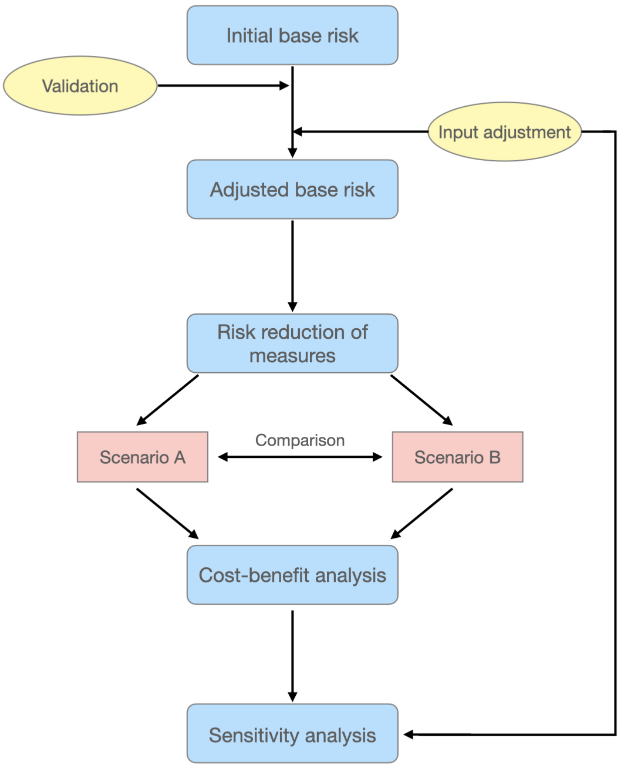


Figure 6.1: Flowchart of chapter 6 procedures

6.1. Initial risk and measure selection

At first the expected annual damage is calculated without any measures present and with the standard input parameters from SSM-2017. For all land-use categories the risk is estimated at an expected annual damage of 8.15 million euro, with in table 6.1 the top ten categories most at risk that are identified.

Table 6.1: Top ten risk categories without measures

Land use category	EAD (Million €)
Urban areas	1.56
Family home (content)	1.01
Commercial: Shops	0.91
Commercial: Industry	0.68
Agriculture	0.58
Extensive recreation	0.49
Ground floor apartments (construction)	0.46
Sewage treatment plant	0.45
Ground floor apartments (content)	0.36
Transportation	0.28

The urban areas category causes most risk in the area. This category consist mostly of urban public spaces with a damage estimate of 70 €/m^2 and fall outside the scope of private measures. Second is the family home category with damages to household contents and in addition ground floor apartments are also seen in the top ten. For the commercial areas shops are prone to most risk followed by industry. The identified measures from chapter 5, dry-proofing and wet-proofing, can not be applied to all categories. It is decided to apply the measures to the family home (content & structure) and ground floor apartment (content & structure) category and combined name this the "residential" category. If the complete list of categories is observed, also first floor apartments would be prone to a small risk, but due to the elevation of this category are not considered within the "residential" category. For commercial areas it is assumed that these measures are applicable to shops. Measures to prevent damages to industry objects are considered not to be represented by the derived reduction factors due to considerable difference in the structures. As a side note, in the Valkenburg city centre a number of areas are classified as industry, which in reality seem to be related to the catering industry. By excluding the industry category in this area a potential effect of private measures is not considered, however, since the measures for a category are applied for the whole research area it is nevertheless decided to exclude the category to avoid an overestimation of the effect of private measures.

With the identification of categories where the measures will be applied, scenarios can be defined that describe how and to what extent the measures will be implemented. The measures will be applied on objects within the 1000 year floodplain only, hereby assuming that enough knowledge in the area is present to at a minimum identify if objects lie within the river floodplain. Since only river flooding is considered, any measures outside of the floodplain are not modelled, such as measures to prevent damage caused by water through overland flow, which occurs at flow-paths in the hilly area.

6.2. Validation of model input

The set-up of SSM-2017 for the base risk assessment from section 6.1 is validated by a comparison with the flood event in July 2021 and by expert judgement to verify the plausibility of the outcome. In figure 6.2 the damage-probability curve based on the assessment in section 6.1 is presented. It can be observed that for a T=10 year event the damage is estimated at 37.5 million euro, of which 7.4 million euro is residential damage. It is unlikely that such high damages would occur, statistically, every 10 years. Furthermore, for a T=1000 year event the damages are estimated at 268 million euro, of which 89.6 million euro is residential damage. For a T=1000 year event, 89.6 million euro residential damage is lower then expected. This expectation is based on the reported damages for the July 2021 event and estimated return periods. These two outcomes, an overestimation and underestimation within the same model, are contradicting and indicate to an error in the input data. The apparent overestimation for the T=10 year event indicates problems in the hazard and/or exposure component. The expected underestimation for the T=100 year event indicates problems in the ability to capture the damage mechanisms correctly and is thus related to the vulnerability component.

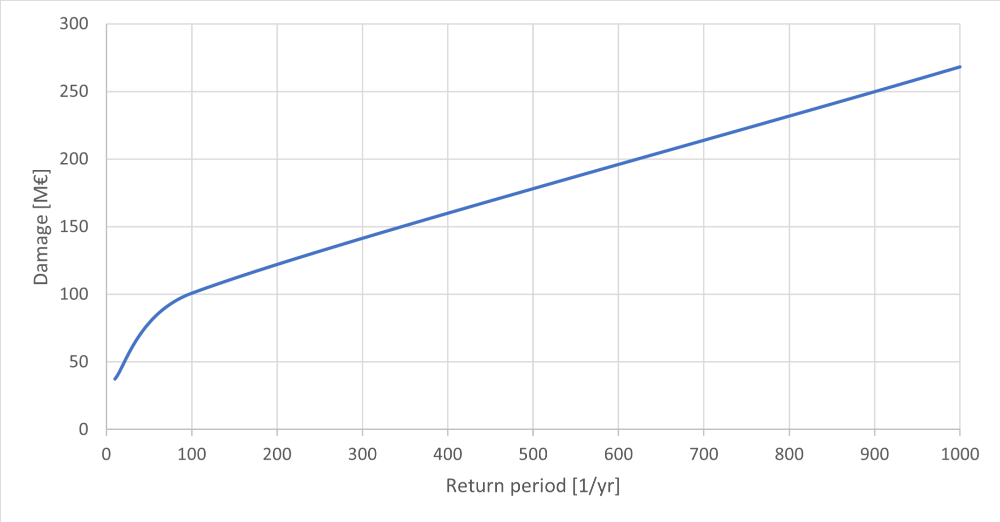


Figure 6.2: Damage-probability curve initial assessment all categories

Each component (hazard, exposure and vulnerability) is reviewed and corrected if deemed necessary. To review the hazard and exposure component a visual justification of the input data is performed. For the vulnerability a comparison is made with the flood event in July 2021. Therefore an inundation map provided by Van Heeringen et al. (2022) that simulates the event of July 2021 is used as input in SSM-2017. This inundation map is modelled with the latest available hydrodynamic model for the area and validated at several points around Valkenburg. The calculated damages are compared with all available other damages estimated for the Geul. Based on this comparison either components and parameters are validated or rejected and adjusted.

6.2.1. Hazard & exposure validation

In this section the Liwo inundation maps in combination with the exposure are reviewed, with focus on the T=10 year inundation map. Summarized four types of evident errors are present: wrong exposure category, wrong spatial location of assets, non-plausible vulnerability estimates and unrealistic inundation patterns. The complete area is visually assessed for these type of errors and corrected. The combined results of these correction lead to a decrease of 30.6 million euro and a specification is listed in table 6.2.

Table 6.2: Errors and corrections for the T=10 year damage assessment

Type of error	**Correction [M €]**
Wrong exposure category	-7.2
Wrong spatial location	-4.0
Non-plausible vulnerability	-1.1
Wrong inundation pattern	-18.3

An example of a wrong inundation pattern in the Liwo map is caused by the rasterization of the river itself. The provided resolution is 25 meters, which is relatively coarse to represent more linear objects. In figure 6.3 it is seen that at the location of the river itself, the modelled water level in the river leads to a complete pixel of 25x25 meters with that water level. This leads to the assumption of inundation along the river bed. Especially in areas where the river crosses urban areas, this leads to a large cumulative effect and overestimation of residential damages. A volume calculation per pixel confirms that the water volume per pixel is able to be stored within the canal section of the river (at Valkenburg) and thus inundation will not occur. To correct this error every pixel that is in contact with the river itself is omitted from the hazard map at T=10 year. For the two higher return periods this correction is not made. At T=100 year the Geul will cause inundation and therefore omitting river pixels will lead to an underestimation of the damages. Here there is a trade-off between underestimation and overestimation. Given the large cumulative effect of underestimation, identifying the correct number of objects that inundates is most important. The absolute value of the potential overestimation is expected to be less, since the difference in the damage factor for higher inundations is less. This can be explained by the steepness of the function, which is high in the first meter, but evens out for higher inundation depths. Therefore underestimation in this case has a higher weight compared to overestimation.

Figure 6.3: The figure shows the location of the Geul river (in brown) in the city centre of Valkenburg. The blue areas are marked as inundation by Liwo for T=10 year, which is determined to be an error.

Furthermore, the inundation map for T=10 year and the location of damages (exposure component) is visually reviewed. A wastewater treatment plant in the area contributes with 4.06 million euro in damages significantly in the total estimate. For these special and critical objects it can be assumed that if the location is prone to these frequent high water levels, mitigation measures are in place. Furthermore, a review of the area shows a misalignment of the wastewater treatment plant in combination with the hazard. The complete facility is represented in one pixel of 25x25 meters and located in the floodplain, while visually it can be observed that the facility is not inundated even for higher return periods. The damage assessment of the facility is an example of a wrong spatial location of assets and therefore a clear error, which is omitted from further estimates.

Another error is introduced at the confluence of the Geul river with the Meuse, where high inundation depths are modelled. In this area the inundation map is expected to be less reliable due to negligence of the influence of water levels in the Meuse. Furthermore the area is assigned as "intensive recreation" leading to a high damage estimate for the area, while in reality the area is an unused meadow. This area is an example of a wrong exposure category in combination with an unreliable inundation pattern. The complete area is decided to be disregarded in the damage and risk assessment to obtain a more reliable estimate. The boundary of the investigated area now coincides with the location of the culvert under the Juliana canal.

The last error correction leads to the omitting of several watermills that in the model lead to more than 400,000 euro damage per object at T=10 years, which is assumed to be caused by a non-plausible vulnerability component for an object that is designed to be present near the riverbed. In addition, the watermills were wrongfully assigned to the family housing category.

Finally a review of the total number of residential objects that are included in the assessment is important. As mentioned in section 6.1, the measures will be applied to the residential category and shops. Before any meaningful comparison with reported damages and other assessments can be made, it must be verified if the comparison is honest in terms of number of objects. In the Factfinding mission an inundation extent is used based on observations in the field. The total number of objects affected is estimated at 2000-2500 in the Geul catchment and the main source for this estimate is the BAG database from 2021. When the same flood extent is used in SSM-2017 this results in 1748 residential objects. This difference can be contributed to the different dataset from BAG that is present in the SSM-2017 model, namely from 2014. The method to develop exposure maps from the BAG database is described in the manual of SSM-2017, however, lacks the level of detailed description to be reproducible. Therefore in this thesis the BAG2014 dataset is maintained.

In section 6.2.2 the validation of the vulnerability component will be performed based on a Sobek model from Deltares and comparison with the Factfinding damage estimate. If the inundation extent from that Sobek model is assessed, this leads to 1187 affected houses with BAG2014. An overview of the differences are given in table 6.3. The Sobek model and the extent of the Factfinding have a difference of 561 houses. This difference can be contributed to three main aspects: overestimation, inundation near the culvert of the Julianacanal and overland flow. In Schin op Geul the observational flood extent was verified to be an overestimation based on observations from residents. Furthermore, the flood characteristics in Bunde require special attention. Due to the obstruction of the culvert, water flowed past the dike in a north-eastern direction leading to flooding in Bunde. This specific mechanism is not described in the Sobek model, but is present in the observational flood extent (figure 6.4). Finally there remains a difficulty to distinguish the interface between inundation from river water and inundation from rain water. The Sobek model exclusively represents inundation from overflowing of the riverbank. In the observational extent also water on the streets is identified of which the origin can be found in overland flow through flow paths over the hills, caused by more local rainfall. These three aspects indicate that the larger number of houses considered in the Factfinding assessment is justifiable. To make a honest comparison any estimates have to be corrected for this difference in number of objects.

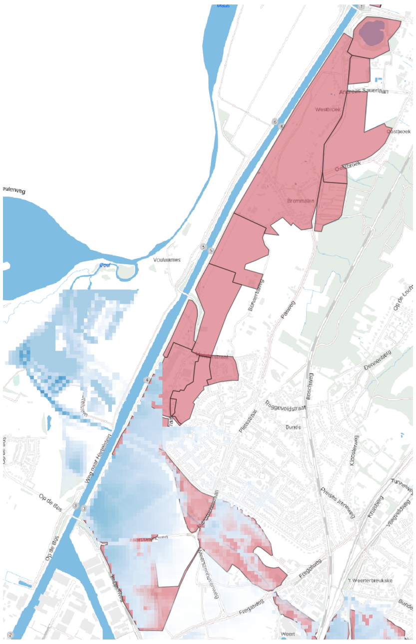


Figure 6.4: Flooding near culvert Julianacanal. In blue Liwo hazard and in red Factfinding flood extent.

Table 6.3: Overview of exposure differences between assessment

Assessment	Number of houses	Source
Factfinding	2000-2500	BAG2021
Flood extent factfinding in SSM-2017	1748	BAG2014
Sobek model Deltares	1187	BAG2014

6.2.2. Vulnerability validation

As mentioned in section 6.2, for larger return periods an underestimation of the residential damages is expected. This indicates that the damage mechanism is not captured correctly and thus leads to a review of the used depth-damage functions. In order to do so, a comparison is made with the July 2021 event, based on an inundation map from the Sobek model from Deltares. If this input is used in SSM-2017, this leads to 22 million euro direct damages in the residential category, while the estimate of the Factfinding is 54.0-67.5 million euro. In addition the study of Wever (2022) describes an estimate of 56 million euro based on a flood damage model and 65 million euro based on an estimate from one insurance company. The estimate through SSM-2017 is a clear underestimation, however, still needs to be corrected for the differences in the number of objects that are considered. First the depth-damage functions are reviewed and after that a method to correct for the differences in the number of objects is described.

The three functions that are used for the residential category are shown in figure 4.1. The majority of the damages occur in family houses, which is split into structure and content. The content function shows a shape which can be expected: after 1 meter the function evens out a bit and after 2 meters rises again, which corresponds with a cross-over to a higher floor. The structure function on the other hand increases relatively slow and only after 2 meters a steep increase is observed. In section 3.3 the origin of the function is discussed where it was found that the function is scaled towards the reconstruction cost in case of a collapsed house. In the Geul floodplain mainly damages for low inundation depths occur, which correspond more to repair costs than reconstruction activities. To obtain a better understanding of the behaviour of the function, a calculation example is made with an assumed inundation depth of 30cm.

Calculation example 30cm inundation family home:

- Average family house Geul: 150m^2 living space (*note: not footprint*)
- Structure damage: 2,466 euro
- Content damage: 19,770 euro
- Damage family house at 30cm: 22,236 euro

While it can be argued that the structure damage is indeed a low estimate, the total damage for a family house is a reasonable estimate given the expected repair activities. Often there is discussion what type of assets in a house can be attributed to content and what to structure. These type of allocations are usually described in insurance policies and can differ. To verify the outcome of this calculation example, it is repeated with the depth-damage function of the Waterschadeschatter which is based on repair costs. The outcome of the 30cm inundation example then leads to 16,800 - 23,520 euro damage for a family home. The SSM-2017 estimate falls within this range and at this stage there is no evident reason to reject the SSM-2017 damage functions. However, still an apparent underestimation remains. This can be explained by the *epistemic uncertainty* of the depth-damage function due to the heterogeneity of the building characteristics. This is an important difference with the hazard and exposure input data where *evident errors* were present.

First the average damages per house are included in the comparison and in addition this is used to correct for the difference in number of objects. With the Sobek inundation map an average damage of 18,905 euro per house is calculated. The estimate of 22 million euro is corrected by adding 18,905 euro times the difference of 813 houses. This leads to a corrected estimate of 38 million euro with the SSM-2017 model. For the Factfinding assessment an average damage per house of 27,000 euro is obtained, which explains the underestimation that still exist with the SSM-2017 model.

