# Preparing polders for extreme weather events: Strategies to reduce flooding

Bachelor Thesis


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UNIVERSITY OF TWENTE.

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Lieke Nannes (s2615592)

University of Twente
June 26, 2023

# Preface

This report presents the findings of my Bachelor thesis ´Preparing polders for extreme weather events: Strategies to reduce flooding´. This thesis forms my final research assignment for the three years Bachelor program Civil Engineering at the University of Twente.

This research has been conducted at SAWA Wateradvies in collaboration with Hoogheemraadschap Hollands Noorderkwartier from April 11th until June 25th. I did research into a topic that gets more and more significant these days. Moreover, the topic has a lot in common with my interest. By interpreting the results of flood models, you are the link between science and society, which I really enjoy.

I would like to specially thank my supervisor Rick Hogeboom from the University of Twente. The feedback helped guide me in the right direction and challenged me to keep shaping the research.

I would like to thank SAWA Wateradvies for giving me the opportunity to graduate within their cooperation. In particularly, I would like to thank Anne Leskens for the guidance throughout the research by providing feedback and direction. I would also like to thank Bart van Lier for helping me getting acquainted with 3Di in such a short timeframe.

Finally, I hope you enjoy reading this thesis. If you have any comments or question regarding this thesis, feel free to contact me.

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# Executive summary

The goal of this thesis is to investigate how flooding in polders during the preparation phase of an extreme weather event can be reduced, taking climate change into account. This research emerges from the identified gap in literature, where it is indicated how flooding can be reduced by implementing structural measures, but limited to no research has been done into measures that can be employed in the preparation phase of an extreme weather event. Moreover, research has been done on how to protect polders from fluvial flooding, but less research is done into which measures can be taken to protect for flooding caused by extreme precipitation events.

In this research, the Zijpepolder is used as a case study to test how flooding can be reduced in polders during the preparation phase of an extreme weather event. The Zijpepolder has experienced flooding due to an extreme precipitation event in June 2021.

To accomplish the aim of this research, it was first investigated what possible measures could be taken in polders during the preparation phase of an extreme weather event to reduce flooding. Secondly, the measures were tested and assessed using a multi criteria analysis. Then, a sensitivity analysis was performed, in which the area-specific terrain characteristics were varied. This sensitivity analysis was used to generalise the results of the Zijpepolder to an advice on how to reduce flooding in polders in general.

To investigate which measures could potentially reduce flooding, expert interviews were conducted and literature research was done. By applying these methods, four measures appeared to possibly reduce flooding in polders. These measures were; creating a water level buffer, activating the old mills in the area, installing temporary flood barriers, and installing emergency pumps.

To investigate which of these measures is most effective in reducing flooding, the measures were assessed on their performance using a multi criteria decision analysis. Flood duration, maximum water level, flood damage, and inundated area were used as criteria. To test the measures for these criteria, the 3Di hydrodynamic flood modelling program was used. Climate change was taken into account by choosing to test the measures for precipitation scenarios of 2050. From this multi criteria decision analysis, the water level buffer measure appeared to be most effective with a score of 1.86. The emergency pumps measure, the activating old mills measure, and the temporary flood barriers measure, scored 1.08, 0.74, 0.32 respectively. The major difference in the performance of the water level buffer measure and the emergency pumps measure could be found in the maximum water level criteria. The water level buffer measure scores 0.80 here and the emergency pumps measure scores 0.18.

To check for uncertainties in the model results, a sensitivity analysis for the water level buffer measure was performed. For this sensitivity analysis the infiltration rate, the storage capacity, the friction, and the interception capacity were varied over a range from -30% to +30%. It appeared that especially the flood duration and the maximum water level were highly sensitive for a decrease in infiltration rate. A decrease in infiltration rate of 30% led to an increase of 103.3% and 24.3% for flood duration and maximum water level respectively.

A flow chart and the sensitivity analysis were used to form an advise for the Zijpepolder on the reduction of flooding. Subsequently, a broader recommendation was given for polders in general. There can be concluded that, to reduce flooding of polders during the preparation phase preceding an extreme weather event, taking climate change into account, the water level buffer measure is on average most effective. More specifically, the water level buffer appeared to be most effective in reducing the flood duration and the maximum water level in polders. Activating the old mills

appeared to be most effective in reducing flood damage, and the emergency pumps measure appeared to be most effective in reducing the inundated area. For areas with a reduced infiltration rate, or a reduced storage capacity compared to the Zijpepolder, the water level buffer measure is significantly less effective. With this conclusion, the research objective has been achieved.

Due to the limited timeframe of this study, decisions were made that could potentially affect the results of the research. To determine the flood duration and maximum water level, five locations within the polder were chosen to be tested. These locations directly influence the results of the flood duration and the maximum water level. When different test locations were used, it might be possible that the results would have been different. That is why it is recommended for future research to test more locations within the polder to check if the water level buffer measure then still appears to be most effective.

There is also recommended to do further research into the effects of the water level buffer measure on its surroundings. There are risks associated with draining the polder during summer. If the precipitation then falls in the adjacent polder, the whole polder will be dry. Future research should critically weigh the risks of this measure against the benefits. In this way, it can be decided if and how this measure can be put into practice safely.

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# 1. Introduction

## 1.1. Background

Extreme weather events have become increasingly frequent in recent years due to the changing climate. This causes significant problems all over the world. Areas are increasingly flooded which has its impacts on the surroundings. It does damage to properties and infrastructure but it also impacts the social and economic sectors. A study on the changes in future flood risk due to climate and socioeconomic change, found that ‘the annual expected losses may increase by between 96 and 917% by the year 2040 compared to 2000’ (Bouwer, Bubeck, & Aerts, 2010, p. 463). Moreover, ‘the temperature perturbation under present land use conditions increases precipitation amounts by on average 7-8% and amplifies precipitation intensity during summers in the Netherlands’ (Daniel, Lenderink, Hutjes, & Holtslag, 2016, p. 4129). Currently, polders in the Netherlands are not well prepared for these kinds of extreme precipitation events.
While polders have been a successful way of reclaiming land, they are vulnerable to flooding during excessive precipitation, because they are low lying areas. This causes the water to not naturally flow away. Polders are thus dependent on pumps and pumping stations to drain the water that has not infiltrated into the ground. Pumps do have their maximum capacity, which often proofs to be insufficient during an extreme weather event. Given the increasing frequency of extreme weather events, there arises a need to devise a strategy on how to protect polders from flooding.

This thesis will therefore investigate the research question ‘How can flooding of polders be reduced during the preparation phase preceding an extreme weather event, taking climate change into account?’. Extreme weather events refer here to situations in which excessive rainfall occurs. Flooding due to other extreme weather events are beyond the scope of this project. The preparation phase of the extreme weather event refers to the two-day period preceding the extreme weather event.

## 1.2. Current state of the research field

In previous research, various studies have focused on developing strategies to reduce flooding in vulnerable areas. These studies have employed modelling methods to visualise possible flooding scenarios. Additionally, these researches have investigated different measures that can help to protect against flooding. Furthermore, evaluation methods have been proposed that can assess these measures. These three topics will be discussed below.

### 1.2.1. Flood models

There are various methods and models that can be used to model floods. These models can be roughly subdivided in empirical methods, simplified (non-physics-based) models, and hydrodynamic models (Teng, et al., 2017).

Empirical methods use data of the past to make predictions about the future. A common disadvantage of empirical models is the need for experimental data. This is what also makes these models only valid and applicable within the context of the modelled experiment and its corresponding operating conditions. Therefore, the capabilities of the predictions as outcome of the model are limited (Ashoor, Giwa, & Hasan, 2019). An advantage of empirical models is that they provide relative accurate results for the specific case of the implemented experimental data. Moreover, they often have a short computation time as they are based on relatively simple mathematical relationships (Heiyanthuduwage, Mounoury, & Kovacevic, 2011).

Simplified models use simplified hydraulic equations. A disadvantage is that these models are not able to simulate the flood (Teng, et al., 2017). However, its advantage is that it has short computational time compared to other models and ‘it can produce high approximate predictions of final inundation distributions’ (Teng, et al., 2017, p. 206).

Hydrodynamic models are based on solving equations using laws of physics (Teng, et al., 2017, p. 203). A disadvantage is that in order to make a hydrodynamic model many terrain specific data is needed, which is not accessible for everyone. An advantage is that hydrodynamic models produce high resolution outcome for many timesteps along the simulation process .

For this study a hydrodynamic model will be used. In hydrodynamic models the Digital Elevation Map (DEM) is used to accurately route the flow of water (Damayanti, 2011). That is what makes these models most commonly used in flood modelling. There are many types of hydrodynamic models available nowadays. In this research, the 3Di program will be used, since the company is licensed for it.

### 1.2.2. Flood reducing measures

The literature identifies several measures that can reduce flooding. This include measures which reduce both the chance and consequences of pluvial as well as fluvial flooding. These measures are, compartmentalisation (Klijn, Asselman, & Van der Most, 2010), self-reliance of citizens (Baan & Klijn, 2003), nature-based solutions (Huang, Tian, Ke, Liu, & Irannezhad, 2020), and the concept of transitional polders (Weisscher, Baar, & Van Belzen, 2022). These measures are discussed below.

Klijn, Asselman, & Van der Most (2010), researched the effectiveness of compartmentalisation of polder areas on the reduction of the flood consequences. This method would reduce the area subject to flooding, which reduces economic damage and the number of people exposed to flooding. Since it was proven that compartmentalisation can effectively reduce the consequences of flooding, they did further research into under which conditions and where a further compartmentalisation would be helpful. The most important aspects for this study that they found are mentioned below;

- Compartmentalisation appeared especially effective for large dike ring areas in case of dike breaches.
- Compartmentalisation is most effective when it is combined with other measures such as installing outlets along rivers, implementing varying levels of protection for different places, and creating evacuation plans.

Baan & Klijn (2003), examined that in order to reduce flooding, government policies against flooding should be combined with increasing the self-reliance of Dutch citizens. Following this, Botzen, Aerts, & van den Bergh (2009), researched the willingness of homeowners to take measures themselves to reduce local flood risk is performed. According to this study, a significant amount of homeowners are willing to make investments to reduce flood risk;

- Two out of three people are willing to invest in water barriers (sandbags) for premium flood risk reduction.
- One out of five people is willing to change to replace floor types that are vulnerable to flooding with water resistant floor types.
- One out of four people is willing to move central heating installations to floors which are safe against flooding in favour of a reduction in the insurance premium.

For a case study of a dike ring area in the Netherlands, the effectiveness of these mitigation measures appeared to be able to limit flood damage in the order of hundreds of million euros (Botzen, Aerts, & van den Bergh, 2009).

Huang, Tian, Ke, Liu, & Irannezhad (2020), did research to the effect of nature-based solutions for urban pluvial risk management. They found that nature-based solutions could effectively mitigate flooding caused by high-frequently precipitation events. However, they also found that nature-based solutions are less effective for flooding caused by extreme precipitation events over a short period of time. With nature-based solutions they refer to solutions such as green roofs, permeable pavements and increasing infiltration rates.

Weisscher, Baar, & Van Belzen (2022), addressed the concept of transitional polders. Transitional polders serve as a dual-purpose approach, mitigating flood risk while also managing land-level rise. This method includes a temporary opening of a dike-protected area to the tide to capture sediment until it surpasses the mean sea level. This appeared to be an expensive way of flood protection.

### 1.2.3. Evaluation method of flood reducing measures

In order to make a choice in how flooding can be reduced in the preparation phase of an extreme weather event, a systematic evaluation on the implemented flood reducing measures should be performed. There is no leading framework that should be used. However, the multi criteria analysis is the most commonly used framework to evaluate the performance of different alternatives. 'It is a powerful tool used widely for evaluating and ranking problems containing multiple criteria' (Isisklar & Büyüközkan, 2007). The multi criteria decision making tool offers decision makers the flexibility to choose the alternative that fits their criteria best (Kumar, et al., 2017). This can be done by assigning the criteria weights depending on their importance.

## 1.3. Research gap

As outlined above, several studies have focussed on the reduction of flooding in polders. These investigations have primarily focused on protecting polders against flooding from rivers and dike breaches. However, there is a notable absence of research focusing on floodings caused by excessive precipitation specific for polders. Moreover, non of them mentioned how flooding could be reduced specifically in the preparation phase preceding such an extreme precipitation event. The measures studied, are mainly measures that need much time to become operational

## 1.4. Research objective and research questions

The objective of this research is ''to investigate how flooding of polders during the preparation phase preceding an extreme weather event can be reduced, taking climate change into account''.

Flooding is defined as pluvial flooding. This means that only floodings which occur because of extreme precipitation events are taken into account. The preparation phase of the extreme weather event refers to the two-day period preceding the extreme weather event.

In this research, the Zijpepolder will be used as a case study to test how flooding in polders can be reduced during the preparation phase of an extreme weather event.

Based on the research objective, the main research question with the sub questions can be formulated. The sub questions function as a structure to follow in order to answer the main question. If the main question is answered, the research objective is fulfilled.

**Main research question is: How can flooding of polders be reduced during the preparation phase preceding an extreme weather event, taking climate change into account?**

**Sub questions:**

1. What are potentially effective measures to reduce flooding in polders, that can specifically be taken, during the preparation phase preceding an extreme weather event.

2. How effective are these measures for a case study of the Zijpepolder?
    a. How can these measures be modelled in 3Di?
    b. What flood prevention measure is most effective in the Zijpepolder in reducing flooding?
    c. What uncertainties are associated with the model results?

3. What lessons can be drawn from modelling flood prevention measures for the Zijpepolder case study that can be applied to polders in general?

## 1.5. Reading guideline

Chapter 2 explains the study area and gives an elaboration on the model that is used. Chapter 3 describes the methodology that has been used to answer the sub questions. Chapter 4 presents the results and in chapter 5, a critical discussion is given on the results and how the methodology that has been used has affected the results. Finally, in chapter 6, a conclusion will be given and the recommendations are described.

# 2. Case study and model description

In this chapter, first the case study is discussed. Second, the polder water management system of the Netherlands is discussed. To test different measures that would potentially be effective in reducing flooding, measurement locations were chosen to test the flood duration and the maximum water level, which are among others used as criteria for the multi criteria decision analysis. To understand why these locations are chosen, it is essential to understand the process of how the water is drained from the polder. After this, a detailed model description is given in order to be able to understand how 3Di determines the surface water runoff. Finally, the used data with their types and sources are described.

## 2.1. Case study

In this research, the Zijpepolder will be used as a case study to test how flooding in polders can be reduced. A description of the study area is given below.

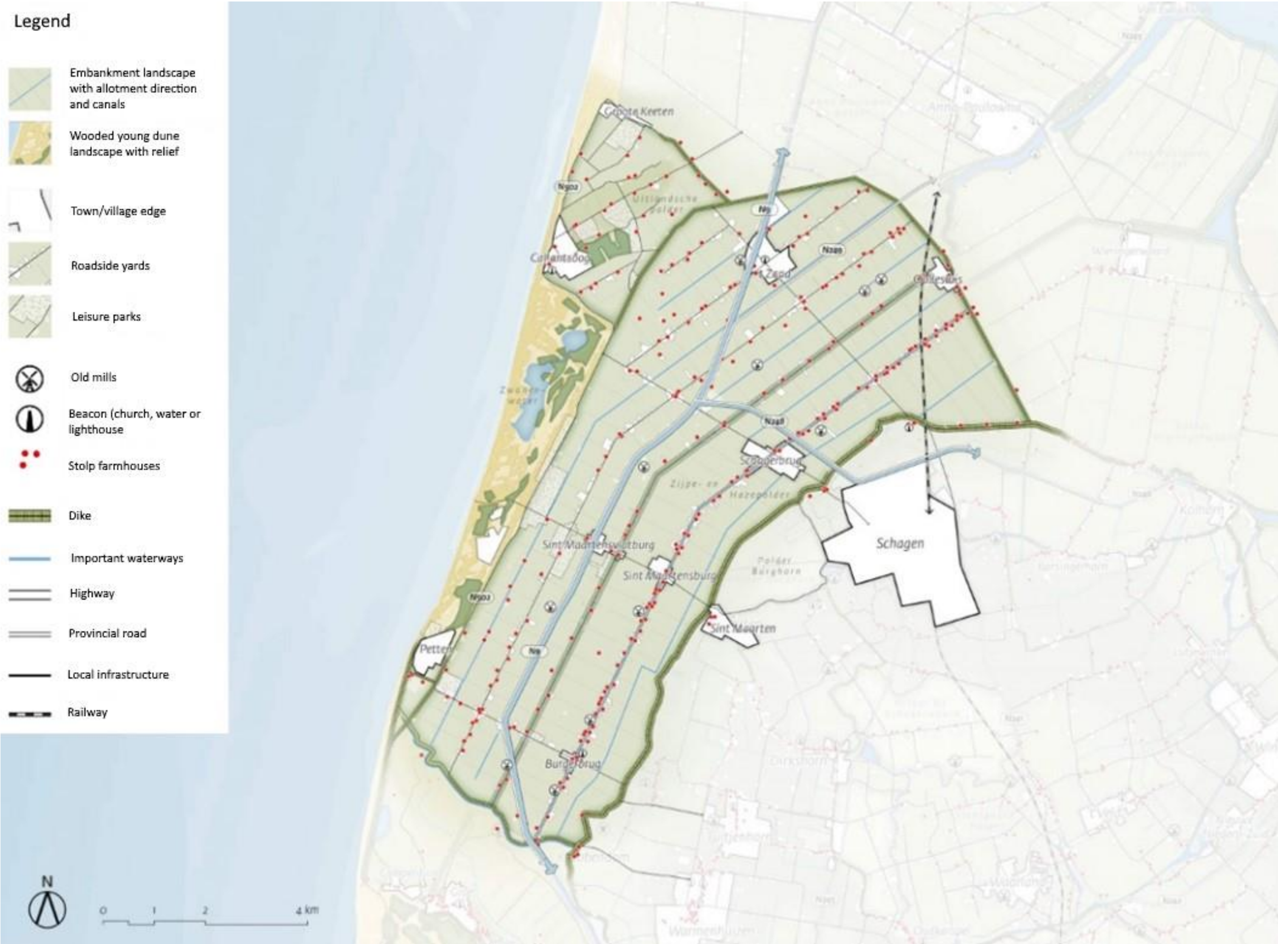


*Figure 1: Map which gives an overview of the Zijpepolder (Noord-Holland, Provincie, 2018).*

The Zijpepolder, located in the North West of Noord-Holland, is the result of the first diking and reclamation of a polder of size in North Holland' (Noord-Holland, Provincie, 2021). The polder consists of a grid of long North South oriented buckled polder lines, roads perpendicular to them with villages settled at the intersections of the polder ribbons and cross roads (Noord-Holland, Provincie, 2018). In figure 1, a map of the overview of the area is shown.

An important ambition and developing principle of the province for the Zijpepolder is to cherish and strengthen the character of the long polder lanes. This means that they want to preserve the characteristic buildings and planting along the lanes and that they do not want to make any changes in the shape of the polder lanes. In figure 2, an overview of the different polder lanes is shown. The widest polder lane is het Grote Sloot, which is located in the East of the polder. Others are the Ruigeweg and the Belkmerweg. The North Holland Canal runs through the polder from South to North and crosses the grids diagonally in the north. This canal functioned as the connection between Amsterdam and the North Sea (Noord-Holland, Provincie, 2018).

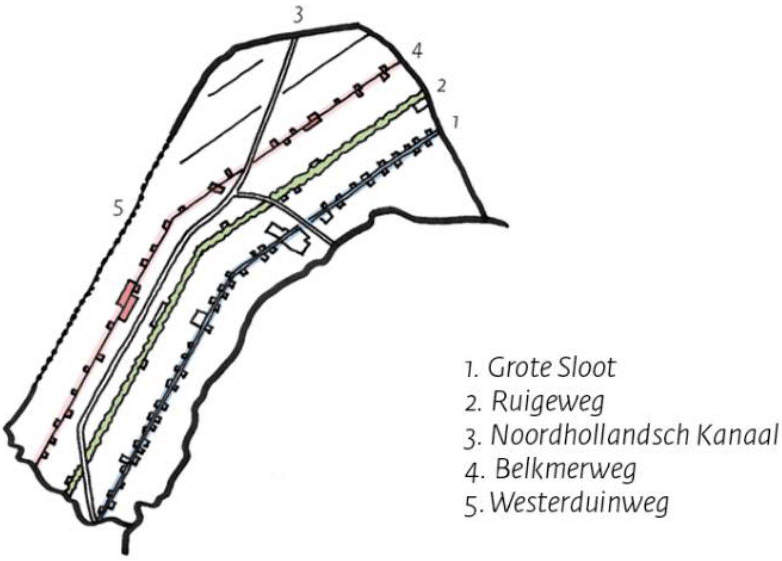


*Figure 2: Map in which the polder lines are indicated with their names (Noord-Holland, Provincie, 2018).*

At the left side of the polder a beach is located, which gradually overflows into a dune landscape. This dune landscape is widening towards the north. There, the nature reserve Zwanenwater is located. This is a dune landscape interspersed with wet valleys. Both the Zwanenwater and the Pettemerduinen, located in the south of the area, are part of the Natura-2000 areas. This means that they are among Europe's protected natural areas (Groenendrijk & de Rooij, 2017).
The dune landscape is separated from the polder by the Hondbossche and Pettermer dike. At the Northern side the polder is surrounded by the Zijper(zee) dike and the Slikker dike. At the right side the polder is surrounded by the Westfriese Omringdijk and at the South the polder is surrounded by the Oude Schroolse Zeedijk. In figure 3, an overview of the surrounded dikes of the Zijpepolder is shown. In the picture can also be seen that several mills are located in the area. These mills helped reclaim the area. 'They retained their function for a long time until they were decommissioned between 1950 and 1966' (Noord-Holland, Provincie, 2018).

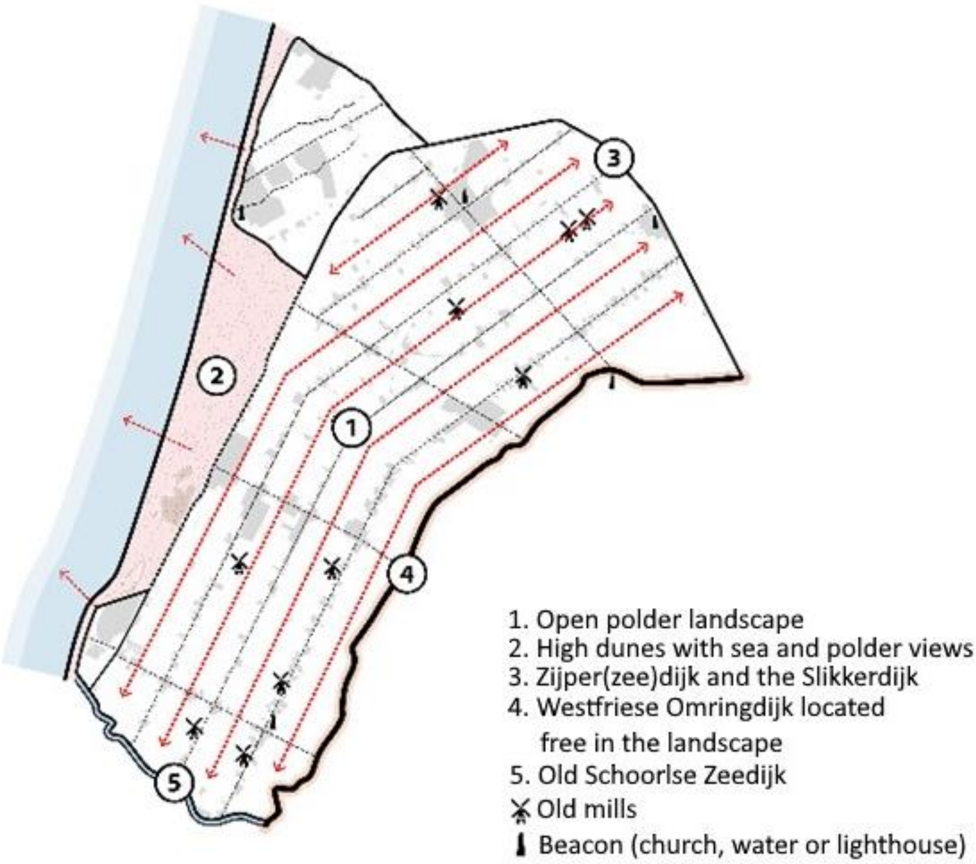


*Figure 3: Map which gives an overview of the surrounding dikes (Noord-Holland, Provincie, 2018).*

The area has a gradient in elevation and in soil type from West to East. At the West side the area has a higher elevation which decreases towards the East. The soil type in the Western part of the area is sand and changes more towards clay in the East (Gemeente Zijpe). This also has its effects on the infiltration capacity of the area. The infiltration capacity in the West is higher than the infiltration capacity in the East. Bulb cultivation mainly takes place on the western side of the area. The eastern area is used as grassland for agricultural area and farms (Noord-Holland, Provincie, 2018).