The hypothesis is that the uncertainty in the shape of the structure depth-damage function is predominantly responsible for the underestimation. Since the function finds it origin in 1953 in the west of the Netherlands, several differences can be expected compared to Limburg. Many houses in the area are built with marlstone, which are known to be very porous with long drying times. Already at low inundation depths this would lead to relatively high damages. In addition, many houses in Limburg have basements, which are expected to be completely neglected with the current structure function. Based on the local characteristics of the housing it is therefore justified that the function should lead to higher damages at lower inundation depths, which corresponds with a steeper function. To obtain a range for the estimated damages and express the uncertainty of the structure depth-damage function, in the first two meters the shape of the function is altered. Two variants of the depth-damage function are presented in figure 6.5. For each version the resulting damage estimate is given in table 6.4.

Based on this corrected comparison, the estimate in the Factfinding is approached. For the further assessment the adjusted version 1 will be used, which can be seen as the midpoint of the estimates. It is described that in the Factfinding assessment large areas are assumed to have 0.5m inundation. This assumption is imposed for areas where the hydrodynamic model did not predict inundation, but from observations water on the street was recorded. This assumption of 0.5m will most definitely lead to an overestimation of average

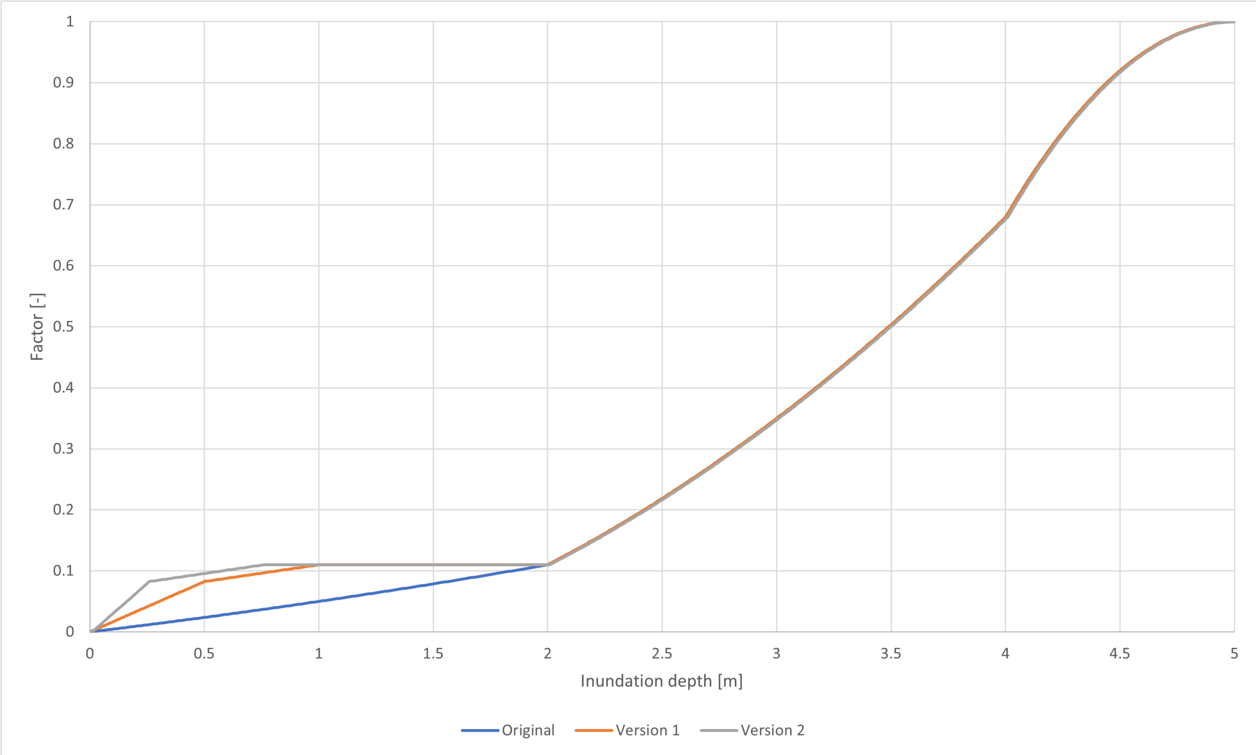


Figure 6.5: Original family home structure DDF and alternative versions

Table 6.4: Corrected damage assessment validation

Damage function	Average per house [€]	Corrected estimate [million €]
Factfinding	27,000	54
Original SSM-2017	18,905	38
Adjusted SSM-2017 V1	24,000	46
Adjusted SSM-2017 V2	27,000	51

damages. Wever (2022) found that 47% percent of the flood map was manually adjusted in the Factfinding mission corresponding to approximately 26 million euro residential damage. Although version 2 will lead to the exact same average damage per house, it is not correct to "calibrate" the model to this value because of the expected overestimation. Version 1 of the function approaches the estimate of the Factfinding reasonably and the estimate is in the same order of magnitude with also the study of Wever (2022).

6.3. Adjustment of model input

Based on the validation in section 6.2, flood risk is calculated again with the adjusted input parameters. This results in a new expected annual damage of 5.9 million euro, of which the corresponding damage-probability curve and comparison is seen in figure 6.6. The most clear difference is the damage estimate for T=10 year, which reduced to 7.0 million Euro compared to initially 37.5 million euro. If the residential category is reviewed independently, a different pattern is seen. For T=10 year, again the estimated damage is reduced from 7.4 to 2.0 million euro. However, for larger return periods the damages are estimated higher than the original. The damage-probability curve with the adjusted parameters shows a satisfactory pattern and addresses the concerns regarding underestimation expressed in section 6.2.

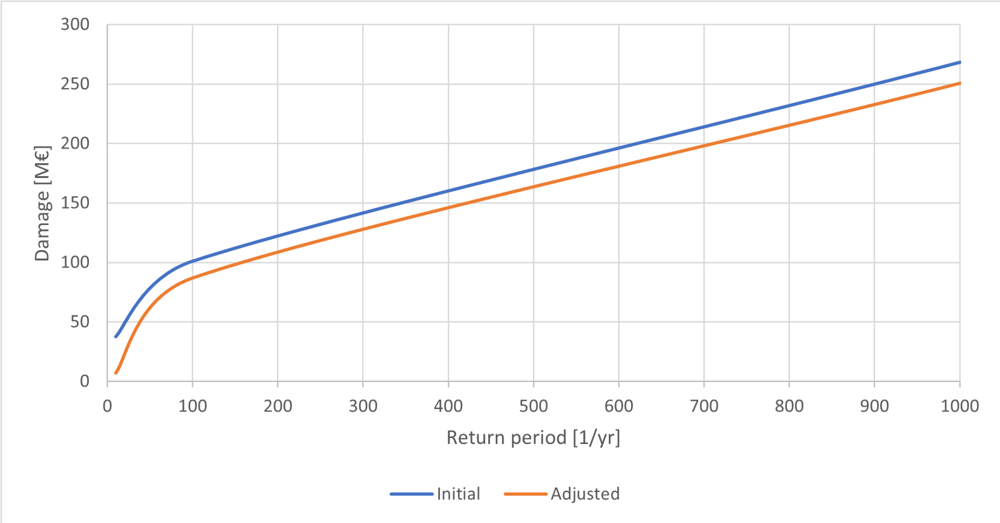


Figure 6.6: Damage-probability curve all categories initial and adjusted.

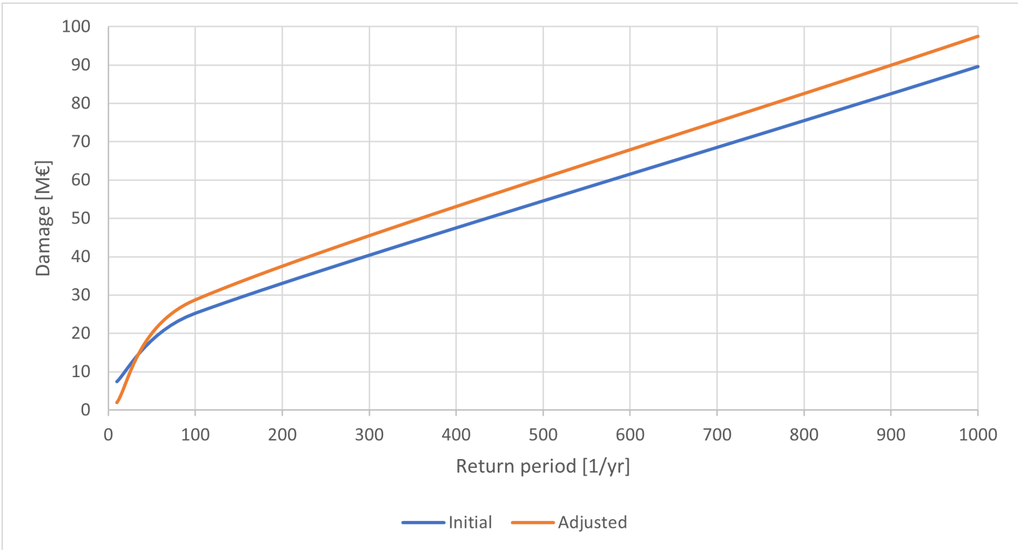


Figure 6.7: Damage-probability curve initial and adjusted residential category only

6.4. Investigated scenarios of measure implementation

First, a scenario is considered in which local government takes an active role in advising and informing residents and business owners about the actual risk on their specific location (within the 1000-year extent floodplain. This includes successful motivation of private actors, by recommendations on the specific type of measures and their effects, as was found to be important by the Protection Motivation Theory to stimulate the implementation of measures. Alternatively, this can be seen as a scenario in which residents and business owners possess high awareness about the specific flood risk of their object and possibilities to avoid damages. This is described by a situation in which the top X% of the areas most at risk take measures and is named "*Scenario A: Top*".

Secondly, a scenario is considered which is more in line with the current policy and strategy in the area, without specific guidance to residents. In addition, this scenarios represents unsuccessful motivation of private actors. It was found in section 5.5 that the current strategy does not comply with the outcomes of the Protection Motivation Theory. It is therefore expected that this results in a more randomly distributed implementation of measures within the floodplain, where main drivers are not only related to actual flood risk but also to subjective criteria and social influences. This scenario is named "*Scenario B: Random*" and is described by a random distribution where X% of the objects within the floodplain take measures. The results of this scenario reflect the effect of the spatial variability of private measures. The difference between the two scenarios indicates the potential benefits of high awareness or specific guidance with high motivation in the floodplain. Finally, to obtain the maximum effect possible with private measures also a scenario is calculated where 100% of objects implement measures, which mainly functions as a reference point.

6.4.1. Scenario set-up and modelling

In this section the procedures for scenario A and B are described. First the damage functions are adjusted corresponding with the reduction factors of table 5.1. This process is automatised with a Python script (Appendix B) to ensure that any future improvements and insights to the factors can easily be adjusted. In figure 5.3 the adjusted depth-damage functions were presented based on the original functions. This approach is repeated with the validated functions. These functions will be used for both scenarios to represent wet-proofing, dry-proofing and the high and low bound. The implementation of measures is represented by calculating a coverage of 20%, 40% and 60% for both scenario A and B. Then the scenarios are calculated with a set of steps and procedures. The coverages are related to the total number of pixels in the 1000-year extent floodplain. Within each pixel the number of objects and corresponding area can slightly vary. For example: 40% of the pixels in the random scenario corresponds with 38%-44% of the actual residential objects.

For scenario A the following steps are performed:

1. Calculate risk without measures.
2. Define for each category the top X% locations prone to most risk.
3. Split exposure map of each category in X% measures and (1-X)% without measures based on top X% locations.
4. Couple exposure map indicating areas with measures with adjusted DDF.
5. Calculate risk with FIAT.
6. Repeat procedure with Dry-proof/Wet-proof, low/high bound.
7. Post process FIAT output.

For scenario B the following steps are performed:

1. Calculate risk without measures.
2. Create 20 random rasters representative for locations with and without risk.
3. Split exposure map of each category in X% measures and (1-X)% without measures based on the random rasters.
4. Couple exposure map indicating areas with measures with adjusted DDF.
5. Calculate risk with FIAT.
6. Repeat procedure with Dry-proof/Wet-proof, low/high bound.
7. Post process FIAT output.

Initially these steps are derived in Qgis, however, this leads to repetitive processes. This occurs mainly in the residential category, due to the division in content and structure. An overview is given in figure 6.8, where it can be seen that 24 rasters need to be created and combined with four runs indicating the type of measure. For scenario B, this is further increased by the set of random rasters that is used to split the exposure maps. For the three investigated coverages this leads to 480 rasters and 1,920 data points, but in case of the entire range between 10%-90% this increases to 1,440 rasters and 5,760 data points. For the commercial category the processes are less intensive because no difference between content and structure is made, but still 120 rasters need to be constructed to simulate scenario B.

With a total of 600 rasters for only three coverages it becomes apparent that an automatic procedure is needed to make the calculation process feasible. This is also achieved with a Python script that can identify the top X% locations most at risk, generates random rasters, splits the exposure maps based on top location or random rasters and creates a structured output of raster files corresponding to each scenario and coverage that is investigated. The Python scripts are presented in appendix B.