In the area close to Schagen the 'Duikersluis van de Burghorn' is located. This lock is designed to drain excessive water in an area. 'However, the lock can only function for water management if the water level behind the lock (the inland water) is higher than the water level in front of the lock (the outside water)' (Stichting Historische Sluizen en Stuwen, Nederland, sd). Also, the Lock 'Kolksluis 't Zand' is located in the area. However, this lock is intended to help for shipping and has no water management function.

## 2.2. Polder water management system in the Netherlands

Since this research will specifically focus on reduction of flooding in polders, there will be briefly examined here how the water management system works in polders in the Netherlands. Every polder has a similar water management system. It must be designed in such a way that it is able to store and drain excessive precipitation and seepage from the dikes. Moreover, it should be able to supply water in times of drought (Schultz, waterbeheersing van een polder, 2022).

All polders consist of the same kind of water management system in which the water is drained from the polder to a larger receiving water body. A water management system roughly consists out of three components. The first is the dewatering system. This drains water from the ground or from the farmland by subsurface pipe drains into the collector drains (Schultz & Wandee, Some practical aspects of the new policy on water management in the Netherlands polders, 2003). The second component of the water management system is the drainage system. With this system, the water is drained from the collector drain through sub-main drains and main drains. This is then drained into the third system, the discharge system. This system moves the water outside the polder, to the receiving waterbody. This is often done using locks and pumping stations. In this way, water levels in the polders can be kept manageable in times of precipitation (Schultz, waterbeheersing van een polder, 2022). A schematic overview of the water management systems in polder can be seen in figure 4.

Discharging water from polders during high water levels or flooding therefore also has a major impact on water levels outside the polders. However, this study will specifically focus on water levels and water drainage within the polder. How this affects the water levels of the receiving waterbody will not be considered here.

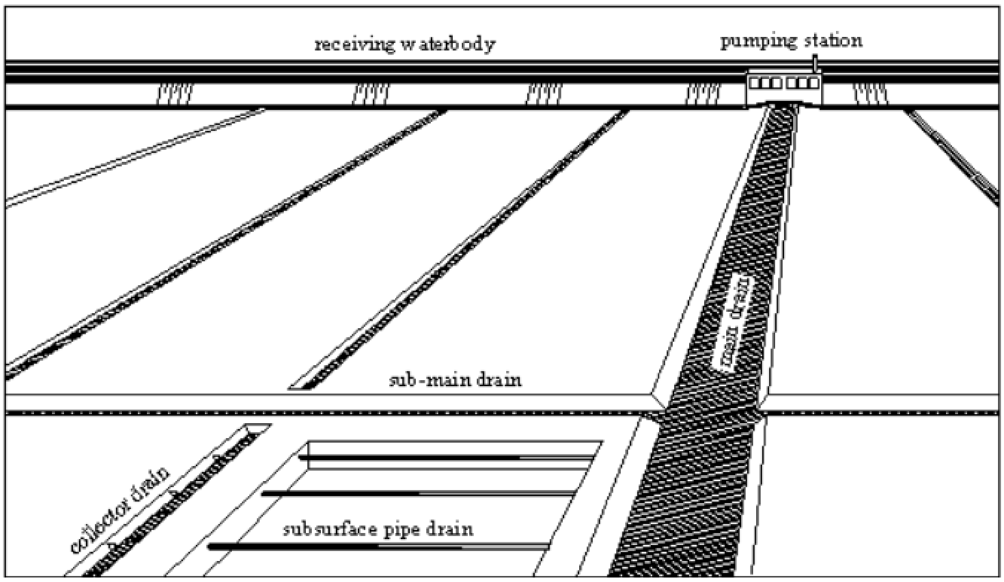


Figure 4: Schematic overview of a polder water management system (Schultz & Wandee, Some practical aspects of the new policy on water management in the Netherlands polders, 2003).

## 2.3. Model description

To model the effectiveness of flood prevention methods, the 3Di modelling program will be used to simulate different flooding scenarios in this research. In this section an explanation is given on how the model works.

### 2.3.1. From input data to simulation results

3Di is a program in which interactive flood simulations can be made for both urban and polder areas. This program has the possibility to provide a realistic and detailed simulation of the water flow in an area in a short time (van Luijtelaar, 2014).

3Di works with a schematisation of the reality. This schematisation includes all information that 3Di needs in order to create a calculation grid and sub grid tables. The data for the schematisation is based on the real world data and is subdivided in data that is processed in rasters, vector based information and schematisation settings. The raster data includes for example the Digital Elevation Model (DEM). The vector based info includes for example the sewer network and in the schematisation settings you can make choices about the grid size among others. It is possible to build more than one version of the schematisation. These other versions are called revisions. Each revision can be converted into a 3Di model. The 3Di model together with the scenario information creates the simulation. The scenario information adds knowledge on for example wind conditions, which is called forcing, information on precipitation events, initial condition and on the simulation settings. From the simulation, the results can be derived (Nelen&Schuurmans, Basic Modelling Concepts, 2023). In figure 5, an overview of the modelling concept, which is just explained, is given.

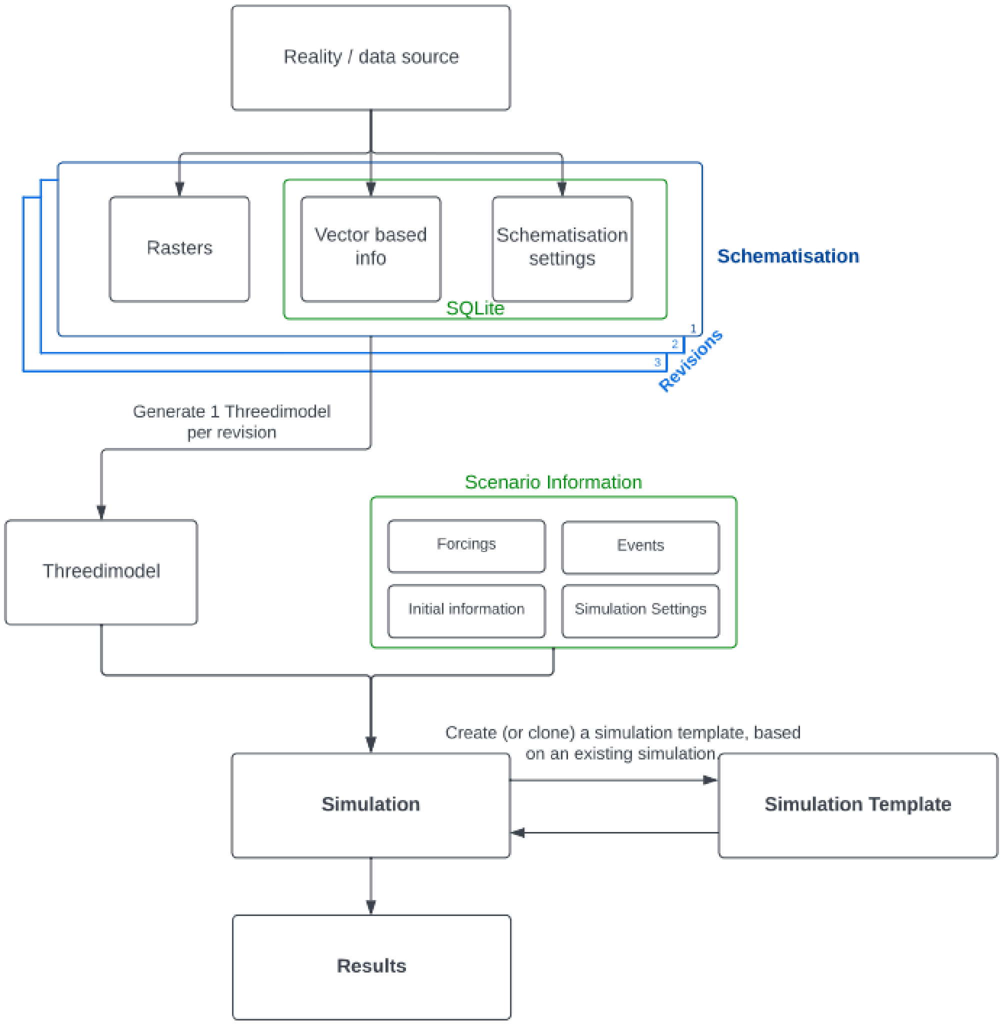


*Figure 5: Schematic overview of the modelling process in 3Di (Nelen&Schuurmans, Grid, 2023).*

### 2.3.2. Surface water

In order to define space in 3Di, staggered grids are used. This makes the surface water domain divided in perfect squares. In these squares the velocity and discharge are determined at the edge and the volume is determined in the centre of the square. There is assumed to be a uniform water level within one square. It is possible to require a refiner resolution for areas you want to know about in more detail. Normally, the refinements are done by dividing the neighbouring cells by 4 (Nelen&Schuurmans, Grid, 2023). This creates the possibility to know four different water levels for for example an area of 1000 $m^2$, while somewhere else you know only one water level for an area of 1000 $m^2$.

Since a flow is strongly affected by the bathymetry of the region, it is important to have trustworthy data of the bathymetry. However, when using accurate information about the bathymetry, the computational time of the model gets high. To get an optimal balance between computation time and accuracy, the subgrid method is implemented in 3Di (Nelen&Schuurmans, Grid, 2023). The difference between the traditional method and the subgrid method is that in the traditional method it was assumed, just as for the water level, that there was a uniform height within one square. For the subgrid method, it is allowed to have different values of the bathymetry within one square. This makes it possible for a square to be partly wet instead of only wet or dry. In figure 6, an example is shown of a bathymetry defined on a subgrid within one square for the water level (Nelen&Schuurmans, Grid, 2023).

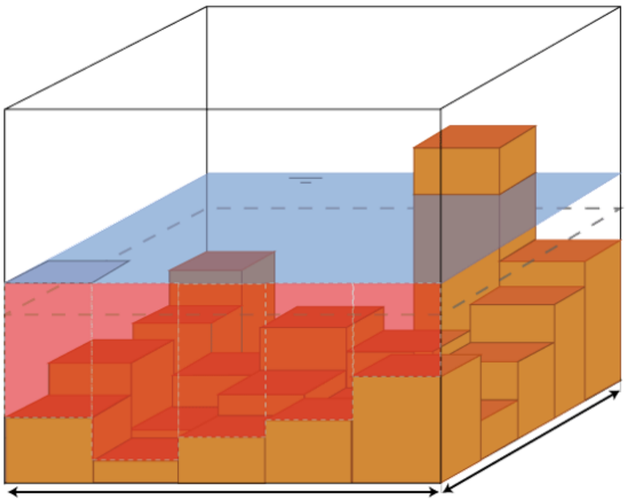

*Figure 6: Sub-grid method (Nelen&Schuurmans, Grid, 2023).*

### 2.3.3. Time steps

3Di analyses and computes changes to the water system in discrete time intervals, which are called time steps. The model divides the entire simulation period into smaller steps. This allows precise tracking of the water system dynamics. The size of the time steps in 3Di are variable and are dependent on many different factors, such as the complexity of the water system, but also the required accuracy. Overall, smaller time steps make it possible to generate more accurate results. However, smaller time steps also increase the computational time.

For the model that is used in this research, 3Di uses a default value for the simulation time step of 15 seconds. This means that every 15 seconds the changes in the water system are analysed and applied to the internal calculation.

The default output time step for this model is 300 seconds. The standard output indicates how often the model saves the results and exports this for visualisation. Therefore, the smaller the value of output time step is, the more time steps are visualised and the more accurate the results are.