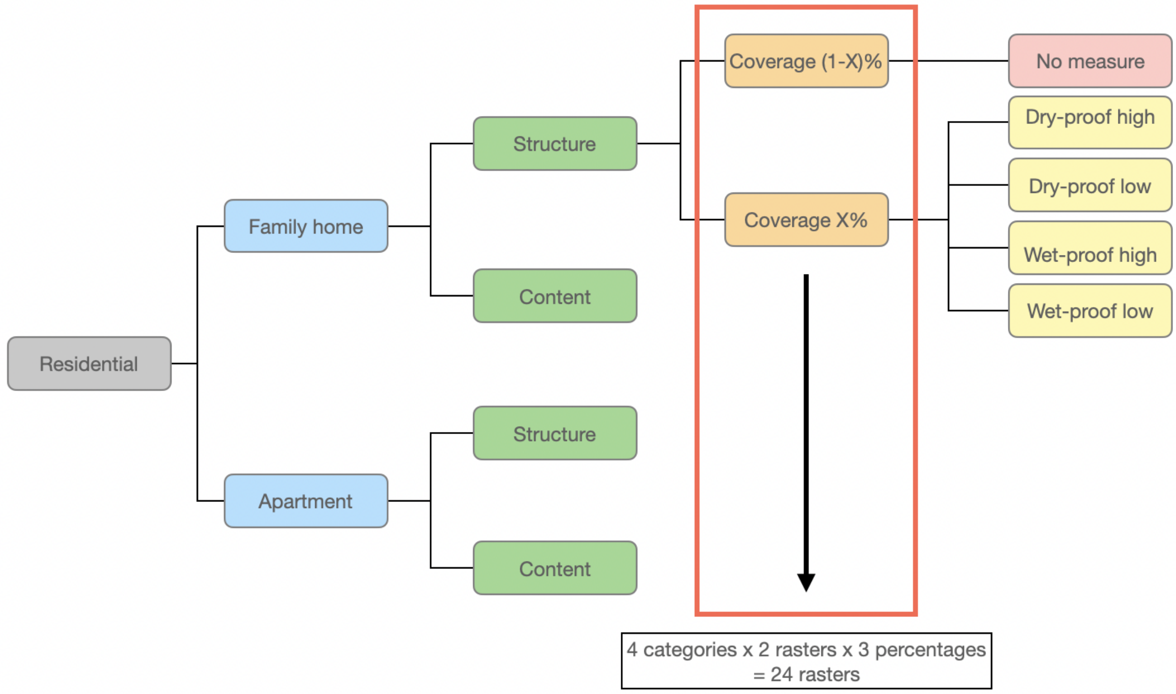


Figure 6.8: Outline of scenario A residential category

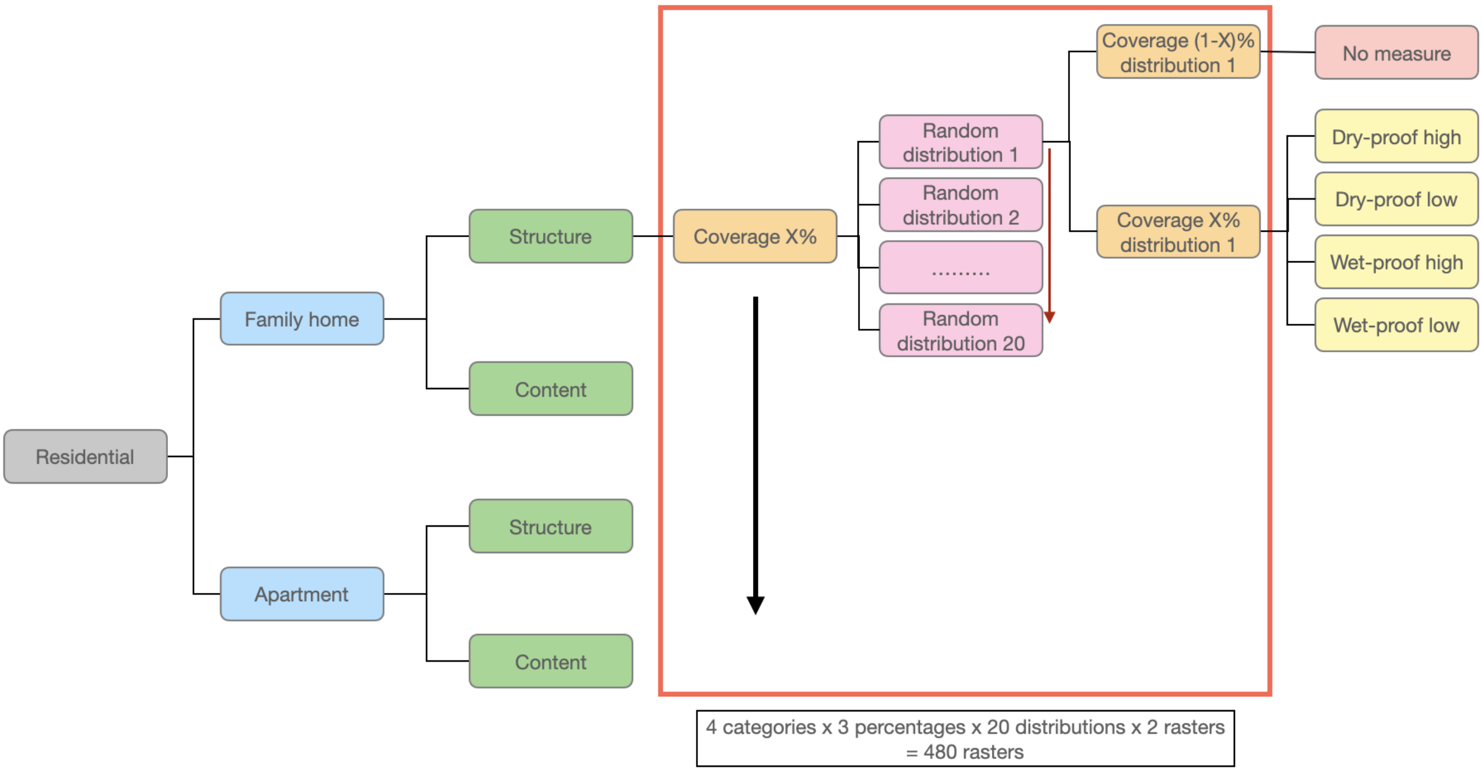


Figure 6.9: Outline of scenario B residential category

6.5. Results of risk reducing effect of measures and scenarios

In figure 6.10 and 6.11 the risk reductive effect of flood-proofing measures is shown for the residential and commercial category. For a coverage of 20% the median of random residential dry-proofing is at 7% risk reduction. For the top scenario the risk reduction is on average 26.2%. With a factor 3.7 difference between the two scenarios, identifying the top 20% is clearly more effective. At 20% coverage wet-proofing provides on average 1.4% more risk reduction than dry-proofing, but for higher coverages dry-proofing always scores higher than wet-proofing.

From 20% to 40% coverage a significant increase in the risk reductive effect is seen. For example top dry-proofing increases from 32.8% to 47.5%. From 40% to 60% coverage this increase is only 4.2%. This indicates that after 40% of locations that take measures, little additional risk reduction is achieved. Another pattern can be observed for the commercial category. Here even after the top 20% coverage, the additional risk reduction is relatively low with 6.3%. A clear difference with the residential category is the relatively higher effect of wet-proofing for commercial areas, that scores for all coverages higher than dry-proofing. Based on the described patterns of risk reduction, for the residential area the optimum implementation of measures is expected around 40% and for shops around 20%. The optimum implementation will be further analysed with a cost-benefit calculation in section 6.6.

For both categories it can be seen that the areas where most risk occurs are very localised. This can be explained by the topography of the area, with incised valleys and small floodplains. This observation is verified by the flood extent for the 10, 100 and 1000 year return periods. From 10 to 100 years a large increase in flood extent is observed, but from 100 to 1000 years the flood extent increase is relatively small. For the family home content category, 89% of the total risk is generated within only 40% of the areas that are prone to flooding. This clearly shows the importance of transparency and guidance within the flood risk management of the Geul valley to obtain an efficient allocation of measures. This is further emphasized by the difference in flood risk reduction between the "top scenario" and "random scenario".

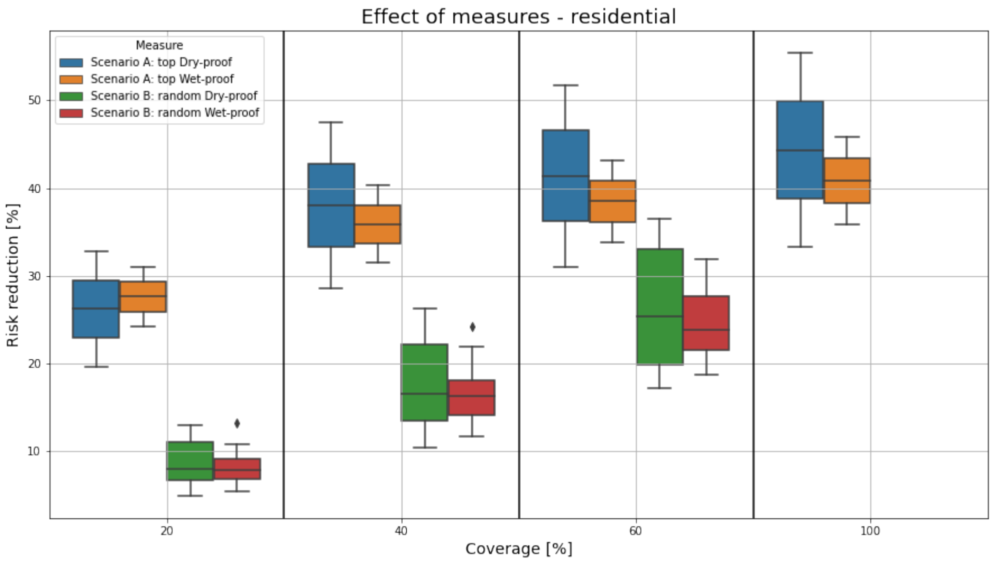


Figure 6.10: Relative risk reduction per measure and scenario within residential category

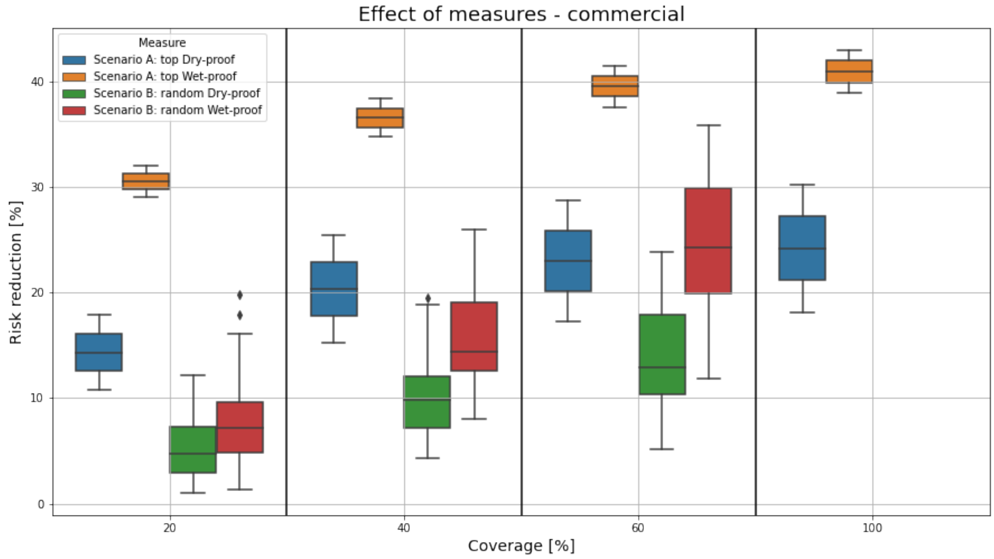


Figure 6.11: Relative risk reduction per measure and scenario within commercial category

6.6. Cost-benefit analysis of measures

In the cost-benefit analysis the risk reduction of the measures, expressed as the reduction in expected annual damage, is compared with the cost of the measures. The avoided risk is considered to be equal to the benefits of the measure. The costs for wet-proofing are based on documentation provided by the waterboard Limburg (Waterschap Limburg, 2022a). For the costs of dry-proofing an estimate is provided by the waterboard Limburg based on their current project in the Mechelderbeek. An overview is given in table 6.5. Temporary dry-proofing was mentioned in section 5.3 and is estimated at only 2,800 euro per object (Gersonius et al., 2008). The costs that are used in this study are based on the, more expensive, permanent dry-proofing measures. For an honest comparison also for wet-proofing structural measures are considered, as flood-adapted use of buildings is more difficult to express in a monetary value.

Due to constraints in the input parameters, the benefit-cost ratio could only be determined for the residential category and not for the commercial category. The provided exposure map only contains the area of the commercial category and not the number of objects. Therefore it is not possible to assess the benefit-cost ratio of dry-proofing. An attempt was made to estimate the average area of a commercial object and based on that derive the number of objects. However, this will introduce an additional uncertainty. For the residential category the number of objects and exact area are directly related per raster cell. For the commercial category this relationship does not exist and therefore an honest comparison between the measures can not be made. It is therefore decided not to include the cost-benefit assessment for the commercial category.

Table 6.5: Cost per type of measure (price level 2021)

Measure	**Cost [€]**	**Unit**
Dry-proofing	8,000	per object
Wet-proofing	100	per m^2

For each scenario the total number of objects and subsequently the living area of objects that implement measures are determined. The total costs of the measures are then determined by multiplying the cost per measure with the number of objects for dry-proofing and living area for wet-proofing. The calculation to obtain the costs for wet-proofing based on the living space can be found in section D.1. For the scenario A the number of objects and living area is fixed per coverage. For scenario B it is dependent on which of the 20 runs is assessed. To obtain the full range, the run with the lowest and highest risk reduction is identified for the low bound and high bound respectively. For that specific run the number of objects and living area is determined to obtain the costs.

It is assumed that the measures have a life-span of 30 years without maintenance costs. The Net Present Value is calculated using equation 2.3 and compared with the calculated costs. As mentioned in section 5.7, a low bound and high bound are calculated corresponding with the estimated effect of the measures. To indicate the full range of benefit-cost ratios of the measures, the boundaries are calculated explicitly instead of using an average. This results in the benefit-cost ratio listed in table 6.6. A full overview of the calculations, including absolute values, can be found in section D.2.

From the benefit-cost ratios it can be observed that wet-proofing is only cost-efficient in the top 20% of locations most at risk. Dry-proofing is cost-efficient in a higher number of locations, but the benefit-cost ratio slowly decreases with a higher implementation. This can be explained by the lower absolute value of risk reduction that is achieved for objects outside of the areas most at risk, while the investment cost remain similar. Based on the analysis it is derived that after a coverage of 55%, the benefit-cost ratio for dry-proofing becomes negative. The ratios describe what the boundary of cost-efficiency is, but do not directly address the economic optimum of implementation. To derive the economic optimum, the *total cost* are calculated. The total cost are defined as the investment costs, plus the remaining expected damages after measure implementation. This approach is further described by Kind (2014b): "Investments are made until the cost of the last investment (the marginal costs) no longer outweighs the further decrease of the expected flood damage (the marginal benefits)." The total cost are at a minimum where the marginal cost are equal to the marginal benefits, which indicates the economic optimum (Kind, 2014b). In figure 6.12 this is presented for dry-proofing low bound, for the total life span of the measure. The economic optimum lies around 32%. Based on the available data points from the modelling, the economic optimum is best described by the top 40% scenario.

Table 6.6: Benefit-cost ratios for the residential category per measure and scenario. A low bound and high bound is calculated, corresponding with the low and high estimate of the effect of measures. **Absolute values are listed in section D.2**

Scenario	Coverage [%]	Dry-proof low	Dry-proof high	Wet-proof low	Wet-proof high
Top	20	1.5	2.5	1.1	1.5
Random	20	0.6	1.4	0.3	0.8
Top	40	1.3	2.2	0.9	1.1
Random	40	0.6	1.3	0.4	0.7
Top	60	1.0	1.6	0.6	0.8
Random	60	0.6	1.3	0.4	0.6
Full	100	0.7	1.2	0.4	0.6

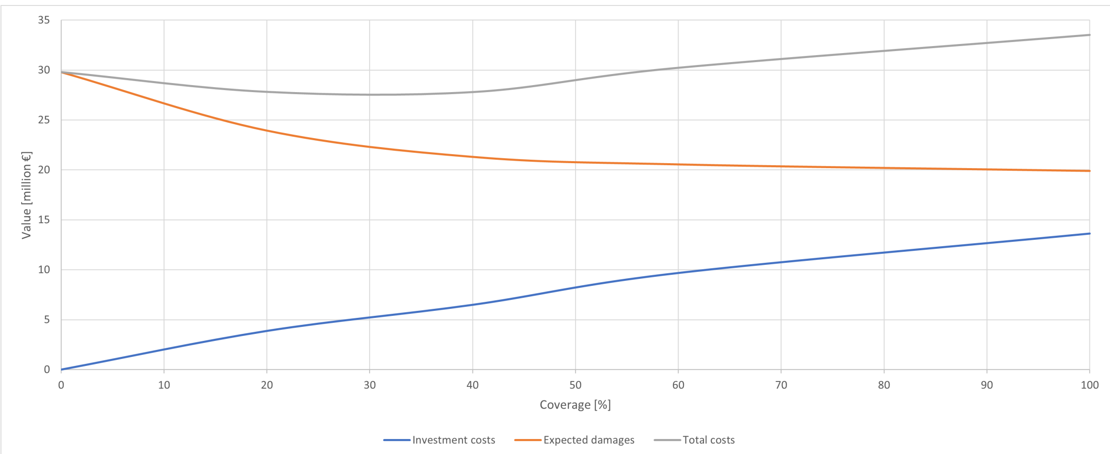


Figure 6.12: Economic optimum of dry-proofing low bound. The total cost are minimal at a 32% coverage, which indicates the economic optimum of measure implementation.

6.7. Sensitivity analysis depth-damage function

Previous research using an unit-loss model to assess flood damages and risk describe uncertainties especially for low inundation depths (Jongman et al., 2012). The main driver for this uncertainty is the depth-damage function. For a correct interpretation of the results and formulation of recommendations, a sensitivity analysis is performed to identify the influence of the depth-damage function uncertainty on the results.

First the sensitivity of the initial risk due to the different depth-damage functions (described in section 6.2.2 and figure 6.5) is calculated. Furthermore two type of results can be distinguished: relative results and absolute (non-relative) results. The risk reductive effect of measures in section 6.5 are relative values and are considered a robust metric (Koks et al., 2014; Bubeck et al., 2011). The sensitivity analysis in section 6.7.2 will verify this statement. The calculated benefit-cost ratios are based on the absolute values of risk reduction and therefore expected to be more sensitive, which is investigated in section 6.7.3.

6.7.1. Initial risk sensitivity

The three depth-damage functions in figure 6.5 are investigated. Only the function for the family home structure category was changed and for version 1 and 2 the risk increase compared to the original function is presented in table 6.7. Viewed within content category only, the risk increase is significant with 110% for version 1 and 161% for version 2. The effect on the total residential category is less pronounced but still significant with up to a 19% increase for version 2 of the depth-damage function. The significant differences indicate that it is worthwhile to investigate how this propagates through the other results.

Table 6.7: Initial risk sensitivity due to depth-damage function.

Depth-damage function	EAD structure category [€]	Increase structure category [%]	EAD full residential category [€]	Increase full residential category [%]
Original	215,459	-	1,814,151	-
Version 1	451,566	110	2,050,258	13
Version 2	563,285	161	2,161,976	19

6.7.2. Relative risk reduction sensitivity

To calculate the sensitivity of changes in the input parameters on the risk reductive effect of measures, a comparison is made between the use of the original depth-damage functions of the SSM-2017 model and the adjusted depth-damage function for the residential structure category. In figure C.1 the relative risk reduction based on the original parameters is presented. These values are subtracted from the values obtained after the adjustments. The outcome of this difference is presented in figure 6.13.

For the residential category a difference up to 3.2% is seen for a 100% coverage of dry-proofing measures. For the optimum coverage of 40% the median of the differences are within 2.2%. This endorses the statement that relative risk reduction is a robust metric and the differences are considered not significant. The statement of non-significance is made since the derived differences have no influence on the analysis of the measures, conclusions or decision-making process.