### 2.3.4. Zijpe North

A model encompassing the entire Zijpepolder area does not exist, because the computation time would then have become too big. Instead, three distinct models have been developed; Zijpe West, Zijpe North, and Zijpe South. In this research, the Zijpe North model will be used due to its relatively short computation time compared with the other two models. Whenever the Zijpepolder results are mentioned in the remainder of this report, it will specifically refer to the results of Zijpe North. The area of Zijpe North is shown in the figure 7.

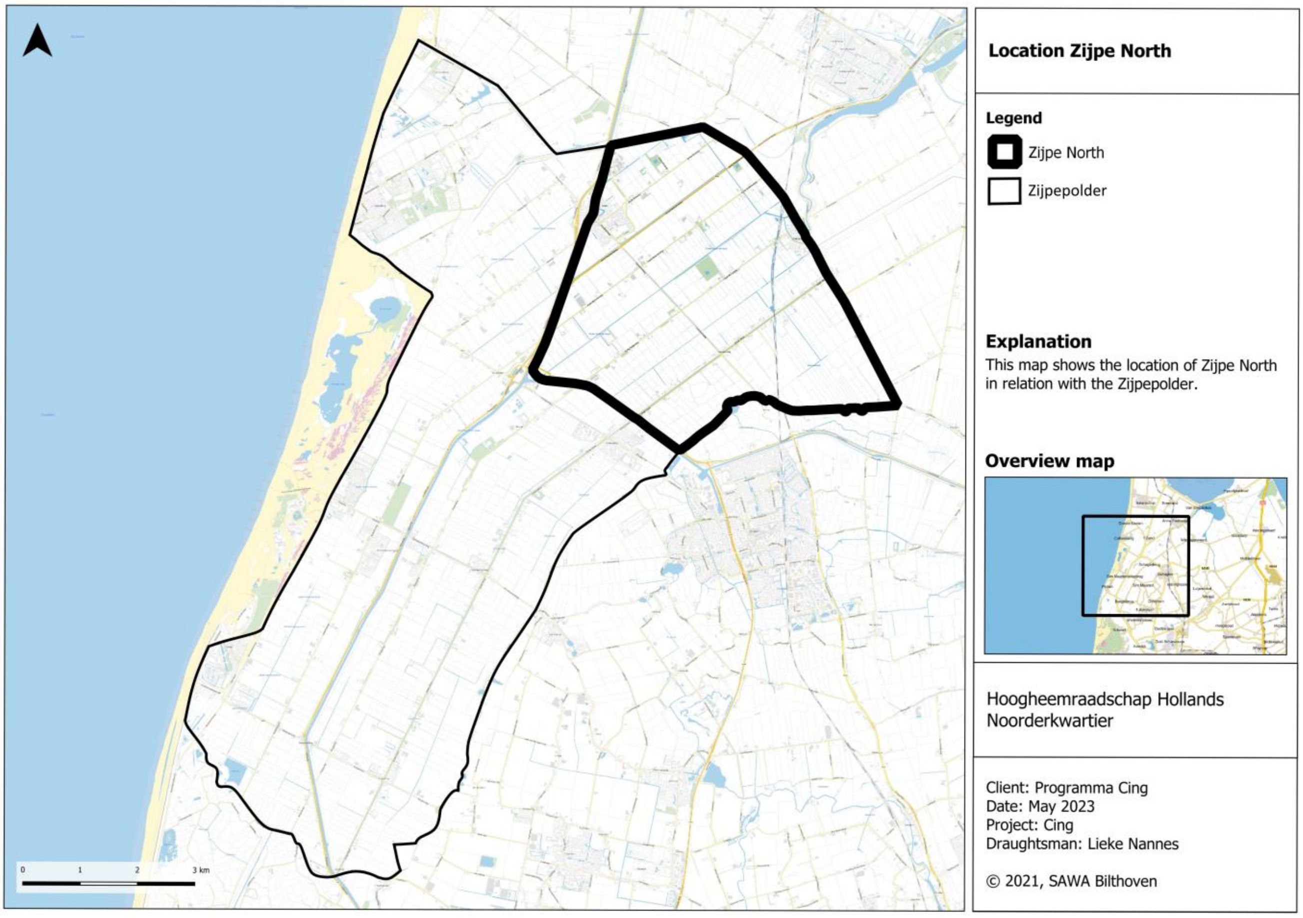


*Figure 7: Location Zijpe North in relation with the Zijpepolder*

## 2.4. Data

This section discusses what data is included in the model, the data type, and the source of the data.

For this model, five rasters are used. These are also called the terrain characteristics and include the Digital Elevation Model (DEM) , the infiltration rate raster, the storage raster, the friction raster and the interception raster. The DEM data is sourced from the Actueel Hoogtebestand Nederland (AHN), which is provided by the Publieke Dienstverlening Op de Kaart (PDOK). All other rasters are made and provided by Hoogheemraadschap Hollands Noorderkwartier (HHNK). A more detailed explanation of what the terrain characteristics entail can be found in section 3.4.

The most important vector based information that is used in this model are the levees, the pumps and pump station locations, and the channel locations. The data for pumps and pumping station include information of the location of the start node, which is called the suction side of the pump, and information of the location of the end node, which is called the delivery side of the pump. The data for the levees, the pumps and pumping station locations, and the channel locations all come from Data Afspraken Modelmatig Ondersteund (DAMO). This is the overarching data model of and for the water boards.

In order to test the measures that will follow from the first research question, the model in which the measures are implemented need to be tested for a realistic amount of precipitation. Therefore, the precipitation data from the Stichting Toegepast Onderzoek Waterbeheer (STOWA) will be used (Beersma et al., 2019). The duration of the precipitation is variable and the intensity of the precipitation is dependent on the chosen return period.

An overview of the used data with their type and source can be seen in table 1.

*Table 1: Overview of the data used in the model with their type and source.*

| | **Type** | **Source** |
|---|---|---|
| Digital Elevation Model (DEM) | Raster | AHN (PDOK) |
| Infiltration rate | Raster | HHNK |
| Storage capacity | Raster | HHNK |
| Friction | Raster | HHNK |
| Interception capacity | Raster | HHNK |
| Levees | Vector-based information | DAMO |
| Pumps and pumping stations | Vector-based information | DAMO |
| Channels | Vector-based information | DAMO |
| Precipitation | Time series | STOWA |

# 3. Method

In this chapter, a detailed elaboration is given on what methods are used to answer the research questions.

## 3.1. Investigating potentially effective measures to reduce flooding (RQ 1)

In order to determine what possible flood reducing measures could be implemented to reduce flooding, different methods were used. There was first determined what measures are currently being taken to reduce flooding during the preparation phase of an extreme weather event, then there was examined what additional measures could be effective in polders to reduce flooding in the preparation phase of an extreme weather event. Both of these components were answered using two research methods; desk research and expert interviews.

Thus, to determine what measures that are currently being taken in reducing flooding during the preparation phase preceding an extreme weather event in the Zijpepolder, desk research was first conducted. Also, expert interviews were conducted. Applying both of these methods gave the opportunity to have two different views regarding the situation. The desk research method was mainly theoretically oriented due to the limited practical information available in academic documentation. With the expert interviews, practical knowledge from the profession was emerged, which led to new insights.

For answering what additional measures could be effective in reducing flooding in the preparation phase of an extreme weather event, also both desk research and expert interviews were conducted.

For the expert interviews, two semi-structured interviews were conducted. There was chosen for semi-structured interviews to provide the experts with a clear outline of what the research is about and what was expected from them. The interview consisted out of more or less seven questions. For these questions, also sub questions were made, which could be asked if the experts did not come up with that answer themselves.

## 3.2. Modelling flood reducing measures in 3Di (RQ 2a)

The measures found in RQ 1, were implemented in 3Di by giving the most accurate representation of reality possible. In order to be able to do that, there had been thoroughly investigated how the programme works by following the basic tutorials offered by 3Di.

## 3.3. Selection of most effective measure in reducing flooding in the Zijpepolder (RQ 2b)

To evaluate the possible flood reducing measures, a multi criteria decision analysis was performed. Below, firstly, an elaboration is given on how the measures were tested for the criteria flood duration, maximum water level, flood damage, and inundated area, which were used in the multi criteria decision analysis. In previous studies, often the damage was used as criteria to assess the effectiveness of the measures (Benoit, Forget, & Jean, 2003) and (de Moel, van Vliet, & Aerts, 2014). However, in the way that 3Di calculates damage, a uniform inundation duration is used. Therefore, the damage on itself, would give an incomplete picture of the effectiveness of measures. That is why flood duration, maximum water level and the inundated area are also included. Secondly, there will be explained for what precipitation scenarios the measures were tested and how climate change is taken into account here to conclude with an explanation of the setup of the multi criteria decision analysis.

### 3.3.1. Flood duration

The first factor for which the measures were tested is the duration of the flood in hours. The duration of the flood is determined by measuring the time that the water level is higher than the target water level. In order to do this, five locations within the study area were chosen. These locations were chosen based on the current flooding situation of the area. The locations, including a detailed explanation on the choice of these locations, are shown in figure 8. A detailed explanation of the choice of these locations can be seen in Appendix A.

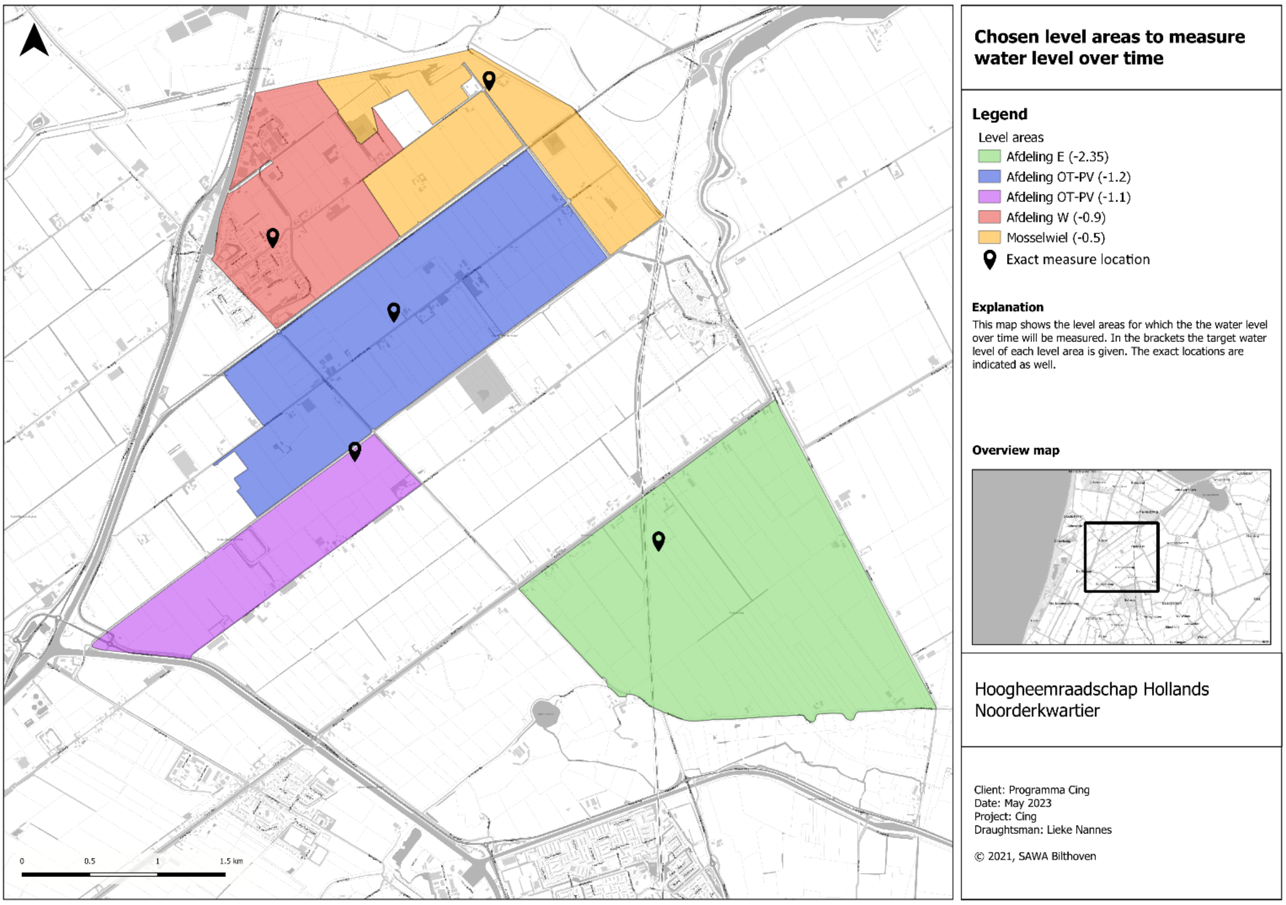


*Figure 8: Measurement locations for flood duration and maximum water level.*

To assign how the alternatives scored on the flood duration criteria, a percentage change for each alternative was calculated. This percentage change was the new situation in which an alternative measure was implemented compared to the original situation in which no measures were applied. Since each alternative has multiple scores because of the different locations, a percentage change for each location was determined, from which an average was calculated. If the flood duration in the original sitation for a certain location was already zero, no improvements could have been made. These values were therefore not taken into account to determine the average percentage change.