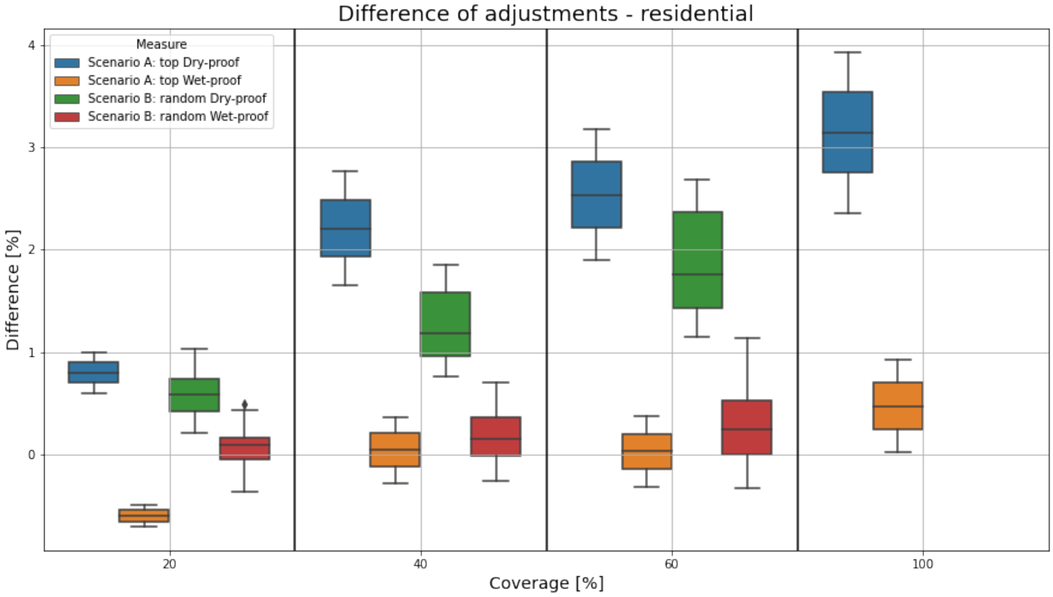


Figure 6.13: Absolute difference of adjustments in input data of risk assessment residential category.

6.7.3. Benefit-cost ratio sensitivity

For the calculation of the benefit-cost ratio the absolute value of risk reduction was determined and compared with the cost of measures. Again the benefit-cost ratios based on the original input parameters of the SSM-2017 model are compared with the obtained values with the adjusted parameters. The initial benefit-cost ratios are presented in table C.1. In table 6.8 the results of the comparison are given. For all scenarios an increase in the benefit-cost ratios is seen. This is directly explained by the higher base risk estimate with the adjusted depth-damage function: a higher base estimate leads to higher benefits of the measures. This effect is divergent with the number of objects that have measures implemented. For the top 20% scenario the increase in the BCR is 16.6% and for a full coverage of measures 21.6%.

As expected the benefit-cost ratio shows higher sensitivity to input changes. For the optimum coverage of 40% an increase in the CBR of 19.98% for dry-proofing and 14.06% for wet-proofing occurs. If the second damage-function version in figure 6.5 would be assessed the effect on the benefit-cost ratio is even higher. These differences are considered to be significant as it can directly influence the decision-making process regarding the implementation of measures. Given the sensitivity of input parameter changes on the benefit-cost ratio it is recommended to address this in the advices that are given in chapter 7.

Table 6.8: Relative difference of adjustments in benefit-cost ratios residential category per measure and scenario

Scenario	Coverage [%]	Dry-proof low [%]	Dry-proof high [%]	Wet-proof low [%]	Wet-proof high [%]
Top	20	+16.6	+16.6	+9.8	+11.3
Random	20	+22.1	+22.1	13.5	+11.2
Top	40	+20.0	+20.0	+12.0	+14.0
Random	40	+24.9	+20.3	+15.4	+13.4
Top	60	+20.4	+20.4	+12.0	+14.0
Random	60	+21.4	+21.1	+14.8	+13.6
Full	100	+21.6	+21.6	+13.0	+15.4

7

Location specific effect of measures

7.1. General selection of measures

In this chapter location specific recommendations will be given based on the analysis in chapter 6. It was found that focussing on the top 40% of residential areas with the highest expected damages is the most beneficial for the implementation of measures. In figure 7.1 an overview is given with the hotspots belonging to the residential top 40%. In Valkenburg city centre most damages are expected, followed by the neighbourhood Neerhem in Valkenburg. After this the villages of Gulpen, Eys and Schin op Geul are prone to high expected flood damages. The village of Bunde, which in the flood event of July 2021 received damages, is not within the top 40% due to the limitation to capture the flooding mechanism in close proximity to the culvert.

Based on reports and the geographical location of Valkenburg it was expected that the city centre is at the top location prone to highest expected damages. The Neerhem neighbourhood received less attention, but still contributes with 14% of the total residential risk. In addition the more upstream villages of Gulpen en Eys are less reported in the media, but nonetheless require attention, as in Gulpen up to 155 residential objects are prone to damages. Even more so since the higher upstream locations have less preparation time for a high-water peak originating in Belgium.

In the following sections each hotspot will be addressed in more detail. For this analysis the highlighted locations in figure 7.1 are used as a guide to indicate which areas need to be investigated. A location specific research area is defined, which encompasses the hotspots. Within these boundaries all objects within the 1000 year floodplain are assumed to belong to the top 40% and thus implement measures.

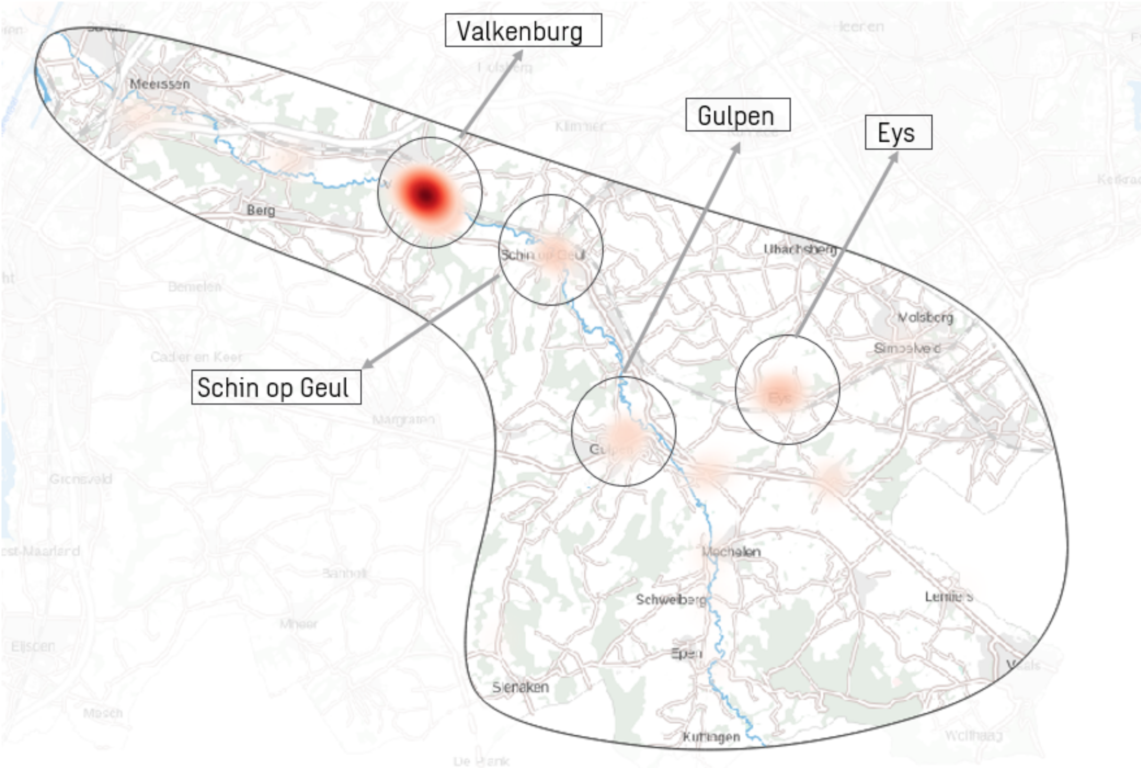


Figure 7.1: Top 40% risk hotspots in The Geul Catchment

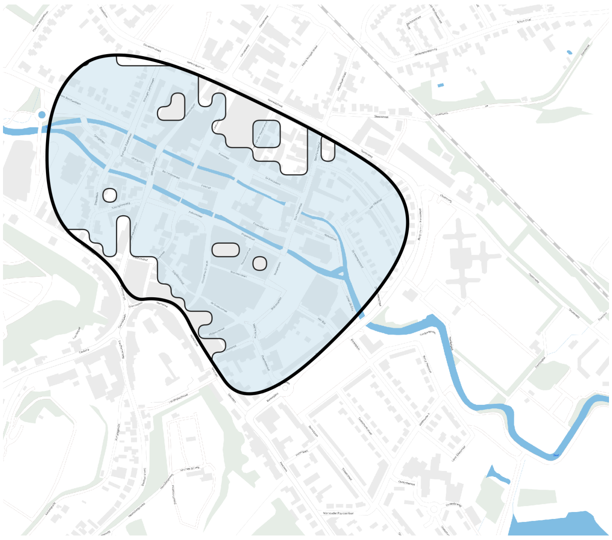
7.2. Location specific selection of measures

For each of the hotspots the relative risk reduction and benefit-cost ratios of measures are calculated. Based on these results, locations specific recommendations are made. The absolute values used to calculate the benefit-cost ratios are presented in section D.3.

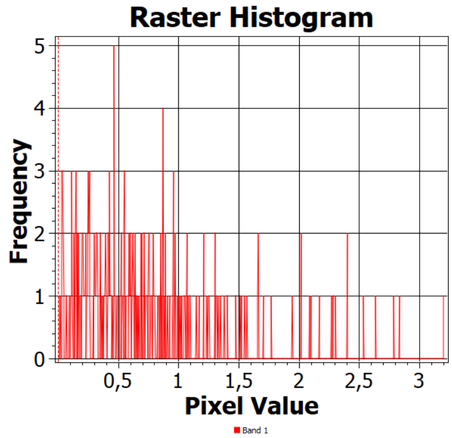
7.2.1. Valkenburg Centre

For the city centre the risk reductive effect of dry-proofing and wet-proofing are in the same order of magnitude. Given the different ranges of effect this would suggest a high variability of water levels in the city centre. However, visual confirmation reveals a problem with the hazard map. As discussed in the validation section, the river pixels were deleted for a return period of T=10 year. For higher return periods this procedure was not performed to prevent underestimation of the risk. Although the inundated objects along the Geul are correctly identified, the corresponding water levels are estimated too high. Due to channelised section of the Geul and the backwater effect of the bridges, the water levels of the river in the city centre are relatively high. These high water levels are projected on the objects adjoining the river. An estimate of the water levels that is too high has a direct effect on the applicability of dry-proofing for those objects. There will always remain uncertainty in the modelled water depths, however, for this particular area it is considered an error.

Ignoring the wrongly modelled inundation areas, it is found that for the majority of the area the inundation depth remains below 1 meter, see figure 7.2b. Some areas more perpendicular on the Geul river are modelled with inundation depths above 1 meter, as for example the Berkelplein. At these specific objects wet-proofing could be more favourable. For the majority of the residential objects, dry-proofing is recommended. The benefit-cost ratio of dry-proofing is positive with 1.0-1.7, but is expected to be even higher if the inundation in the direct vicinity of the Geul is correctly modelled. Another aspect in favour of dry-proofing is the building material in the old city center. The area is known for marlstone houses with high porosity. Successfully wet-proofing this material can be costly and difficult. Prevention through dry-proofing is therefore a better solution for the majority of the objects.



(a) Overview investigated area Valkenburg Centre. In blue the 100 year floodplain.



(b) Frequency of inundation depths T=100 year Valkenburg Centre

Figure 7.2: Inundation information for investigation of measures in Valkenburg Centre

Table 7.1: Benefit-cost ratios of measures in Valkenburg Centre

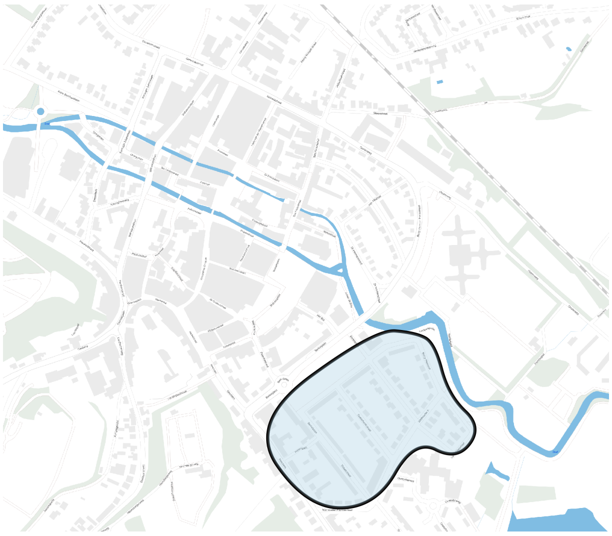
Measure	Risk reduction [%]	BCR
Dry proof low	24.9	1.0
Dry proof high	41.5	1.7
Wet proof low	32.2	0.8
Wet proof high	43.0	1.0

7.2.2. Valkenburg Neerhem

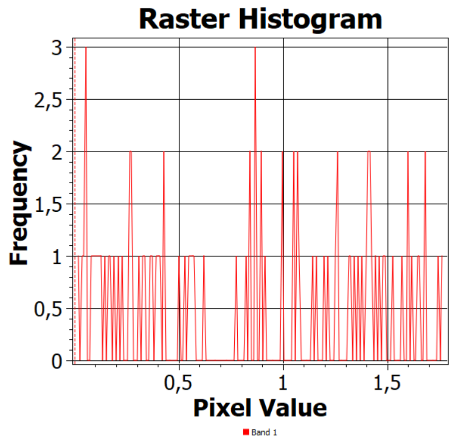
Close to the city centre, the neighbourhood Neerhem is located. Mainly the Louis Eliasstraat was heavily affected during the flood event in July 2021. For the street high inundation depths are modelled. The histogram of the hazard map for T=100 year shows inundation depths with the majority of cells between 0.8m - 1.5m. The houses around the Louis Eliasstraat are located lower than the surrounding area which could be clearly observed during a site visit. The water flows from the Geul over the Betsy Perklaan towards the lower lying area where it accumulates and can't drain properly. The houses closest to the river received none to minimal damages, since water could not accumulate and water levels remained low.

Based on the risk reductive effect of measures, wet-proofing is clearly more effective in this area, directly related to the high inundation depths. The benefit-cost ratio however remains negative with a value of 0.78. Still there remain possibilities to implement wet-proofing with the "building back better" principle. Several houses are completely stripped and still uninhabitable. The current cost is based on existing buildings. If currently repair and reconstructive activities are planned, the additional cost to "upgrade" to wet-proofing are expected to be lower than the current estimate, making the benefit-cost ratio more favourable.

For the Neerhem neighbourhood it is recommended to combine wet-proofing with current or planned activities. For objects without current or planned activities, the implementation can be assessed taking into consideration intangible effects of flooding, making it a personal and more subjective consideration. Only dry-proofing is not advised in the area.



(a) Overview investigated area Valkenburg Neerhem. In blue the 100 year floodplain.