### 3.3.2. Maximum water level

The second factor for which the measures were tested is the maximum water level. The maximum water level is measured in m+NAP. These maximum water levels were measured for the exact same locations as for the flood duration, which are shown in figure 8. An explanation why these locations were chosen can be found in Appendix A. Also, for the maximum water level, there was determined how the alternatives scored for this test factor by determining the percentage change between the new situation and the original situation. The scores for all locations were averaged to end up with one final score for each measure for the maximum water level.

### 3.3.3. Damage

The third factor for which the measures were tested is damage. 3Di calculates the damage using the 'WaterSchadeSchatter'. The WaterSchadeSchatter takes the direct damage as well as the indirect damage into account. The direct damage is considered to be the damage that is caused by direct contact with the surface water level. The way the direct damage is calculated can be seen in Appendix B.

The indirect damage is the damage that is caused by the direct damage. An example of this is the costs of the fact that a store can not open due to broken devices. The WaterSchadeSchatter only calculates the indirect damage for buildings, as they assume that other land uses barely experience any indirect damage. The formula that is used to calculate the indirect damage can also be seen in Appendix B.

### 3.3.4. Inundated area

The fourth factor for which the measures were tested was the inundated area. Only the inundated area that led to damage was taken into account. The inundated area is measured in squared meters. It is considered that the less area inundates the better, because fewer people, houses and nature will then be affected.

### 3.3.5. Test scenarios

The flood prevention measures that should reduce flooding in the preparation phase of an extreme weather event, were each tested for different precipitation scenarios. Choosing these precipitation scenarios, climate change was taken into account. The statistics for the upper climate scenario for 2050 were used to account for the climate change. Thus, the statistics for the worst case scenario for 2050 were used. In the decision for what scenarios the measures should be tested, there was decided for what duration and for what return period the measures should be tested.

For rural areas, especially long-duration rain events cause flooding, where for urban areas especially short rain events cause problems (van Leeuwen, 2017). As most of the area considered in this case study can be considered as rural area, the measures were tested against prolonged precipitation events. There was chosen to test the measures for a precipitation duration of 4 hours and 48 hours.

There was tested for two different return periods, for 1/10 years and for 1/100 years, because this both tested a situation that occurs more often and a situation that is rare. The precipitation values that belong to the scenarios that were used, are shown in the table 2 (Beersma et al., 2019).

*Table 2: The precipitation event statistics in millimetres for the Netherlands according to the 2050 scenario (Beersma et al., 2019).*

| **Return period [years$^{-1}$]** | **4 hours event [mm]** | **48 hours event [mm]** |
|---|---|---|
| **1/10** | 51.7 | 86.4 |
| **1/100** | 94.2 | 129.2 |

These values were thus used to test the proposed measures in 3Di. The complete test setup for the simulations can be seen in Appendix C.

Using these test scenarios, each measure gets multiple scores. To assign a score in the multi criteria decision analysis for each measure, the average of the percentage change between each alternative and the original situation for each scenario was used.

### 3.3.6. Multi Criteria Decision analysis

All criteria for the multi criteria decision analysis had an equal weight of 1. A conscious decision was made not to decide which criteria are more important than others by assigning them different weights. In this way, decision makers can decide for themselves and their area what they consider important and, based on that, decide which measure or measures fit best. Thus, this study determined which measure was most effective in reducing flooding during the preparation phase preceding an extreme weather event, based on equal scoring of criteria. In practice, decision-makers may therefore choose to select a different measure to implement in their area because they consider certain criteria more important than others for their specific area.

Since every criteria counts equally towards the end result, for each criteria, 1 point was subdivided among the alternatives. The maximum score that an alternative could achieve was therefore 1, and the minimum score was 0. If all alternatives score equally, they are all given a score of 1/number of alternatives. If an alternative scored twice as well as another alternative, its score in the multi criteria decision analysis is also twice as high. The points were thus distributed in a straight-line manner. If an alternative had a negative effect on a test factor, the alternative is assigned a zero for that criteria. When the multi criteria decision analysis was filled in, the measure with the highest score was selected to be most effective.

## 3.4. Uncertainties of the model results (RQ 2c)

In order to test the uncertainties of the model results, a univariable sensitivity analysis was performed. For this sensitivity analysis the terrain characteristics of the model were varied over a range from -30% to +30% to test if the flood duration, the maximum water level, the flood damage and the inundated area are sensitive to these changes. The terrain characteristics that 3Di takes into account, are the infiltration rates, the storage capacities, the friction, and the interception capacities of the area. This sensitivity analysis is performed for the situation in which the water level buffer measure is implemented in the model. How the sensitivity is calculated, can be seen in Appendix D. Below, an explanation of the terrain characteristics is given.

### 3.4.1. Infiltration rate

The infiltration rate is defined as the velocity at which water enters the soil (USDA Natural Resources Conservation Service, 2008). The velocity at which water enters the soil, is a fundamental process within the hydrological cycle (SepaHvand, Singh, Ghobadi, & Sihag, 2021). In situations of extreme weather events, a high infiltration rate is beneficial as it causes less water to drain directly to the waterways. This way, waterways are less overloaded. As described in section 2.1, the Zijpepolder area has a gradient in soil type from West to East. The soil type in the Western part of the area is sand and changes more towards clay in the East (Gemeente Zijpe). As water moves more quickly through large pores of sandy soils as it does through the small pore spaces of clayey soils, the infiltration rate of sandy soils is higher than the infiltration rate of clayey soils. The infiltration rate of the Zijpepolder varies between 0 mm/day for roads and 1000 mm/day for sandy soils according to the model. In Appendix E, there is shown in detail which values the model currently uses for the infiltration rate of the Zijpepolder. These values originate from the infiltration raster, which is provided by Hoogheemraadschap Hollands Noorderkwartier, as shown in section 2.4.

### 3.4.2. Storage capacity

The storage capacity was defined as the amount of water that can be stored underground in meters. The storage capacity is dependent upon both the volume of the soil and the volume of available pore space that can retain water. The higher the storage capacity the more water can be stored during precipitation events. This is beneficial as less water has to be drained in this case. As mentioned previously, sand has bigger pore space than clay, which makes the storage capacity of sand higher than the storage capacity of clay. Since the western part of the Zijpepolder has more sand and the eastern part has more clay, the storage capacity of the western part is higher than the storage capacity of the eastern part. In the Zijpepolder, the storage capacities vary from 0 meter to 0.5 meters. In Appendix F, there is shown what storage capacities the model currently uses for different parts of the Zijpepolder, which are provided by Hoogheemraadschap Hollands Noorderkwartier.

### 3.4.3. Friction

Friction is a resisting force that is generated when two things interact. The higher the friction is, the slower the water is drained. For the Zijpepolder only three different friction values are used in the model. For buildings, the friction is 0.2 $s/m^{1/3}$. For roads the friction is 0.01 $s/m^{1/3}$, and for all other land uses a friction of 0.07 $s/m^{1/3}$ is used. These values originate from the friction raster, which is provided by Hoogheemraadschap Hollands Noorderkwartier, as explained in section 2.4.

### 3.4.4. Interception capacity

The interception capacity was defined as the amount of water retained by the sewerage system in urban areas. The higher the interception capacity is, the more water is retained and the less water that has to be drained. For all rural areas in the Zijpepolder, the interception capacity that the model uses is 0 meter, and for all urban areas in the Zijpepolder the interception capacity that the model uses is 0.00464 meters. These values come from the interception raster, which is provided by Hoogheemraadschap Hollands Noorderkwartier, as shown in section 2.4.

## 3.5. Lessons learned from the Zijpepolder which can be applied to polders in general (RQ 3)

In order to generalise the results of the Zijpepolder, first, an overview of the advice for the Zijpepolder itself was made. This was done in a flow chart. The advice was based on the criteria, the flood duration, and the return period. The short precipitation event refers to an event equal to 4 hours of precipitation, and the long precipitation event refers to an event of 48 hours of precipitation. The results in this flow chart were based on the simulations that were done for the multi criteria decision analysis.

For the generalisation, this flow chart was used in combination with the sensitivity analysis. The sensitivity analysis was used to determine the decrease and increase of the effectivity of the water level buffer measure under changing terrain characteristics.

# 4. Results

In the sections below, the results are presented.

## 4.1. Potentially effective measures to reduce flooding (RQ 1)

From the desk study, it follows that measures that can be taken in the preparation phase of an extreme precipitation event to reduce flooding, are; creating a water level buffer (Penning de Vries, 2013), activating old mills in the area (Molenfederatie, 2019), setting up temporary flood barriers (Asselman & van Heeringen, 2023), and installing emergency pumps (Deltares, 2016). The specifications of each of these measures will be discussed below. The comments from the expert interview are used as validation for the information found in literature.

### 4.1.1. Water level buffer

A water level buffer can be created by releasing the water from the waterways within the area one to two days before the extreme precipitation event (Penning de Vries, 2013, p. 11). This way, the waterways are more empty at the time the extreme precipitation event starts, allowing more water to be stored in watercourses themselves at the beginning. Interviewee #1 confirms that this would indeed be possible; ‘it would also be possible to pre-emptively maintain lower water levels in waterways to reduce flooding’ (For a full transcript of interview #1, see Appendix G). To create this buffer, the pumps are set to start pumping at a lower water level. Also, the stop level is adjusted so that the pumps only stop pumping at a lower water level.

Although this measure has been named in the water board's mitigation plan, not much research has been done on it. There is also no documentation whether this measure has already been applied in practice. Also, interviewee #2 mentions that this measure has not yet been actively applied (For a full transcript of interview #2, See Appendix G). Thus, the effect that this measure has on the reduction of flooding, is still unknown.

An advantage of this measure is that it involves no cost and is easy to implement because the pumps can be controlled from a distance. Interviewee #2 mentions that a major drawback of this measure is that there is never known in advance exactly where the extreme precipitation will exactly fall. It could be the case that extreme precipitation is predicted in the middle of summer and a decision is made to apply this measure. The whole area is then drained by pumps, but later it turns out that the precipitation just fell in the adjacent polder. Consequently, the area becomes dry while it may be the case that no more precipitation will fall in the coming weeks. Therefore, the implementation of this water level buffer measure can have significant risks (for a full transcript of interview #2, See Appendix G).

This measure can reduce the water level for big waterbodies up to 20 to 30 cm (Penning de Vries, 2013). As there are no large water bodies in the Zijpepolder, it should be tested how big of a water level buffer can be created by lowering the start level and the stop level of the pumps.

### 4.1.2. Activating old mills

In order to increase the drainage capacity of the polder, the old mills in the area could be activated again (Molenfederatie, 2019). There are four mills located in the area. The location of these mills can be found in Appendix H.

These mills have helped before during heavy rainfall. However, this has been done at the initiative of the millers rather than at the initiative of the water board (Molenfederatie, 2019). Therefore, the effect of the activation of the mills in reducing flooding has also not yet been established.

An advantage of this measure is that the mills can be activated immediately when needed without the need for preparatory work. Apart from the fact that the people who have to keep the mills running have to be paid, no major disadvantages are associated to this measure.

According to the mill federation, all four of these mills are capable of draining a precipitation event of 14.4 mm/day (Molenfederatie, 2019). This is roughly equivalent to what the other pumps in the area are capable of.

### 4.1.3. Temporary flood barriers

Temporary flood barriers are temporary defences to protect a particular or individual object against flooding (Asselman & van Heeringen, 2023). It is also useful in protecting areas of high costs and damage (Mac Cormack, Van Dyke, & Suazo, 2013).

Interviewee #1 claims that in current disaster management of Hoogheemraadschap Hollands Noorderkwartier, there is no steering within an area except for maximum runoff. The interviewee emphasizes that if it is known that certain areas cause more damage when it floods, it would be interesting to explore whether extra protection of these sub-areas by temporary flood barriers is effective (For a full transcript of interview #1, see Appendix G).

An advantage of this measure is that specific areas that cause a lot of damage can be closed off from the water in this way. According to interviewee #1, a disadvantage is that this may cause other areas to experience more inundation (For a full transcript of interview #1, see Appendix G). It also takes a relatively large amount of manpower to install these temporary flood barriers compared to the previously mentioned measures.

Temporary flood barriers come in different shapes and sizes. There are, of course, the traditional sandbags. 'Sand bags however, while often effective, require more labour effort and time to fill, which means less extensive areas of infrastructure can be protected on short notice' (Mac Cormack, Van Dyke, & Suazo, 2013). In figure 9 can be seen how the sandbags could be used to protect from flooding.

*Figure 9: How sandbags can be used to protect an area from flooding.*

There also exist water inflatable temporary barriers, which are made of synthetic EPDM rubber. These are recyclable and have a life span of 100 years, which makes them ecologically responsible (Beketov, 2022). These water inflatable temporary flood barriers have a height up to one meter. Different parts of the water inflatable flood barriers can be connected together to obtain a flood barrier with a sufficient length to protect buildings (Beketov, 2022). In figure 10 can be seen how a water inflatable flood barrier can be used to protect an area from flooding.


*Figure 10: How a water inflatable dam can be used to protect an area from flooding.*

The reductional power of the temporary flood barriers is strongly dependent on many factors. An example of these is the inundation depth as most of the temporary flood barriers are only up to 1 meter high.

### 4.1.4. Emergency pumps

Emergency pumps can be installed to provide additional discharge capacity. That extra discharge capacity can be put to good use when a lot of water enters the area in a short period of time.

The measure of using pumps to increase the drainage capacity of the area has also been used previously. However, there was no plan where best to put these pumps and it was not clear to what extent this measure reduced flooding (Hoogheemraadschap Hollands Noorderkwartier, 2022).

An advantage is that the pumps are relocatable and so can be installed in places where they are needed most. A drawback is that the water board only has limited availability of emergency pumps (For a full transcript of interview #2, see Appendix G). However, interviewee #2 mentions that pumps can be rented from local companies and can then be made operational within an hour and a half (For a full transcript of interview #2, see Appendix G).

The water board has three types of pumps. These are electric motor pumps, diesel motor pumps and tractor pumps. Electric motor pumps and diesel motor pumps generally have a higher capacity; from 50 to 150 m3 per minute. However, these are scarce and thus are limited available during emergency situations. The vast majority of pumps are tractor pumps. These have a capacity of 30 to 45 m3 per minute (Deltares, 2016). These pumps are usually used as additional pump capacity for the final pumping station of the polder. In figure 11, a tractor pump can be seen.

*Figure 11: Tractor pump operating for additional pump capacity.*

These four measures described, creating a water level buffer, activating old mills in the area, setting up temporary flood barriers, and installing emergency pumps would possibly reduce flooding during the preparation phase of an extreme weather event according to the mentioned literature and the interviews. Therefore, an explanation on how these measures are implemented in the model is given in the next section.

## 4.2. Modelling flood reducing measures in 3Di (RQ 2a)

### 4.2.1. Water level buffer

The water level buffer can be implemented into the model in two ways. The first option is to lower the initial water level, which is the starting level of water in the area at the moment the simulation starts. A disadvantage is that in this way it can not be checked whether the pumps are capable of draining this amount of water within the preparation phase of the extreme weather event.
The second option is to lower the water level at which the pumps start and stop pumping. In this way, an overall lower water level is targeted by the pumps. The advantage of this option is that only the amount of water can be drained that the pumps can actually handle.

As the second option, in which the start and stop level of the pumps were lowered is more advantageous, the second option was chosen to create the water level buffer. Through an educated guess based on the results presented in the previous section, it had been decided to lower the start and stop level of the pumps by 10 cm, 24 hours before the extreme weather event started. For each of the five measurement locations, which can be seen in figure 8, this resulted in a 13 cm reduction in the water level. This means that by assuming to lower the start and stop level of the pumps by 10 cm, a buffer of 13 cm was created in the waterways as a result.

### 4.2.2. Activating old mills

As the old mills are actually the same as pumps, the mills are integrated in the 3Di model as pumps and no other options were considered. They are installed to only react on the suction side of the pump. This means that the pump only monitors the polder side of the pump, and starts when that is necessary according to the water levels, independent on the water level on the delivery side of the pump. For the pumping start level and pumping stop level of the mills, the standards of the Hoogheemraadschap Hollands Noorderkwartier will be used. The start water level of the pumps are installed to be 0.02 meter higher than the target water level. The stop level of the pumps are installed to be 0.03 meter lower than the target water level. If these values are different from other pumps in the area, then the water level will rise in the waterway the mill is located in or, on the contrary, the water will be discharged quickly compared to the rest causing the water level to rise in other areas. For each mill, the target levels of the target level areas in which the mills are located, are shown in table 3. Also, the pumping start and stop level, and the capacity of the mills are shown. The mills are indicated using their names; mill P, mill P-V, mill O-T, and mill D. The locations of the mills are shown in Appendix H. A detailed description on how the capacity is calculated can be found in appendix I.

*Table 3: Characteristics old mills. For the locations of the mills, see figure 24.*

| | Mill P | Mill P-V | Mill O-T | Mill D |
|---|---|---|---|---|
| **Target water level [m+NAP]** | -0.9 | -1.2 | -0.85 | -1.95 |
| **Start level [m+NAP]** | -0.88 | -1.18 | -0.83 | -1.93 |
| **Stop level [m+NAP]** | -0.93 | -1.23 | -0.88 | -1.98 |
| **Capacity [L/sec]** | 194.65 | 494.05 | 279.49 | 187.1 |

### 4.2.3. Temporary flood barriers

There are four places assigned within the Zijpepolder for which the temporary flood barrier could possibly help. As a temporary flood barrier could potentially best help in protecting areas of high damage, four areas of high damage are chosen to apply this measure to. For all four locations, the temporary flood barrier encloses a building or several small buildings.

The temporary flood barriers are modelled as levees in 3Di, each with a height of 0.7 meters. Sand or clay could be chosen as soil type of the levee. Since the temporary flood barriers are not permeable, clay is chosen for the soil type.

### 4.2.4. Emergency pumps

The emergency pumps have been installed at three polder pumping stations. Here, water is pumped from the polder into the storage basin. The explanation why these 3 locations were chosen can be found in appendix J. The emergency pumps could either be implemented as a separate pump or as extra discharge capacity for the current pump. The choice between these has no impact on the results so the choice was made to implement the emergency pump as additional pumping capacity at the current pumping station. These were increased in capacity with 500 L/sec which is equal to 30 $m^3$/minute. This was the minimum tractor pumps could handle as explained in section 4.1.4.

## 4.3. Selection of most effective measure in reducing flooding in the Zijpepolder (RQ 2b)

The multi criteria analysis in table 4 shows the scores for each of the four measures for all criteria. According to this multi criteria decision analysis, the water level buffer is the best way to reduce flooding in the preparation phase of an extreme weather event, taking climate change into account. With a score of 1.86, it scores 0.78 better than the emergency pumps with a score of 1.08. The origin of this difference mainly comes from the difference in maximum water level. The water level buffer scores 0.80 here, where the emergency pumps alternative only scores 0.18. The alternative in which the old mills were activated scored 0.74, and the temporary flood barriers scored 0.32.

*Table 4: Multi criteria analysis for most effective measure in reducing flooding in the preparation phase preceding an extreme weather event, taking climate change into account. Higher scores indicate better performance.*

| | **Water level buffer** | **Activating old mills** | **Temporary flood barriers** | **Emergency pumps** |
|---|---|---|---|---|
| **Flood duration** | 0.56 | 0.10 | 0 | 0.34 |
| **Maximum water level** | 0.80 | 0.02 | 0 | 0.18 |
| **Flood damage** | 0.17 | 0.33 | 0.32 | 0.19 |
| **Inundated area** | 0.33 | 0.29 | 0 | 0.37 |
| **TOTAL** | 1.86 | 0.74 | 0.32 | 1.08 |

Below, for each criteria, the most important results are discussed.

For the flood duration, the water level buffer scored best with a score of 0.56 compared to a score of 0.34 for emergency pumps and a score of 0.10 and 0 for activating old mills and temporary flood barriers respectively. It turns out that the water-level buffer alternative has a particularly strong positive effect on flood duration in the measure location of ‘Afdeling W’, which is located in the North-Western part of the area as can be seen in Appendix A. There the flood duration decreased with an average of -56.3%, where the average of all locations was -22.4%. A decrease of 56.3% is equal to a reduction of 9.2 hours in flood duration. In table 5, it can be seen that for all the test scenarios, the flood duration decreased for Afdeling W after implementation of the measure, except for scenario in which there was tested for a 48 hour precipitation event with a return period of 1/10 years, as the flood duration was already 0 there. It can also be seen that there is no location for which the flood duration increases for a certain scenario of the water level buffer measure situation compared to the original situation. The flood duration of the other measures can be seen in Appendix K. In this appendix, also the relative scores of the measures can be seen, which were used to assign a score in the multi criteria decision analysis.

*Table 5: Flood duration in hours for original situation and for the water level buffer measure for five different locations.*

| Flood duration [Hours] | Afd W | Afd OT-PV (-1.1) | Afd OT-PV(-1.2) | Mosselwiel | Afd E |
|---|---|---|---|---|---|
| **Test scenarios** | Original situation | | | | |
| **1/10 years, 4 hours** | 7.66 | 0.00 | 0.00 | 0.00 | 26.50 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 71.91 |
| **1/100 years, 4 hours** | 29.42 | 24.92 | 23.50 | 19.17 | 89.50 |
| **1/100 years, 48 hours** | 28.92 | 0.00 | 39.25 | 0.00 | 136.00 |
| | | | | | |
| | Water level buffer | | | | |
| **1/10 years, 4 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 22.17 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 52.67 |
| **1/100 years, 4 hours** | 22.67 | 24.83 | 23.08 | 16.75 | 86.50 |
| **1/100 years, 48 hours** | 15.67 | 0.00 | 37.00 | 0.00 | 122.25 |

In figure 12, the water level over time for each scenario for all measurement locations for the original situation in which no measure is applied can be seen. In figure 13, the water level over time for each scenario for all measurement locations for the situation in which the water level buffer measure is applied is shown. As described in 4.2.1, for the water-level buffer implementation, the area is first drained for 24 hours by installing a 10 cm lower pumping start level. That is also why the water level in the case of the applied water level buffer, only starts rising after 24 hours.

It is clearly visible that the main pattern of the water level over time between the original situation without measure, and the new situation with the water level buffer measure are the same. However, the durations of the flooding do differ, as shown in table 5. Also, the graph shows the drop of the water level in the water level buffer situation in the first 24 hours. This can be explained by the fact that the starting level of the pumps have been lowered.

For the maximum water level criteria, the water level buffer measure scored best with a score of 0.80, compared to a score of 0.18, 0.02, and 0.0 for emergency pumps, activating old mills, and temporary flood barriers respectively. Table 6 shows that for every test scenario for every location the water level has dropped, or at least stayed the same. Especially for Afdeling W and Mosselwiel, the maximum water levels drop significantly. On average, the water level for Afdeling W dropped with 7.83% and the water level for Mosselwiel with 6.5% when the water level buffer measure was implemented. The average drop in water level for all test scenarios and all locations is 3.4%. The reason that the maximum water level has more decreased for Afdeling W and Mosselwiel can be deduced from the fact that these two target level areas are located in the West of the polder where the elevation is higher. The water therefore drains naturally into the lower parts of the polder (the eastern side). For activating the old mills, the temporary flood barriers, and the emergency pumps, the change in maximum water level on average is -0.05%, +0.03%, and -0.76% respectively. The decrease of 0.76% for the emergency pumps measure is equal to a reduction in water level of 0.01 meters. The water level reduced from -1.01 in the original situation in which no measure was applied, to -1.02 in the emergency pumps situation. For the temporary flood barriers, the maximum water level increases on average (+0.03). This can be explained by the fact that certain surfaces are being blocked from water by the flood barriers, which means the water level increases in other places. The normative as well as the relative results for the other the measures can be seen in Appendix L.