(b) Frequency of inundation depths T=100 year Valkenburg Neerhem

Figure 7.3: Inundation information for investigation of measures in Valkenburg Neerhem

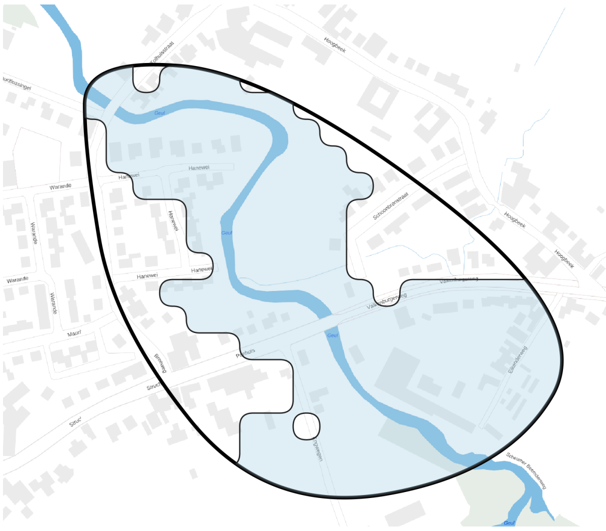
Table 7.2: Benefit-cost ratios of measures in Valkenburg Neerhem

Measure	Risk reduction [%]	BCR
Dry proof low	7.7	0.2
Dry proof high	12.8	0.4
Wet proof low	32.5	0.6
Wet proof high	40.6	0.8

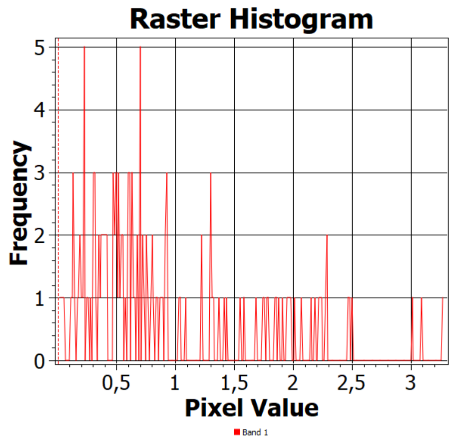
7.2.3. Schin op Geul

In Schin op Geul mostly the Hanewei street was heavily affected. The street was developed in the early seventies and built slightly elevated. The river cuts off the meandering part and inundates the street. Inundation depths remained low, although flow velocities were found high. The relatively low inundation depth can be seen in the risk reductive effect of measures, where dry-proofing scores significantly higher. Only a few objects received inundation above 1 meter. These are mainly located in the vicinity of the bridge over the Geul from the Valkenburgerweg. The Geul makes a sharp bend directly after and forms a bottleneck, creating a backwater effect. Recorded water levels in an object close to this location were with 1.15 meter indeed higher than 1.

For the Hanewei, dry-proofing measures are recommended. Special attention is needed to the orientation of any barriers in relation to the flow direction. Additional strengthening might be necessary to withstand water pressures at this location. Finally, the street consists solely out of free standing family homes, making the number of entry points into the object higher compared to a standard row house. This can lead to higher costs for this location. Given the current benefit-cost ratio there still remains margin for higher cost. With a average cost estimate of €10,700 and €17,500 per object for dry-proofing, the benefit cost-ratio remains positive for the low bound and high bound respectively. For the objects located directly next to the river, near the described bottleneck, wet-proofing is advised. The measures taken by the business owner mentioned in section 5.6.2 are therefore considered favourable measures and exemplary for these type of objects. For wet-proofing a decision making action plan is recommended if any contents need to be placed to higher floors. Especially for the described business it is essential to start preparations in time. In such a plan the owners of the object can formulate indicators for themselves that indicate at which moment preparations for flood damage mitigation should be started.



(a) Overview investigated area Schin op Geul. In blue the 100 year floodplain.



(b) Frequency of inundation depths T=100 year Schin op Geul

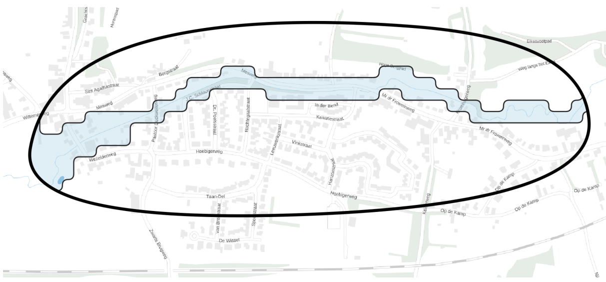
Figure 7.4: Inundation information for investigation of measures in Schin op Geul

Table 7.3: Benefit-cost ratios of measures in Schin op Geul

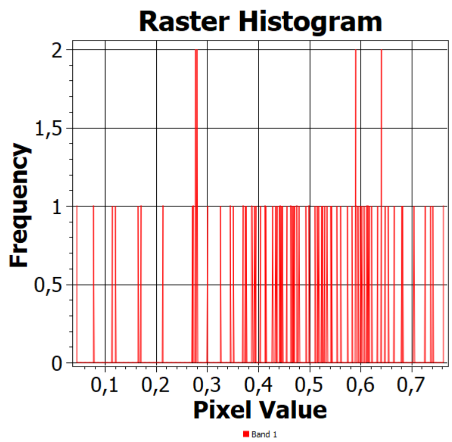
Measure	Risk reduction [%]	BCR
Dry proof low	46.1	1.4
Dry proof high	76.9	2.2
Wet proof low	38.7	0.6
Wet proof high	46.9	0.7

7.2.4. Eys

The Eys is located along the Eyserbeek, a small tributary of the Geul. Inundation depths remain almost completely under 1 meter for the whole village. The maximum risk reduction of dry-proofing therefore reaches the maximum with 94.9% risk reduction. The benefit-cost ratio is high with 2.36-3.93. Additionally, the histogram of inundation depths shows not a single outlier cell estimated above 1 meter water depth. This implicates a high confidence in the measure type selection and in addition low financial risk with the estimated BCR.



(a) Overview investigated area Eys. In blue the 100 year floodplain.



(b) Frequency of inundation depths T=100 year Eys

Figure 7.5: Inundation information for investigation of measures in Eys

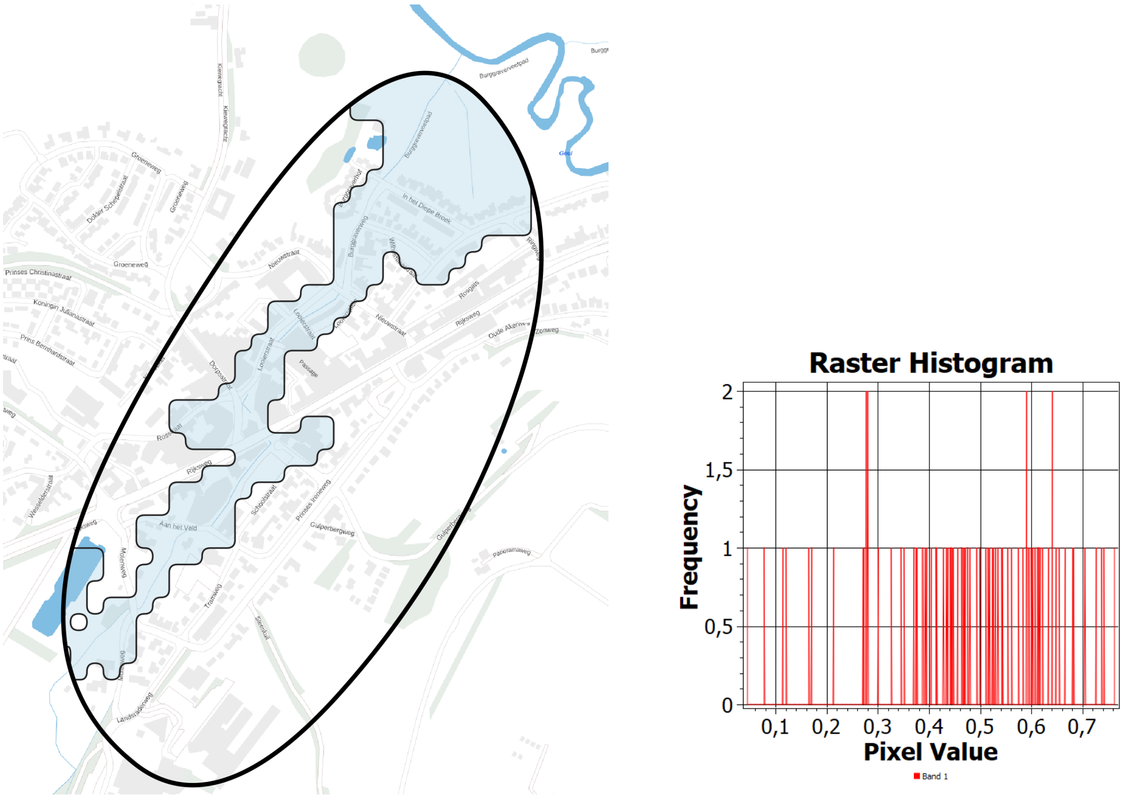
Table 7.4: Benefit-cost ratios of measures in Eys

Measure	Risk reduction [%]	BCR
Dry proof low	57.0	1.8
Dry proof high	94.9	3.0
Wet proof low	43.8	0.8
Wet proof high	52.4	0.9

7.2.5. Gulpen

The village of Gulpen is located at the Gulp, a small tributary of the Geul. In the centre of the village the Gulp is embanked, similar to the situation in Valkenburg centre. During the event in 2021 the Gulp almost overtopped the quay walls. Several bridges in the centre created backwater, as the water levels reached the top of the bridges. Just downstream of the city centre, towards the confluence with the Geul, the Gulp did overflow and the flooding caused damages. If the hazard map for the Geul is observed, the pattern of inundation downstream of the centre is identified. However, for T=100 year and above the Liwo hazard map models inundation in the city centre along the quay walls. It is difficult to assess the validity of the overtopping of the quay walls, but given the protection standards in Limburg it is plausible that for T=100 year and above overtopping occurs.

Also for Gulpen dry-proofing has a significant better risk reductive effect. Again the measure type selection can be done with confidence, based on the histogram of inundation depths. The benefit-cost ratio varies with 0.8-1.4 on the interface of what is an economically good investment. Given the sensitivity of the benefit-cost ratio that was determined, for Gulpen it is difficult to address the cost-effectiveness of measures with confidence.



(a) Overview investigated area Gulpen. In blue the 100 year floodplain.

(b) Frequency of inundation depths T=100 year Gulpen

Figure 7.6: Inundation information for investigation of measures in Gulpen

Table 7.5: Benefit-cost ratios of measures in Gulpen

Measure	Risk reduction [%]	BCR
Dry proof low	49.2	0.8
Dry proof high	82.0	1.4
Wet proof low	41.3	0.5
Wet proof high	52.9	0.6

7.3. Summary and reflection on recommendations

Based on the ranges of dry-proofing and wet-proofing, the inundation depth is the main driver to select the type of measure. For Eys, Gulpen and Schin op Geul, dry-proofing provided most risk reduction. The selection of dry-proofing for these villages is expected to be reliable, based on the low sensitivity in section 6.7.2 and plausible estimates of water depth at these locations. Also the frequency of damages is important in the benefit-cost ratio. The damages calculated for a 100 year event are in these specific cases most dominant for the risk estimate. For T=10 year none to little damage occurs, for example in Schin op Geul only 1 object received damages. Damages at T=1000 year contribute in lesser extent to the initial risk.

Given the importance of the 100 year event, the corresponding inundation maps for the three villages are reviewed in more detail. Although the majority of the inundation depths was found plausible, uncertainty in the hazard for inundation depths around 1 meter could influence the decision making regarding the measure type selection. A review of the histogram of the inundation map provided insight in the likelihood of wrong measure type selection. For Gulpen it can be observed that frequencies of water depths are skewed left and lie for the majority well below 1 meter. Several cells are approaching 1 meter and incidental some above 1 meter. Similar histograms are seen for Schin op Geul and Eys. Based on this distribution it is unlikely that inundation depth uncertainty will have a decisive effect on the type of measure that is selected for the three villages.

Focussing on the benefit-cost ratio, Gulpen stands out from the three villages. The lower ratio compared to for example Schin op Geul can be explained by the number of affected objects. As an indication the total risk for the village is divided by this number. In Gulpen 152 objects are affected by flooding with an average expected annual damage per object of €925. In Schin op Geul the average expected annual damage per object is €1605. Note that the resolution of the model does not allow to use these values directly, but only for comparative purposes. This indicates that in Gulpen a large number of objects receive little damage, while the full cost of the measures are being made, putting the benefit-cost ratio under pressure. Similarly to the analysis in chapter 6, it can be concluded that also at the spatial scale of a village a certain optimum distribution and coverage of measures exist. Nevertheless, for multiple areas it is found that the benefits of dry-proofing clearly outweigh the cost. Therefore, despite the present uncertainties, dry-proofing can be considered as a "no regret" measure in those locations. For wet-proofing the main applicable area was Valkenburg Neerhem and a few objects directly along the Geul near Schin op Geul.

8 Discussion and limitations

The discussion will focus on the general relevance of the research, model set-up, its sources and the uncertainties of the accompanying results. Finally a reflection is made on the advices that are given based on the model-outcome.

8.1. Relevance for private actors

Based on a literature review two types of structural resilience measures are identified for the household scale: dry-proofing and wet-proofing. It was found that mostly dry-proofing is effective for residential objects in the area and wet-proofing for shops. Focus on the top 40% and top 20% provides the optimal risk reduction for the residential and commercial category respectively. The maximum reduction for the residential category was estimated at 33%-55%, whereas (Poussin et al., 2012) found a reduction of 21%-40% for the Meuse floodplain. This demonstrates that private resilience measures in the regional system are more effective, compared to primary systems.

The neighbourhood advices are based on the risk reduction capacity and the benefit-cost ratio. For the risk reduction capacity the type of measure is mainly dependant on the predicted inundation depth. For the inundation maps of T=100 year and T=1000 year it was decided not to omit river pixels, to avoid underestimation of the risk. However, mainly in terms of inundation depth this led to an overestimation in Valkenburg and it influenced the measure type selection. Therefore careful evaluation of the plausibility of inundation depths remains important. The recommendation of Jongman et al. (2012) to review the frequency histogram of inundation depths provided additional substantiation and decreased uncertainty for the measure type selection.

The number of interviews held in the area is too low to allow any statistically founded statement about the current willingness of residents to adapt. Nevertheless, the interviews and field visit did provide additional insights otherwise not obtained. This was mostly related to the intangible impact of the flood event and the inability to effectively take private measures despite willingness. From a private perspective it showed that benefits and costs of measures are not solely responsible for decision making. Prevention of experiencing another stressful event or disruption more so. Bubeck et al. (2020) endorses the importance of the intangible damages such as trauma. In the study it was found that many respondents recovered fully from the flooding, but also that "a substantial part of the respondents is chronically affected by a (flood) event" (Bubeck et al., 2020). Therefore long-term psychological assistance is advised as part of flood-resilient societies. Also Hudson et al. (2021) mentions the "psychological domain as the most important driver of recovery and flood impacts the least", based on two studies.

Research using the Protection Motivation Theory did provide useful insights what motivates residents to undertake private measures. Using the coping appraisal, indications from the interviews are confirmed that response efficacy and self efficacy is more important than costs for most type of measures. For example the business owner stated regarding measures and costs: "I didn't look into costs, for us it's important to avoid business disruption and it's something we just had to do". The interviewed resident replied when asked about dry-proofing: "I'm not sure if barriers will work and where to begin, because the water came from all sides of the house". Therefore following the advice of Botzen et al. (2009), clear communication of the expected results of private flood mitigation measures and the implementation should be included in the strategy as well. Only communication of risks is not enough to effectively improve resilience, as residents need to have a strong feeling to be able to reach the intended results. Similar findings are described by Oakley et al. (2020) who states that "it is apparent that simply providing information is unlikely to be an effective tool in increasing take up of resilience measures". The water board or insurance companies can play an important role here. Botzen et al. (2009) describes a Swiss example where national insurance experts give local building advice. Together with the finding that social networks play an important role in coping appraisal, there lies potential for community based guidance. The current brochure of the water board Limburg about private measures is insufficiently able to motivate people according to these findings. It provides no information about the effects or structural implementation, but focusses more on measure type and costs. Also it remains unclear for private actors who is responsible for risks, with the presence of insurance options and policy conditions and compensation from the government.

Finally, a remark about the adjusted depth-damage functions to represent the different type of measures must be made. In the used method the effect of measures is set to 0% for inundation depths above the use range. For wet-proofing even above two meters there will be a damage reducing effect, as long as the building does not collapse. In the Geul floodplain no (frequent) inundation depths higher than 2 meter are expected, so this inadequate description is not of decisive importance. In contrary, for dry-proofing Kreibich et al. (2005) described that even after failure 29% risk reduction is possible, which is dependent on the type of failure. In the case of a collapse of a barrier the effect is lost in total, but in case of small overtopping for short inundation events, there will still be less water in the object compared to no measure at all. Further investigation into the residual risk reduction of dry-proofing can lead to a wider use range. In addition, possible combinations of dry- and wet-proofing could be beneficial, as was investigated by Poussin et al. (2012).

8.2. Relevance for water board

In section 5.6.3 the project in the Mechelderbeek was described where the Waterboard Limburg wants to initiate dry-proofing measures to comply with standards. With the current standards and policy this remains a complicated initiative, where especially the difficulty to prove the principle of conformity, as well as the lack of clear legal background form an obstacle. This proves there's a need for studies that assess the effect of private flood mitigation measures and the spatial allocation. This study shows that private measures can be economically beneficial and provides guidance to measure type selection and spatial allocation. There is a clear benefit when top risk areas, within the floodplain, are identified. Besides the Mechelderbeek project, the Waterboard Limburg only provides a brochure for the entire province, which leads to a randomly distributed implementation of measures and is clearly insufficient based on the results in this thesis. Improvements in the communication strategy are therefore needed, based on the findings from the Protection Motivation Theory as discussed in section 8.1.