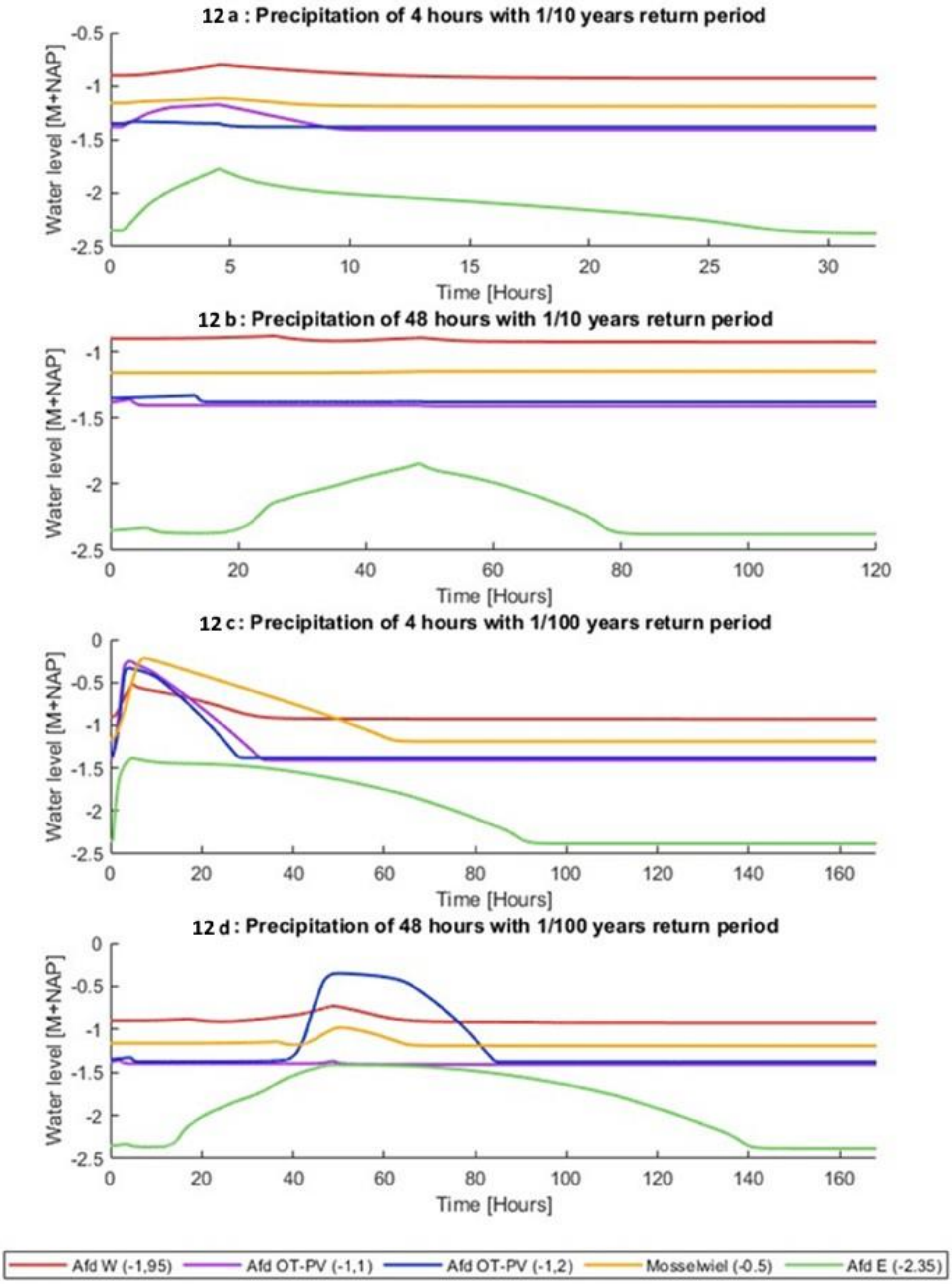


*Figure 12: Water level over time for each target level area for the original situation in which no measure was applied.*

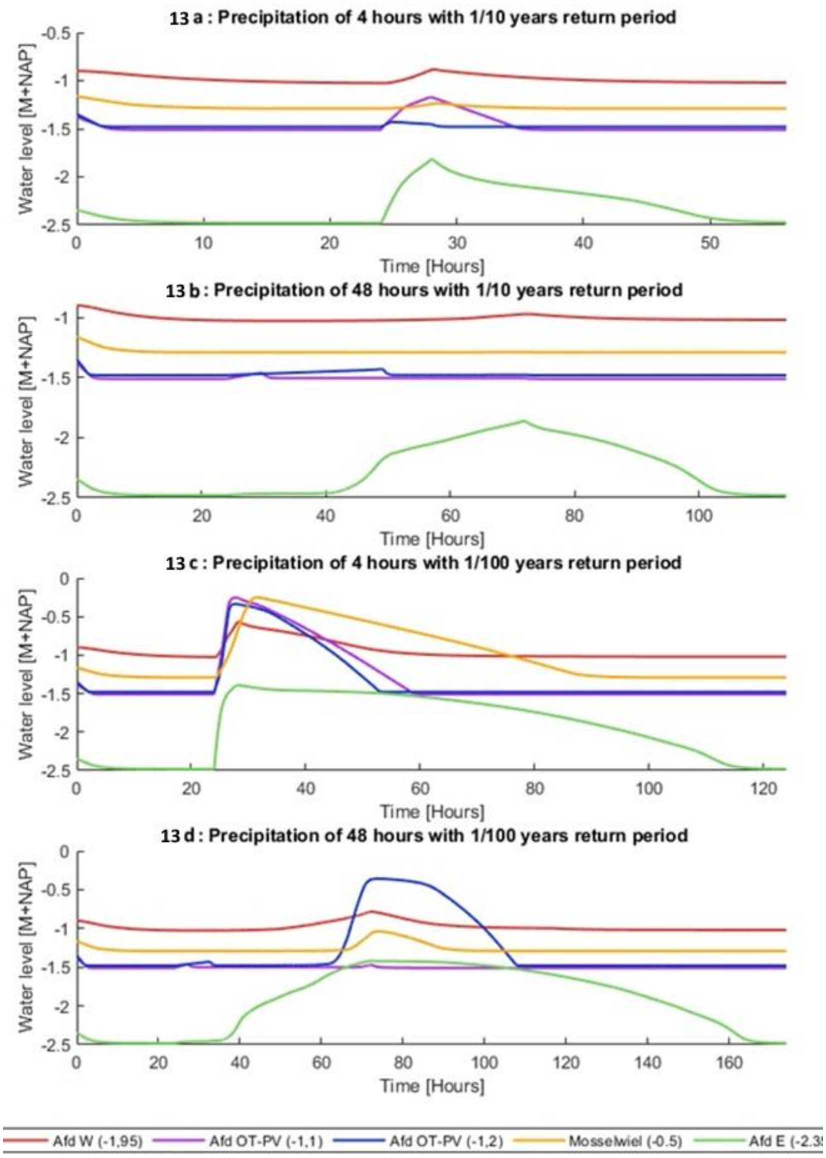


*Figure 13: Water level over time for each target level area for the situation in which the water level buffer measure was applied.*

*Table 6: Maximum water level in meters for original situation and for the water level buffer measure for five different locations.*

| **Maximum water level [m]** | **Afd W** | **Afd OT-PV (-1.1)** | **Afd OT-PV(-1.2)** | **Mosselwiel** | **Afd E** |
|---|---|---|---|---|---|
| **Test scenario** | Original situation | | | | |
| **1/10 years, 4 hours** | -0.80 | -1.17 | -1.33 | -1.11 | -1.77 |
| **1/10 years, 48 hours** | -0.88 | -1.36 | -1.33 | -1.15 | -1.84 |
| **1/100 years, 4 hours** | -0.52 | -0.25 | -0.33 | -0.21 | -1.38 |
| **1/100 years, 48 hours** | -0.73 | -1.36 | -0.35 | -0.98 | -1.41 |
| | | | | | |
| | Water level buffer | | | | |
| **1/10 years, 4 hours** | -0.88 | -1.17 | -1.35 | -1.16 | -1.81 |
| **1/10 years, 48 hours** | -0.90 | -1.38 | -1.35 | -1.16 | -1.86 |
| **1/100 years, 4 hours** | -0.57 | -0.25 | -0.33 | -0.25 | -1.39 |
| **1/100 years, 48 hours** | -0.78 | -1.38 | -0.36 | -1.04 | -1.42 |

The activating old mills measure scored best on the flood damage criteria with a score of 0.33, compared to a score of 0.32, 0.19, and 0.17 for temporary flood barriers, emergency pumps, and water level buffer measure respectively. The temporary flood barriers measure has no positive effect on any criteria except flood damage. This measure thus increases the flood duration, the maximum water level and the inundated area. The temporary flood barriers measure reduced the damage with on average -0.8% and therefore had a score of 0.32, where the water level buffer measure, activating old mills measure, and the temporary flood barriers measure reduced the damage with -0.4%, -0.8%, and -0.5% respectively. The exact changes in flood damage per test scenario for each measure can be seen in Appendix M. Since the relative differences in flood damage reduction are really small, no visual difference can be seen on maps.

The emergency pumps criteria measure scored best for the inundated area criteria with a score of 0.37, compared to a score of 0.33, 0.29 and 0 for water level buffer, activating old mills and the temporary flood barriers measures respectively. The emergency pumps measure decreased the inundated area with on average 2.3%. This is mainly because the inundated area decreased with 8.4% for the test scenario with a return period of 1/100 years and a precipitation duration of 48 hours. For both of the scenarios in which a return period of 1/10 years is used, the inundated area increases slightly with 0.03% and 0.02%.
For the water level buffer the inundated area decreased with 2.1% on average. For the activating old mills measure the inundated area decreased with 1.8% on average and for the temporary flood barriers measure the inundated are increased with 1.11%. The exact changes per test scenario for each measure can be seen in Appendix N. Again, these changes are too small to see a visual difference on an inundation map.

## 4.4. Uncertainties of the model results (RQ 2c)

In figures 14, 15, 16 and 17, the results of the sensitivity analysis are shown for each of the test factors. Figure 14 shows that the flood duration is sensitive for a change in infiltration. If the infiltration rate decreases by 30%, the flood duration increases by 103.3%. This means that the higher the infiltration rate, the lower the flood duration. The inundated area is also sensitive for a change in infiltration rate. For a reduction of 30% in infiltration rate, the inundated area increases with 37.9%.

The storage capacity is negatively correlated to the flood duration. The lower the storage capacity of the area, the higher the flood duration. This negative correlation can be seen for the infiltration rate and the storage capacity for all test factors. For every test factor, it can thus be seen that a decrease in storage capacity increases the flood duration, the maximum water level, the flood damage and the inundated area. However, when the storage increases, no big improvement of the test factors can be noticed. This difference is also visible for the a change in infiltration rate compared to a change in outcome. When the infiltration rate decreases, the test factors decrease more than they increase when the infiltration rate increases. This is probably because with an increased infiltration rate, the storage capacity, which remained the same, is the limiting factor to reduce flood duration for example. In this case, only the rate of infiltration increases, but the amount of water that can be stored remains the same. Thus, to reduce the flood duration, both the storage capacity and the infiltration rate must then increase.