From the viewpoint of the Waterboard Limburg, clear objective parameters to assess when flood-proofing residential objects can be beneficial will help decision-making as well as informing and convincing residents. If the measures are assessed in the framework of the multi-layer safety approach, an additional complication is the intention of the Waterboard Limburg to fully exchange measures between the first and second layer. Current standards in the regional system don't provide the possibility for the exchange of measures between layers and a risk based approach would be necessary. For existing built areas that don't meet the standards, currently private flood mitigation measures can only be implemented *in addition to* structural measures in the water system itself and not as a means to reach the standards. In this study only the effect of measures in the second layer is explored. A more integral assessment where the interaction between the first and second layer is investigated can provide a better understanding how private measures can contribute to meet the standards within the current policy. This should also include the temporal scale of resilience and flood risk. On a short to medium temporal scale the private measure can already contribute to faster recovery and adaptation. In the time-span it takes to increase the standards of an area, new events can occur. Also by the time an area is up to current standards, climate change could already have affected that achievement. Under these circumstances private measures add redundancy, while on a long-term temporal scale contribute to a transition towards shared responsibilities in flood risk management.

For to be developed areas, exchanging measures between the first and second layer is more in reach. Currently the initiatives where "soil and water are leading in land-use" are emerging and gaining attention. If for any reason houses have to be developed in an unfavourable location according to this initiative, it is recommended to make additional requirements and regulations of buildings mandatory. When flood-proofing of houses is regulated during the construction phase, not only costs would significantly decrease, but also future residents are informed beforehand about risks and responsibilities. Such initiatives would increase resilience, awareness and contribute to the transition in flood risk management, without increasing burdens on future generations. Nevertheless, also for to be developed areas policy changes will be necessary.

8.3. Model set-up, sources and limitations

The core sources of the model are the hazard, exposure and vulnerability. The exposure component was unchanged and judged reliable. For the hazard and vulnerability component several adjustments are made.

Discussion of vulnerability

The vulnerability, through the depth-damage function, was reviewed and validated in section 6.2.2. Substantiated adjustments to the family home structure function were made and the shape was steepened. To validate the vulnerability component the event of July 2021 was recalculated with the output of a Sobek model by Deltares. The validation was not fully calibrated towards the Factfinding, but approached closely. Currently still little precise information about damages in the region is known. Insurance companies, who have the most reliable information are not willing to share that information due to privacy concerns or business related policies. It can be argued that the calibration is performed towards a provisional estimate. Nevertheless, the Factfinding is currently the most substantiated estimate. In addition, Wever (2022) created a framework to validate damage estimates and achieved a damage value within the same range. It is therefore justified to use these estimates, but it must be considered that the actual damages could differ and re-calibration is needed.

Currently the function is calibrated towards a relatively rare and extreme event. It is unknown if the function therefore fully represents flooding for more frequent and less extreme events. Besides increased uncertainty when functions are transferred between regions, also transferring functions between events can cause the uncertainty to increase . Not only the spatial scale, but also the temporal scale of depth-damage functions needs to be considered (Wagenaar et al., 2015; Wind et al., 1999; Bubeck et al., 2012). To calculate the expected annual damage, events with a return period of T=10, 100 and 1000 year are used. In the used FIAT version it is not possible to assign damage-functions per return period. An extra remark must therefore be made about the estimate for a T=10 year event. Currently 2.0 million euro residential damage is estimated, which is considered high by expert judgement. Despite efforts in the validation, no additional evident errors in the method could be detected to adjust this estimate. However, for these type of events a large share of the population is expected to have previous flood experience or exposure. It is therefore more plausible that for a T=10 year event there is some level of resilience already present in the area and the depth-damage function should be less steep. Despite the apparent overestimation at T=10 year, the annual expected damage proves to be most sensitive towards the estimate for T=100 year. Therefore the negligence of the temporal scale of the depth-damage function is expected to have little influence in the assessment.

Discussion of hazard

The hazard map was not able to capture the specific flooding mechanism in Bunde and Meerssen and underestimated the damages at those locations. Still the Liwo inundation map is judged by Deltares as the most recent validated probabilistic source for flooding in Limburg. Little elucidation is provided by Liwo about the sources and background of the map. A comparison with the July 2021 event provides insight in the plausibility of the damage-probability curve calculated with the Liwo inundation map. Van Heeringen et al. (2022) estimated for the precipitation event a return period of 900 years. Although Van Heeringen et al. (2022) explicitly does not mention a definitive return period for the resulting discharges and flood event of the Geul, it was estimated that the event was subsequently "somewhat lower than 1/900 years" at Valkenburg. With the Liwo maps 29 million euro was estimated for T=100 year and 100 million euro for T=1000 year. With the estimate of the Factfinding and an interpolation, the return period of the July 2021 event would be 1/450 - 1/575 year based on the Liwo map. This is lower than the estimated value, however, Van Heeringen et al. (2022) is very reserved about the return period and indicates that more investigation is needed. In addition, inundation maps for higher return periods are prone to increased uncertainty due to extrapolation, since little to none measurements in The Netherlands for such events exist. Given the low confidence of any return period predictions, there is also no clear reason to reject the outcomes of the Liwo map. A prediction of up to 1/575 year is therefore considered plausible. Nevertheless, for the purposes of this study the frequency of events can be decisive for the benefit-cost ratio. A tendency to overestimate the frequency of occurrence would lead to a higher initial risk and subsequently higher benefits of measures. Careful considerations are thus advised for benefit-cost ratios close to 1.

The assessment focussed on damages from river flooding only. As a results other sources of flooding are not considered. The Factfinding flood extent was based on observations and captured 561 more residential objects that were not identified with a hydrodynamic inundation model. Probable sources were found to be water from local rainfall and overland flow. Including this source of flooding provides a more complete view on the potential benefits of measures and the frequency of events where private measures could be useful is likely to increase. A limiting factor to include local rainfall and overland flow is the strong heterogeneity and difficult predictability, leading to high uncertainties.

Discussion of cost-estimate
Finally the indirect damages due to flooding are not considered in the regional module of SSM-2017. In addition, the use of the reduction factors applied to *indirect* depth-damage functions is not described in literature and is highly presumptuous. Nevertheless, it is acceptable to assume that there is a certain correlation between structural measures and a reduction of indirect damages . With the use of indirect depth-damage functions from SSM-2017 for areas protected by dikes, an estimate is given for the contribution in the Geul. The indirect damages for the residential objects is 13.5% of the direct damages, for shops this share is 27.3%. This is already a substantial share and including indirect damages is therefore recommended, however, with SSM-2017 not validated for the regional system (De Bruijn et al., 2015). The Factfinding uses indirect damage estimates from Thieken et al. (2016) and mainly described high indirect damages through business losses and disruption, which endorses to include indirect damages. Finally, including the indirect damages will have a positive effect on the benefit-cost ratio.

Discussion of Model set-up
The calculations were performed using a combination of Python scripts, Excel and the object based Excel version of the Flood Impact Assessment Tool. Multiple manual operations were needed to connect all steps of the calculations through the different software programs. Especially the Random scenario required many manual interventions in FIAT to change coverages and types of measures. With the current knowledge of the operability of the program, many steps can be further automatised and the Random scenario could be run in one single batch. This will save time and is less error prone. The total runtime for the Random scenario for the residential category only is then estimated at 24 minutes with a 25m resolution. An attempt to increase the resolution to 5m has been made. However, this resulted in a significant longer runtime up to 12 hours. A runtime of 12 hours is only feasible with the aforementioned extra automatisation of FIAT.

8.4. Uncertainties of the results

Relative risk reduction of measures proved to be a robust metric under the influence of depth-damage function changes. When this is reviewed for the complete catchment, it can be argued that the large number of objects compensate for any outliers. However, further investigation showed that also on a neighbourhood scale the sensitivity remained low. This is in line with multiple studies who found similar low sensitivity (Koks et al., 2014; Poussin et al., 2012).

The benefit-cost ratio showed more sensitivity, as this is based on absolute values. In figure 8.1 an overview is given of the different model components, their relation to each other and input sources. Uncertainty in the BCR can lead to economic losses, therefore it must be identified which parameter is most influential in the BCR uncertainty.

The cost of measures influences the benefit-cost ratio directly. Gersonius et al. (2008) found that the cost was the most influential parameter for the benefit-cost ratio in their study and the inundation depth-frequency relationship was not decisive for the relative performance of measures. However, Gersonius et al. (2008) maintained similar inundation depths up to which the measures were effective. In this study there is a differentiation between dry-proofing and wet-proofing, making it more dependant on the predicted inundation depth. Although there is uncertainty in the costs due to the heterogeneity of buildings, this aleatory uncertainty is expected to decrease when larger number of objects are considered. Based on the current estimated costs of 8,000 euro for dry-proofing, still sufficient margin in the benefit-cost ratio exist for most areas where dry-proofing is advised. It is therefore expected that the influence of the uncertainty of the costs is lower than the uncertainty in the expected benefits. In addition, cost estimates are of a similar order with the research (Gersonius et al., 2008). In their research 8,650 euro (price level 2021) was estimated for dry-proofing and

20,000 euro for wet-proofing. This is similar to the average costs in The Geul catchment of 8,000 euro for dry-proofing and in the same order of magnitude as 15,000 euro for wet-proofing.

The uncertainty of the benefits is based on the product of the effectiveness of measures and the initial risk estimate. The effectiveness of measures is presented with a range of 17% for wet-proofing and 40% for dry-proofing. The estimate is prone to epistemic uncertainties due to the transfer of foreign survey results that are applied in The Netherlands. Given the wide ranges, it was decided to include the full range in the assessment, instead of using an average reduction factor. Therefore it is expected that the effect on the benefit-cost ratio is sufficiently described.

The initial risk estimate is based on the product of hazard, exposure and vulnerability. The number of objects in the area is assessed reliable, while the maximum damage of an object is again prone to aleatory uncertainty. Overall the effect of uncertainties in the exposure component is judged low by Wagenaar et al. (2015). It is therefore expected not to be a decisive factor in the BCR for the whole catchment, given the high number of objects. However, for the advices on a neighbourhood level the aleatory uncertainty can increase again and any expected local deviations should be accounted for.

The influence of depth-damage function uncertainty was calculated in the sensitivity analysis and led to 13%-19% increase of the initial risk estimate. For a 13% increase the benefit-cost ratio responded on average with a 20% increase, showing high sensitivity. The histogram of the inundation maps indicated that the majority of the locations is exposed to inundation below 1 meter. The findings of Wagenaar et al. (2015); Jongman et al. (2012) show that depth-damage uncertainty is higher for low inundation depths an only after 0.8 meter decreases. This means that for the majority of the area the depth-damage function is prone to this uncertainty. In addition, epistemic uncertainty does not decrease, but propagates for larger number of objects.

Regarding the hazard component, the majority of the flood extent of the used hazard maps aligned with the Sobek model from Deltares. Also given the incised valleys of the catchment the extent is assumed reliable, which is directly related to a reliable number of objects that is exposed. The inundation depth and probability of occurrence is prone to an unknown uncertainty, increasingly for the T=1000 year inundation map, albeit that uncertainties for higher return periods have a lower share in the initial risk assessment. Despite the uncertainty in the inundation depth, it is estimated that this is less than the depth-damage function uncertainty.

Concluding, the depth-damage function is expected to have the highest share in the uncertainty of the BCR, followed by the inundation map.

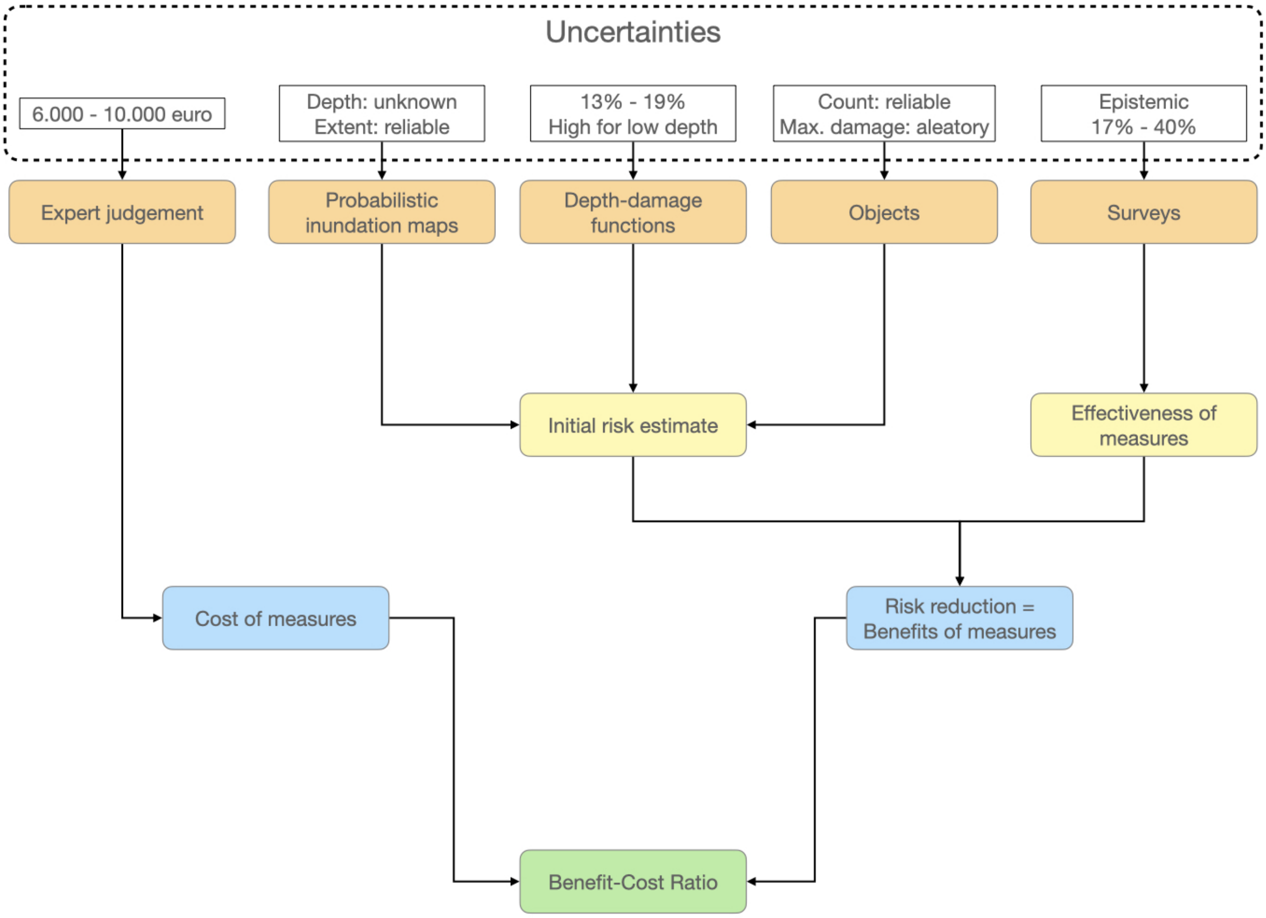


Figure 8.1: Model components, sources and uncertainty

9 Conclusion

The Geul catchment suffered from high damages after a flood event in July 2021. Under the influence of climate change and economical investments, flood risk is expected to increase. It is difficult to cope with this trend and to reduce the probability of flooding. A major complication is the challenging landscape, with incised valleys and fast flowing rivers. This thesis identified improvements in the flood risk reduction strategy, thereby increasing the resilience of the area, through private mitigation measures. Two flood-proofing measures are found to be applicable in the area for residential objects and shops. Dry-proofing houses was applicable in most places with favourable benefit-cost ratios. Wet-proofing is applicable in more selected areas with higher inundation depths. It is determined that implementing measures in the top 40% of residential objects most at risk, can reduce residential flood risk by 47%. Focussing on the top 20% of shops reduced flood risk by 31%. The corresponding benefit-cost ratios are 1.3-2.2 and 1.1-1.5 for the residential category and commercial category respectively. If indirect damages would be included, the benefit-cost ratios will increase.

A shift in Flood Risk Management is observed from protective measures only to a water system where resilience plays a more important role. By the principles of the Protection Motivation Theory and results from survey studies in other areas, the connections between resilience and awareness, preparedness and self-reliance are determined. Communication of risk alone and thus creating high awareness can increase the threat appraisal but does not necessarily lead to the implementation of private measures. This theory was confirmed in an interview, where a resident with high awareness and willingness to implement dry-proofing measures, did not take action. It is important to advise residents about the expected effect of measures and in addition provide clear instructions about instalment to create a high coping appraisal. Current means of communication to residents do not meet these requirements and improvement is suggested. The information can be communicated by the water board or insurance companies and will increase preparedness and self-reliance. In addition, intangible damages are expected to be lower for those affected with measures installed, also decreasing recovery time.

Quantification of the effect of resilience measures proves to be difficult and is therefore often described qualitatively. As a consequence, resilience measures are difficult to include in a monetary based risk assessment. Despite these difficulties, a method is applied to describe the risk reducing effect of private measures. Thereto a connection is identified between the implementation of measures and damage reduction. Reduction rates are derived for flood-proofing measures and connected to the existing risk assessment method SSM-2017. With a validation of the flood event in July 2021, the method is calibrated to approach estimates within 5 million euro. Subsequently the probabilistic Liwo inundation maps are used and after adjustments applicable for the area. Finally, a tool is developed to simulate different scenarios of distribution of the measures and the complete method is applicable in other areas in The Netherlands.

To represent the effect of high awareness or strong guidance, the measures are implemented at the objects with the highest expected damage. These are compared with randomly distributed measures to represent the current situation with little specific guidance. The results show that high awareness or good guidance can increase the effectiveness of measures by a factor 2.7. The used method proved to be robust to derive the type of measure that was most effective at a certain location. The calculated benefit-cost ratios are prone to more uncertainty and should be interpreted carefully. Nevertheless, with a detailed review of the inundation depths, the presence of a positive benefit-cost ratio could be determined with more accuracy for most investigated villages. Despite the uncertainties it is determined that for multiple areas the benefits of dry-proofing clearly outweigh the cost. Therefore the implementation is considered a "no regret" measure. The results show that private measures can have an important role in the reduction strategy of the Geul catchment, but to be effective, clear guidance is needed by the water board or flood risk experts.

10
Recommendations

The recommendations are separated in two section: first recommendations for practice and further research are given, secondly recommendations regarding improvements of the used method are given.

10.1. Recommendations for practice and further research

Improve the Water in Balance program leaflet with the expected effect of measures and clear guidance on instalment.
A relatively inexpensive method to stimulate the motivation of private actors to implement measures, is to better align the leaflet with the principles of the Protection Motivation Theory.

Identify local reduction factors of measures.
Based on the literature study it was found that little data on the effect of measures is available. Given the relatively high exposure to flooding in Limburg, it is expected that households are present in the area with measures in place. Surveys can identify location specific damage reduction factors, potentially reducing the uncertainty that was introduced with the use of foreign data. It is an unique opportunity to gather location specific data for an extreme event in the Netherlands and can also contribute on an European level.

Investigate the effect of private measures in an integral assessment combining the first and second layer of the Multi Layer Safety approach.
A further elaboration on this topic can provide insight if private flood mitigation measures can also be implemented as a means to reach the flood safety standards, in areas where measures to prevent flooding are difficult or expensive. This can again be focussed on the effectiveness and cost-efficiency of private measures, but should also include the policy and standards in the province. It can be used to further inform the water board about the feasibility of the Mechelderbeek project.

Include the temporal scale of flood risk with future urban development and climate change scenarios
In the this thesis the Expected Annual Damage is a fixed parameter. Under the influence of climate change and urban development the benefit-cost ratio of private measures can potentially increase.

Investigate structural capacity of buildings.
In literature, generally a limit of 1 meter is maintained for dry-proofing. The water board Limburg expressed concerns about the structural capacity of buildings during flooding, with special interest towards basement floors.

Derive reduction factors for other categories and indirect and intangible damages.
In the initial risk assessment other categories were found in the top 10 most at risk. Specific measures for these categories can be beneficial. Furthermore the effect of measures on indirect damages was not included. Given the expected high indirect damages this can improve the cost-efficiency of private measures. Finally the relationship between damage reduction and intangible damages is worthwhile exploring.

10.2. Recommendations for improvement of method

Use an inundation model with higher resolution.
It was found that the resolution of 25 meter could lead to large overestimations on the spatial scale of the catchment. Using a higher resolution can reduce this error. Especially for recommendations on a small spatial scale a resolution of at least 5 meter is advised.

Improve cost estimate of measures and provide better specification of measure types.
The cost are estimated based on one project in Limburg. Furthermore dry-proofing and wet-proofing remains a broad concept and can be seen as a category of measures. Better discretization of types of measures and their cost can improve the communication towards private actors by more specific advised.

Construct location specific depth-damage functions based on insurance data.
The depth-damage functions are prone to high epistemic uncertainties. Insurance data is available that could provide a better validation of the function. However, given the time frame of the study and legal constraints, it was not possible to access and use the data.

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A

Interview documents

A.1. Example interview questions

General:

- How long do you live in your current house?
- Did you ever experience flooding on this address or any other, before the July 2021 flooding?

Awareness

- Could you give an estimate what your chances are of experiencing a flood event?
- Before the flood event in 2021, did you consider yourself prepared to avoid damage?
- Have you been warned or informed by local government about flood risk? If yes, how did this communication took place.

July 2021

- Did your town/village experience flooding during the event in July 2021?
- Did water enter or reached your house?
- What was the maximum water level in or at your property?
- During the flooding, how long did it take before the water level reached its maximum, after the water entered? How long did it take before the water withdrew from your property?
- Have you been warned before or during the flooding, if yes, how long did it take from the moment of warning until water reached your property?

(Indirect) damages

- Did you suffer material damages because of the flood event, if yes, what kind of damage?
- What is your estimate of the total damage value?
- How was the damage recovery process for your house organised?
- When was your house fully recovered or when do you expect this to be?
- Do you currently still suffer any disturbance from the flooding? If yes, in what way?
- What was personally the biggest impact of the event for you?

Self-reliance & preparedness

- Which measures did you take to prevent damages due to flooding? Either reactive of preventive.
- Do you expect to implement measures in the near future?
- How difficult do you think it is to implement measures?
- Do you have any conditions to implement measures? Such as subsidies or discount on insurance?
- Did you ever own a flood insurance?
- How well prepared do you consider yourself currently?

Future

- What do you expect to be the consequences of climate change for your flood risk?
- Do you expect compensation from the government for a potential new flood event?

A.2. Informed consent form

U wordt uitgenodigd om deel te nemen aan een onderzoek genaamd "Bewustzijn en voorbereiding bij overstromingen". Dit afstudeeronderzoek wordt uitgevoerd door Sven Suijkens, student van de TU Delft, in samenwerking met Sweco Nederland. De resultaten zullen verwerkt worden in een afstudeerrapport, vrij toegankelijk via de TU Delft bibliotheek (https://repository.tudelft.nl/).

Het doel van dit onderzoek is om te achterhalen in hoeverre bewoners in het stroomgebied van de Geul zich bewust waren van de overstromingsrisico's, welke voorbereidingen zij getroffen hebben in juli 2021 en welke eventuele maatregelen men bereid is te nemen in de toekomst en zal ongeveer 30 minuten in beslag nemen. De gegevens zullen gebruikt worden voor het ontwikkelen van een strategie om de overstromingsrisico's in het stroomgebied van de Geul te beperken. U wordt gevraagd om uw ervaring met de overstroming(en) te delen en vragen te beantwoorden over (privé) maatregelen en opgelopen schade.

Uw deelname aan dit onderzoek is volledig vrijwillig. Vragen over uw persoonlijke ervaringen en toekomstverwachtingen als gevolg van klimaatverandering kunnen mogelijk emotioneel belastend zijn en u kunt zich elk moment terugtrekken zonder reden op te geven. U bent vrij om vragen niet te beantwoorden. Onderzoekdata kan worden verwijderd binnen 2 maanden na afname van het interview.

Van het interview zal een verslag worden geschreven en alleen met uw toestemming kunnen foto's worden gemaakt voor publicatie in het afstudeerrapport. De foto's kunnen door u beoordeeld worden en direct worden verwijderd indien gewenst. Het onderzoek eindigt op 1 september 2022 en voor uw deelname bestaat geen compensatie. Alle gegevens zullen anoniem verwerkt worden om het risico op identificatie via persoonlijk identificeerbare informatie te minimaliseren. Persoonlijke informatie die kan leiden tot identificatie zal niet door de onderzoeker gedeeld of gepubliceerd worden. Tevens worden alle gegevens opgeslagen op een beveiligde harde schijf en worden alle gegevens verwijderd op 1 september 2022. Sweco Nederland heeft geen toegang tot onderzoeksgegevens en heeft geen actieve rol binnen het onderzoeksgebied.

Contactgegeven voor het onderzoek is: s.p.c.suijkens@student.tudelft.nl

Met het tekenen van dit document bevestigt u bekend te zijn met bovenstaande informatie.

Handtekeningen

________________________ ________________________ ________

Naam deelnemer Handtekening Datum

Ik, **de onderzoeker**, verklaar dat ik de informatie en het instemmingsformulier correct aan de potentiële deelnemer heb voorgelezen en, naar het beste van mijn vermogen, heb verzekerd dat de deelnemer begrijpt waar hij/zij vrijwillig mee instemt.

________________________ __________________ ________

Naam onderzoeker Handtekening Datum

Contactgegevens van de onderzoeker voor verdere informatie: s.p.c.suijkens@student.tudelft.nl

Figure A.1: Informed consent form interview.

B
Python scripts

In this appendix all used Python scripts are listed. Several parts of the code are open source and downloaded from stackoverflow.com.

B.1. Depth-damage function adjustment

```
import pandas as pd


df = pd.read_csv('DDF.csv')
print(df)

dfObj = pd.DataFrame(columns=['wd(m)', 'Factor'])

pos = df.shape[0]
for x in range(pos):

if df['wd(m)'][x] <= 1 :
new = df['Factor'][x] * 0.4
dfObj = dfObj.append({'wd(m)': df['wd(m)'][x], 'Factor': new }, ignore_index=True)


if df['wd(m)'][x] > 1 :
dfObj = dfObj.append({'wd(m)': df['wd(m)'][x], 'Factor': df['Factor'][x] },
ignore_index=True)

dfObj.to_csv('DDF_V1.csv', index=False)
```

B.2. Randomize rasters

```
from osgeo import gdal, ogr, os, osr
import numpy as np


def array2raster(newRasterfn,rasterOrigin,pixelWidth,pixelHeight,array):

cols = array.shape[1]
rows = array.shape[0]
originX = rasterOrigin[0]
originY = rasterOrigin[1]

driver = gdal.GetDriverByName('GTiff')
outRaster = driver.Create(newRasterfn, cols, rows, 1, gdal.GDT_Float32)
outRaster.SetGeoTransform((originX, pixelWidth, 0, originY, 0, -pixelHeight))
outband = outRaster.GetRasterBand(1)
outband.WriteArray(array)
outRasterSRS = osr.SpatialReference()
outRasterSRS.ImportFromEPSG(28992)
outRaster.SetProjection(outRasterSRS.ExportToWkt())
outband.FlushCache()


def main(newRasterfn,rasterOrigin,pixelWidth,pixelHeight,array):
reversed_arr = array[::-1] # reverse array so the tiff looks like the array
array2raster(newRasterfn,rasterOrigin,pixelWidth,pixelHeight,reversed_arr)
# convert array to raster

#---------------------
#---------------------

## INFORMATION INTRODUCED BY THE USER

number_maps = 20 # Here you specify how many random maps you want to generate
fraction_of_coverage = [0.2, 0.4, 0.6]

#---------------------
#---------------------

for y in fraction_of_coverage:

x=1
while x<=number_maps:

nums_ini = np.ones(994) # Extent of research area is 994x737
#number_of_zeros = int(994 * fraction_of_zeros)
number_of_zeros = int(994 * (1-y))
nums_ini[:number_of_zeros] = 0
np.random.shuffle(nums_ini)
nums_ini2 = np.ones(994)
nums_ini2[:number_of_zeros] = 0
np.random.shuffle(nums_ini2)

nums_ini3 = np.append([nums_ini],[nums_ini2],axis= 0)
```

```
nrows = 0

while nrows < 737:
nums = np.ones(994)
nums[:number_of_zeros] = 0
np.random.shuffle(nums)
nums_ini3 = np.append(nums_ini3,[nums],axis= 0)
nrows = nrows + 1

#---------------------

if __name__ == "__main__":
rasterOrigin = (176850,324625)
pixelWidth = 25
pixelHeight = 25
percentage_coverage = int(y*100)
name = 'random'
newRasterfn = f'{percentage_coverage}_{name}_V{x}.tif'
nums_ini3 = nums_ini3[::-1,:]
array = nums_ini3


main(newRasterfn,rasterOrigin,pixelWidth,pixelHeight,array)
x = x+1
```

B.3. Scenario A

```
import numpy as np
from osgeo import gdal, ogr, os, osr
from PIL import Image
import rasterio


# INPUT INFORMATION DEFINED BY USER
#---------------------------------
structure_type = "laag" # choose: laag, eeng, winkel
risk_file = Image.open('laag_risk.tif') # base risk map without measures
opp_file = Image.open('laag_opp.tif') # for winkel insert for both 'winkel.tif'
aant_file = Image.open('laag_aant.tif') # for winkel insert for both 'winkel.tif'

top_percent = 0.6 # input here which percentage you want to investigate

# CALCULATION PROCESSES
#---------------------------------

top_percent_num = int(top_percent * 100)
remaining_num = 100-top_percent_num


myarray = np.array(risk_file)
myarray1 = np.array(risk_file)
houses = np.array(opp_file)
houses_inv = np.array(opp_file)
houses_2 = np.array(aant_file)
```

```
houses_2_inv = np.array(aant_file)

myarray_flattened = myarray.flatten()
non_zero = np.count_nonzero(myarray_flattened)

n=round(non_zero*top_percent)
non=non_zero - n
top = myarray_flattened[np.argsort(myarray_flattened, axis=0)[-n:]]

zero = myarray_flattened.size - np.count_nonzero(myarray_flattened)
initial = zero + 1
fin = myarray_flattened.size - top.size
no_top = myarray_flattened[np.argsort(myarray_flattened, axis=0)[initial:fin]]


for x in range(739):
for y in range(994):

exists = myarray[x][y] in top
if exists == True:
myarray[x][y] = myarray[x][y]
else:
myarray[x][y] = 0

#-------------------------
for a in range(739):
for b in range(994):

exists = myarray[a][b] in top
if myarray[a][b] > 0:
houses[a][b] = houses[a][b]
else:
houses[a][b] = 0

#-------------------------
for a in range(739):
for b in range(994):

exists = myarray[a][b] in top
if myarray[a][b] > 0:
houses_2[a][b] = houses_2[a][b]
else:
houses_2[a][b] = 0

#-------------------------------
#-------------------------------

for a in range(739):
for b in range(994):

exists1 = myarray1[a][b] in top
if exists1 == True:
myarray1[a][b] = 0
else:
myarray1[a][b] = 1
```

```
#------------------------
for a in range(739):
for b in range(994):

if myarray1[a][b] > 0:
houses_inv[a][b] = houses_inv[a][b] * myarray1[a][b]
else:
houses_inv[a][b] = 0

#------------------------
for a in range(739):
for b in range(994):

if myarray1[a][b] > 0:
houses_2_inv[a][b] = houses_2_inv[a][b] * myarray1[a][b]
else:
houses_2_inv[a][b] = 0



#------------------------------------
#------------------------------------


def array2raster(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array):

cols = array.shape[1]
rows = array.shape[0]
originX = rasterOrigin[0]
originY = rasterOrigin[1]

driver = gdal.GetDriverByName('GTiff')
outRaster = driver.Create(newRasterfn, cols, rows, 1, gdal.GDT_Float32)
outRaster.SetGeoTransform((originX, pixelWidth, 0, originY, 0, -pixelHeight))
outband = outRaster.GetRasterBand(1)
outband.WriteArray(array)
outRasterSRS = osr.SpatialReference()
outRasterSRS.ImportFromEPSG(28992) #28992 7415
outRaster.SetProjection(outRasterSRS.ExportToWkt())
outband.FlushCache()


def main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array):
reversed_arr = array[::-1] # reverse array so the tif looks like the array
array2raster(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, reversed_arr)
# convert array to raster



# RASTER TIF SAVING
#----------------------------------

if __name__ == "__main__":
rasterOrigin = (176850,324625) #306150
pixelWidth = 25
pixelHeight = 25
```

```
name = 'risk'
newRasterfn = f'{structure_type}_{name}_T{top_percent_num}.tif'
myarray = myarray[::-1,:]
array = myarray

main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array)






if __name__ == "__main__":
rasterOrigin = (176850,324625)    #306150
pixelWidth = 25
pixelHeight = 25
name = 'opp_measures'
newRasterfn = f'{structure_type}_{name}_T{top_percent_num}.tif'
houses = houses[::-1,:]
array = houses

main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array)


if __name__ == "__main__":
rasterOrigin = (176850,324625)
pixelWidth = 25
pixelHeight = 25
name = 'opp_measures'
newRasterfn = f'{structure_type}_{name}_TO{remaining_num}.tif'
houses_inv = houses_inv[::-1,:]
array = houses_inv

main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array)


# #----------------------


if __name__ == "__main__":
rasterOrigin = (176850,324625)    #306150
pixelWidth = 25
pixelHeight = 25
name = 'aant_measures'
newRasterfn = f'{structure_type}_{name}_T{top_percent_num}.tif'
houses_2 = houses_2[::-1,:]
array = houses_2

main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array)


if __name__ == "__main__":
rasterOrigin = (176850,324625)
pixelWidth = 25
pixelHeight = 25
name = 'aant_measures'
```

```
newRasterfn = f'{structure_type}_{name}_TO{remaining_num}.tif'
houses_2_inv = houses_2_inv[::-1,:]
array = houses_2_inv

main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array)
```

B.4. Scenario B

```
import numpy as np
from osgeo import gdal, ogr, os, osr
from PIL import Image
import rasterio
import glob, os


# INPUT INFORMATION DEFINED BY USER
#----------------------------------

structure_type = "laag"
risk_file_code = "60_random_V*.tif"
opp_file = Image.open('laag_opp.tif')
aant_file = Image.open('laag_aant.tif')


#PROCESS CALCULATION
#----------------------------------

lst=[]
for file in glob.glob(risk_file_code):
lst.append(file)

for raster_file in lst:

# CALCULATION PROCESSES
#----------------------------------
raster_file_noext = os.path.splitext(raster_file)[0]
version = raster_file_noext.partition("V")[2]
top_percent_num  = int(raster_file[0:2])
remaining_num = 100 - top_percent_num


risk_file = Image.open(raster_file)
myarray = np.array(risk_file)
myarray1 = np.array(risk_file)
houses = np.array(opp_file)
houses_inv = np.array(opp_file)
houses_2 = np.array(aant_file)
houses_2_inv = np.array(aant_file)



#-----------------------
for a in range(739):
for b in range(994):
```

```
if myarray[a][b] > 0:
houses[a][b] = houses[a][b]
else:
houses[a][b] = 0

#------------------------
for a in range(739):
for b in range(994):

if myarray[a][b] > 0:
houses_2[a][b] = houses_2[a][b]
else:
houses_2[a][b] = 0

#------------------------------
#------------------------------

for a in range(739):
for b in range(994):

if myarray1[a][b] > 0:
houses_inv[a][b] = houses_inv[a][b] * 0 #myarray1[a][b]
elif houses_inv[a][b] > 0:
houses_inv[a][b] = houses_inv[a][b]
else:
houses_inv[a][b] = 0
#------------------------
for a in range(739):
for b in range(994):

if myarray1[a][b] > 0:
houses_2_inv[a][b] = houses_2_inv[a][b] * 0
elif houses_inv[a][b] > 0:
houses_2_inv[a][b] = houses_2_inv[a][b]
else:
houses_2_inv[a][b] = 0


#-----------------------------------
#-----------------------------------


def array2raster(newRasterfn,rasterOrigin,pixelWidth,pixelHeight,array):

cols = array.shape[1]
rows = array.shape[0]
originX = rasterOrigin[0]
originY = rasterOrigin[1]

driver = gdal.GetDriverByName('GTiff')
outRaster = driver.Create(newRasterfn, cols, rows, 1, gdal.GDT_Float32)
outRaster.SetGeoTransform((originX, pixelWidth, 0, originY, 0, -pixelHeight))
outband = outRaster.GetRasterBand(1)
outband.WriteArray(array)
#outband.SetNoDataValue(0)
outRasterSRS = osr.SpatialReference()
```

```
outRasterSRS.ImportFromEPSG(28992) #28992 7415
outRaster.SetProjection(outRasterSRS.ExportToWkt())
outband.FlushCache()


def main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array):
reversed_arr = array[::-1] # reverse array so the tif looks like the array
array2raster(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, reversed_arr)
 # convert array to raster



# RASTER TIF SAVING
#--------------------------------

if __name__ == "__main__":
rasterOrigin = (176850,324625) #306150
pixelWidth = 25
pixelHeight = 25
name = 'opp_measures'
newRasterfn = f'{structure_type}_{name}_R{top_percent_num}_V{version}.tif'
#newRasterfn = 'eeng_opp_measures_T20.tif'
houses = houses[::-1,:]
array = houses

main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array)


if __name__ == "__main__":
rasterOrigin = (176850,324625)
pixelWidth = 25
pixelHeight = 25
name = 'opp_nomeasures'
newRasterfn = f'{structure_type}_{name}_RO{remaining_num}_V{version}.tif'
#newRasterfn = 'eeng_opp_measures_TO80.tif'
houses_inv = houses_inv[::-1,:]
array = houses_inv

main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array)


#---------------------


if __name__ == "__main__":
rasterOrigin = (176850,324625) #306150
pixelWidth = 25
pixelHeight = 25
name = 'aant_measures'
newRasterfn = f'{structure_type}_{name}_R{top_percent_num}_V{version}.tif'
#newRasterfn = 'eeng_aant_measures_T20.tif'
houses_2 = houses_2[::-1,:]
array = houses_2

main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array)
```

```
if __name__ == "__main__":
rasterOrigin = (176850,324625)
pixelWidth = 25
pixelHeight = 25
name = 'aant_nomeasures'
newRasterfn = f'{structure_type}_{name}_RO{remaining_num}_V{version}.tif'
#newRasterfn = 'eeng_aant_measures_TO80.tif'
houses_2_inv = houses_2_inv[::-1,:]
array = houses_2_inv

main(newRasterfn, rasterOrigin, pixelWidth, pixelHeight, array)
```

B.5. Post processing FIAT data

```
import pandas as pd
import glob, os
import csv
from pathlib import Path


os.chdir('C:/.../residential') #specify folder with the risk text files from FIAT

lst=[]
for file in glob.glob(os.path.join('*.txt')):
lst.append(file)

name_list = []
max_list = []
min_list = []
percentage_file = []


for fiat_file in lst:

#file_name = os.path.splitext(fiat_file)[0]
file_name = Path(fiat_file).stem
name_list.append(file_name)
data_original = pd.read_csv(fiat_file, sep = "=", header=None, engine='python')

data_category = data_original.iloc[:-2]
data_sum = data_category.groupby([2]).sum()

risk_initial = 2050257 # residential risk without measures
#risk_initial = 693927      # commercial risk without measures
risk_reduc = risk_initial - data_sum
risk_reduc_perc = (risk_reduc/risk_initial)*100

maximum = risk_reduc_perc.max()
max_list.append(maximum)

minimum = risk_reduc_perc.min()
min_list.append(minimum)

final_list = pd.concat([data_sum, risk_reduc, risk_reduc_perc, maximum, minimum],
```

```
ignore_index=True, axis = 1)
final_list.columns = ['Sum', 'Risk_reduc', 'Risk_reduc_perc', 'max', 'min']
final_list.to_csv(f'{file_name}_analysis_step1.csv')


risk_reduc_perc.columns = [file_name]
percentage_file.append(risk_reduc_perc)


name_list = pd.DataFrame(name_list)
max_list_2 = pd.DataFrame(max_list)
min_list_2 = pd.DataFrame(min_list)
maxmin_list = pd.concat([name_list, min_list_2, max_list_2], axis = 1)
maxmin_list.columns = ['Name', 'Min_perc', 'Max_perc']

maxmin_list.to_csv('max_min_list.csv')

percentage_file = pd.concat(percentage_file, axis = 1)
percentage_file.to_csv('percentage_file.csv')
```

C

Sensitivity analysis data

In this appendix the results of the relative risk reduction per measure and the calculated benefit-cost ratios are presented, based on the original non-adjusted input parameters of the SSM-2017 model. These original values are used in the sensitivity analysis of section 6.7.

C.1. Initial relative risk reduction

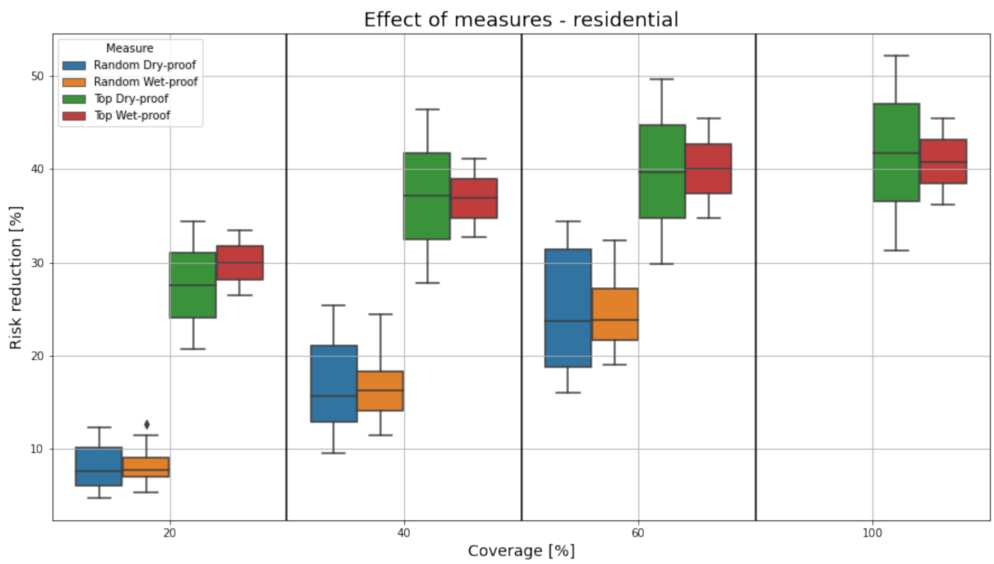

Figure C.1: Initial calculated relative risk reduction per measure and scenario within residential category.

C.2. Initial benefit-cost ratios

Table C.1: Initial benefit-cost ratios residential category per measure and scenario

Scenario	Coverage [%]	Dry-proof low	Dry-proof High	Wet-proof low	Wet-proof high
Top	20	1.3	2.2	1.1	1.4
Random	20	0.5	1.1	0.3	0.6
Top	40	1.1	1.8	0.8	1.0
Random	40	0.5	1.1	0.3	0.6
Top	60	0.8	1.3	0.5	0.7
Random	60	0.5	1.1	0.4	0.6
Full	100	0.6	1.0	0.4	0.5

D

Benefit-cost ratio explanatory notes

D.1. Cost calculation wet-proofing

Table D.1: Average areas residential object and cost wet-proofing

Description	Value	Measure	Cost [€]
Average living space	150 m^2		
Estimate footprint	60 m^2		
Floors	60 m^2		
Walls	65 m^2		
Basement floor	30 m^2	Impregnation basement walls	100 /m^2
Basement walls	55 m^2	Water-resistant paint living room	25-40 /m^2
Basement walls	22 m	Tile floor	100 /m^2
Power outlets	6	Replacement power outlet	60-300 /outlet

Based on the values in table D.1 the cost for an average house without basement is 9,320 euro and with a basement 14,520 euro. Scaled towards the living area this corresponds to 62 - 97 euro per m^2 living space. In the final estimate the value is rounded to 100 euro per m^2 living space to include provisional costs. Given the large presence of basements in the Geul catchment, the higher estimate is used.

D.2. Benefit-cost ratio calculation

Table D.2: Benefit-cost ratio calculation values Scenario A: Top

Scenario: Top 20	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	63,050	63,050
Number of objects [-]	485	485	-	-
Total cost [M €]	3.88	3.88	6.31	6.31
Risk reduction [M €/yr]	0.40	0.67	0.50	0.64
Future benefits [M €]	5.86	9.77	7.21	9.25
NPV [M €]	1.98	5.89	0.91	2.95
BCR [-]	1.5	2.5	1.1	1.5
Scenario: Top 40	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	108,861	108,861
Number of objects [-]	812	812	-	-
Total cost [M €]	6.50	6.50	10.89	10.89
Risk reduction [M €/yr]	0.58	0.97	0.65	0.83
Future benefits [M €]	8.50	14.17	9.39	12.01
NPV [M €]	2.00	7.67	-1.50	1.12
BCR [-]	1.3	2.2	0.9	1.1
Scenario: Top 60	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	165,782	165,782
Number of objects [-]	1,211	1,211	-	-
Total cost [M €]	9.69	9.69	16.58	16.58
Risk reduction [M €/yr]	0.64	1.06	0.69	0.89
Future benefits [M €]	9.26	15.43	10.07	12.88
NPV [M €]	-0.43	5.74	-6.51	-3.70
BCR [-]	1.0	1.6	0.6	0.8
Scenario: Full	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	247,758	247,758
Number of objects [-]	1,705	1,705	-	-
Total cost [M €]	13.64	13.64	24.78	24.78
Risk reduction [M €/yr]	0.68	1.14	0.73	0.94
Future benefits [M €]	9.91	16.52	10.68	13.67
NPV [M €]	-3.73	2.88	-14.10	-11.11
BCR [-]	0.7	1.2	0.4	0.6

Table D.3: Benefit-cost ratio calculation values Scenario B: Random

Scenario: Random 20	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	47,668	51,142
Number of objects [-]	334	355	-	-
Total cost [M €]	2.672	2.84	4.7668	5.1142
Risk reduction [M €/yr]	0.10	0.27	0.11	0.27
Future benefits [M €]	1.46	3.87	1.60	3.93
NPV [M €]	-1.21	1.03	-3.17	-1.18
BCR [-]	0.6	1.4	0.3	0.8
Scenario: Random 40	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	91,334	109,467
Number of objects [-]	655	764	-	-
Total cost [M €]	5.24	6.11	9.13	10.95
Risk reduction [M €/yr]	0.21	0.54	0.24	0.50
Future benefits [M €]	3.11	7.83	3.47	7.23
NPV [M €]	-2.13	1.72	-5.66	-3.72
BCR [-]	0.6	1.3	0.4	0.7
Scenario: Random 60	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	144,045	152,008
Number of objects [-]	1,044	1,072	-	-
Total cost [M €]	8.35	8.58	14.40	15.20
Risk reduction [M €/yr]	0.35	0.75	0.38	0.65
Future benefits [M €]	5.14	10.89	5.59	9.51
NPV [M €]	-3.22	2.31	-8.82	-5.69
BCR [-]	0.6	1.3	0.4	0.6

D.3. Benefit-cost ratio calculation location specific

Table D.4: Benefit-cost ratio calculation values location specific

Valkenburg Centre	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	50,440	50,440
Number of objects [-]	359	359	-	-
Total cost [M €]	2.87	2.87	5.04	5.04
Risk reduction [M €/yr]	0.21	0.34	0.27	0.35
Future benefits [M €]	2.98	4.97	3.86	5.15
NPV [M €]	0.11	2.09	-1.18	0.11
BCR [-]	1.0	1.7	0.8	1.0
Valkenburg Neerhem	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	21,667	21,667
Number of objects [-]	182	182	-	-
Total cost [M €]	1.46	1.46	2.17	2.17
Risk reduction [M €/yr]	0.02	0.04	0.09	0.12
Future benefits [M €]	0.32	0.54	1.36	1.70
NPV [M €]	-1.13	-0.92	-0.81	-0.47
BCR [-]	0.2	0.4	0.6	0.8
Schin op Geul	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	8,849	8,849
Number of objects [-]	54	54	-	-
Total cost [M €]	0.43	0.43	0.88	0.88
Risk reduction [M €/yr]	0.04	0.07	0.03	0.04
Future benefits [M €]	0.58	0.97	0.49	0.59
NPV [M €]	0.15	0.54	-0.40	-0.29
BCR [-]	1.4	2.2	0.6	0.7
Eys	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	7,703	7,703
Number of objects [-]	55	55	-	-
Total cost [M €]	0.44	0.44	0.77	0.77
Risk reduction [M €/yr]	0.05	0.09	0.04	0.05
Future benefits [M €]	0.78	1.30	0.60	0.72
NPV [M €]	0.34	0.86	-0.17	-0.05
BCR [-]	1.8	3.0	0.8	0.9
Gulpen	**Dry-proof low**	**Dry-proof high**	**Wet-proof low**	**Wet-proof high**
Area [m^2]	-	-	17,615	17,615
Number of objects [-]	152	152	-	-
Total cost [M €]	1.22	1.22	1.76	1.76
Risk reduction [M €/yr]	0.07	0.12	0.06	0.07
Future benefits [M €]	1.01	1.68	0.84	1.08
NPV [M €]	-0.21	0.46	-0.92	-0.68
BCR [-]	0.8	1.4	0.5	0.6