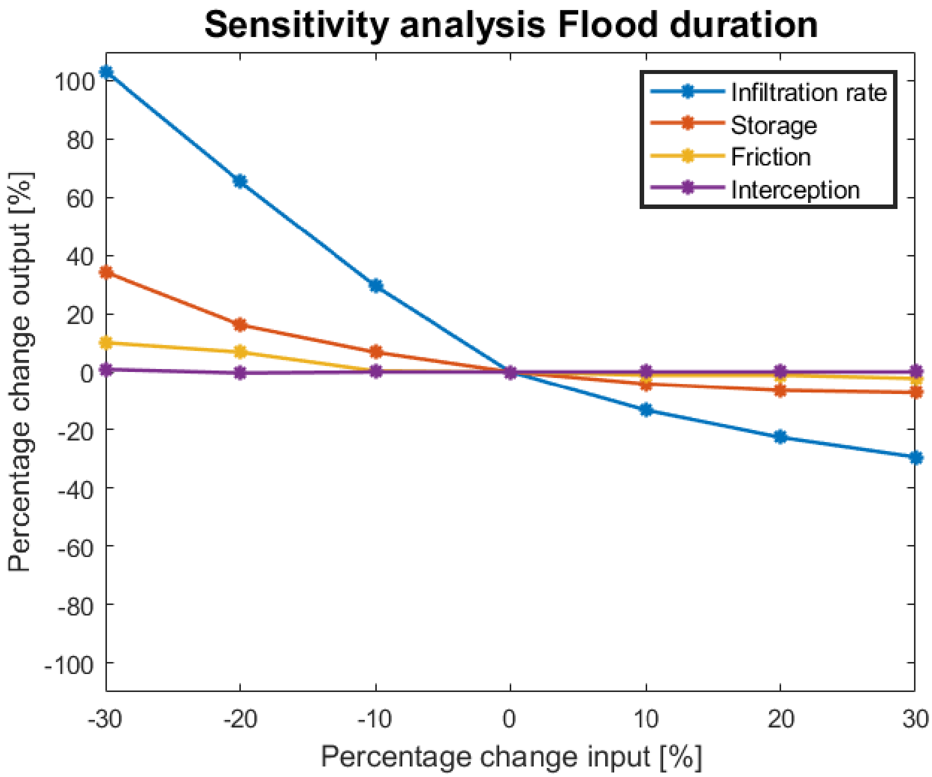


*Figure 14: Sensitivity of the flood duration to a change in terrain characteristics within a range of -30% to +30%.*

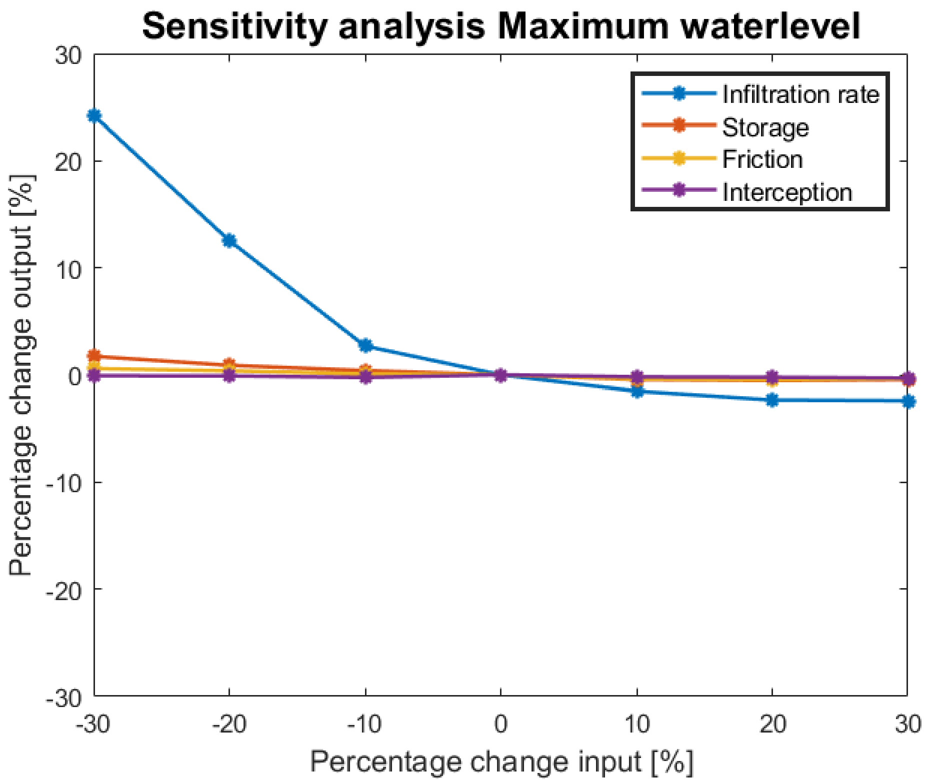


*Figure 15: Sensitivity of the maximum water level to a change in terrain characteristics within a range of -30% to +30%.*

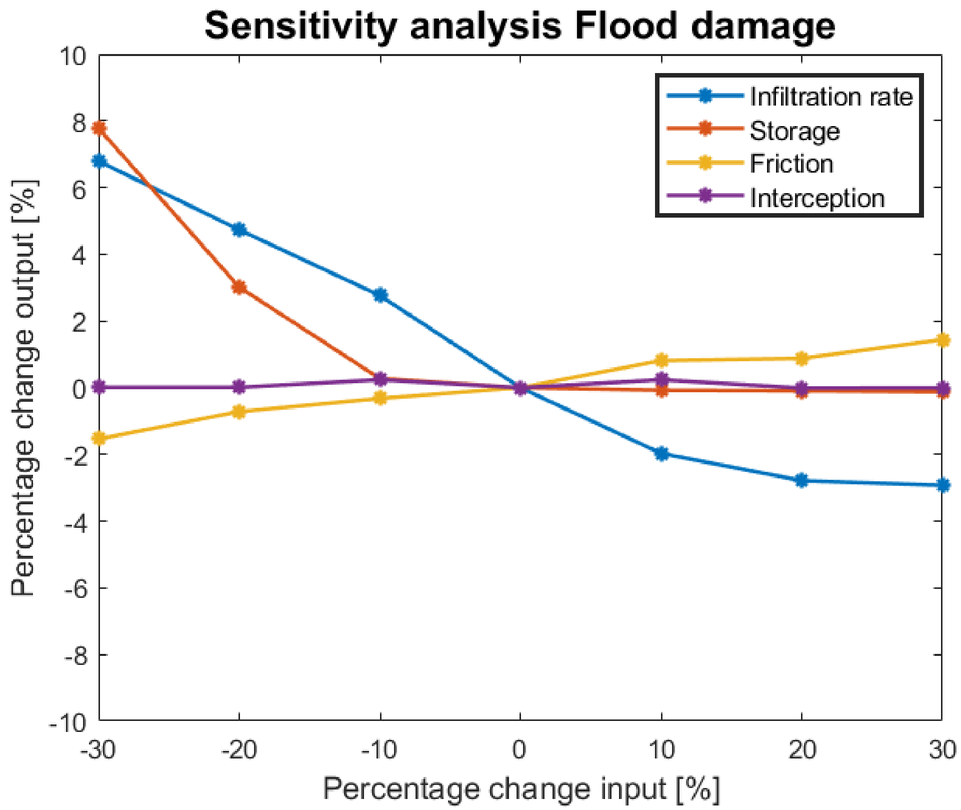


*Figure 16: Sensitivity of the flood damage to a change in terrain characteristics within a range of -30% to +30%.*

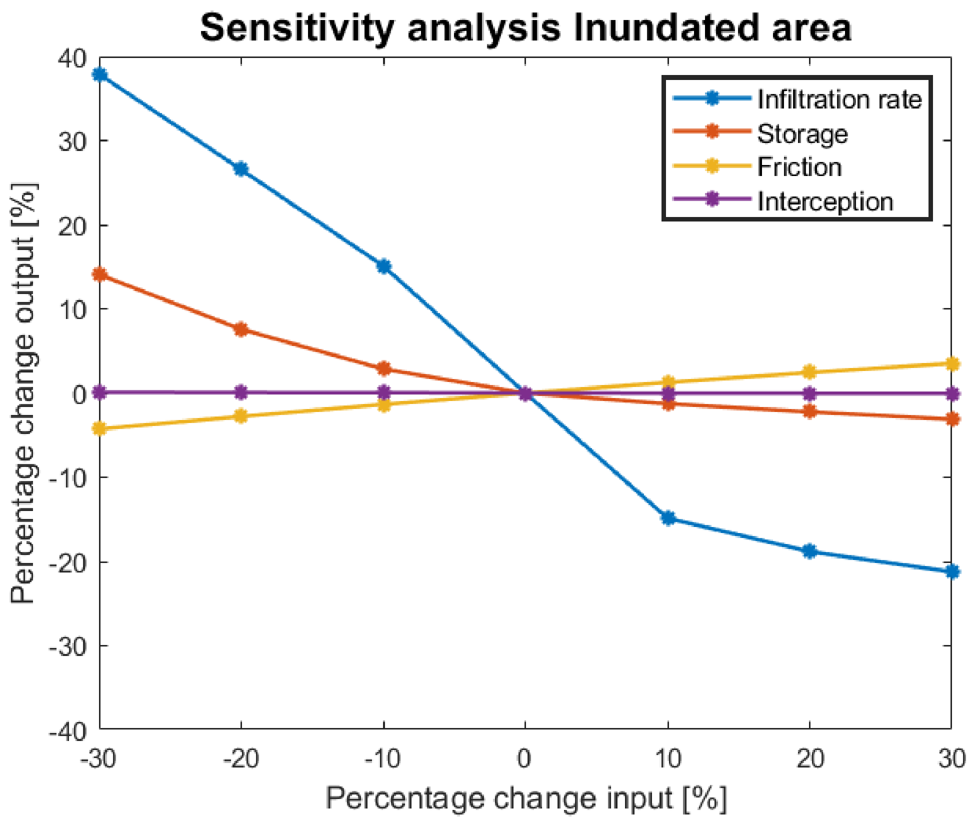


*Figure 17: Sensitivity of the inundated area to a change in terrain characteristics within a range of -30% to +30%.*

Overall, there can be seen that the test factors are not sensitive for a change in interception capacity. For a change in friction however, a change in output can be noticed for the flood duration, the flood damage and the inundated area. The friction and the inundated area as well as the flood damage are positively correlated in contrast to all other relations. This means that the flood damage and the inundated area get bigger when the friction increases. The flood damage increases by 1.4% when the friction increases by 30%. The inundated area increases by 3.5% when the friction increases by 30%. The cause of the enlargement of the inundated area by a higher friction may be that due to a higher friction of the surface, the water does not drain as quickly. As a result, it does not all move directly to the lowest point, but the water stays longer around the spot where it landed. This causes a larger area to be inundated. The flood duration and maximum water level, remain more or less the same with higher friction. The fact that the flood damage increases in the case of high friction is thus probably due to the inundated area that becomes larger.

## 4.5. Guideline for the Zijpepolder (RQ 3)

The guideline for the Zijpepolder on how to reduce flooding during the preparation phase of an extreme weather event is summarized in a flowchart, which is shown in figure 18. Below, for each criteria, there will be discussed what measure is most effective in reducing flooding for what criteria and precipitation scenario.

### 4.5.1. Flood duration

In case the decision maker, which is the water board in this case, considers the reduction of flood duration as most important criteria, the water level buffer measure is overall most effective. This measure reduces the flood duration with 22.3% on average. The water emergency pumps measure is second most effective in reducing flood duration, as this measure creates a reduction in flood duration of 13.6%

For both precipitation events of short and long duration this measure is most effective in reducing flood duration. For the short duration precipitation event the water level buffer decreases the flood duration with 22.5% and for the long duration precipitation event the water level buffer decreases the flood duration with 22.1%. Second most effective is for both durations the emergency pumps with a decrease of 13.3% for the short precipitation event and a decrease of 14.25% for the long precipitation event.

For short precipitation events, the water level buffer is the most effective measure in reducing flood duration for a return period of 1/10 years. This measure reduces the flood duration with 58.2%. For short precipitation events with a return period of 1/100 years, the most effective measure is the emergency pumps measure, which reduces the flood duration with 15.1%. For long precipitation events, the water level buffer is most effective for both a return period of 1/10 years and 1/100 years. This measure reduces the flood duration with 26.8% and 20.6% respectively.

Overall, the water level buffer measure and the emergency pumps are thus most effective in reducing flood duration based on the model results. This can be explained by the fact that the temporary flood barriers do not contribute to draining the area, so this measure does not reduce the flood duration. The mills, on the other hand, do contribute to draining the area. However, the total capacity of the mills is smaller than the total capacity of the emergency pumps, which is why the emergency pumps are more effective in reducing flood duration.

### 4.5.2. Maximum water level

If the decision makers consider the maximum water level as most important criteria, the water level buffer measure is most effective as this measure reduces the maximum water level on average with

3.36% compared to the emergency pumps, second in row, with a reduction in maximum water level of 0.76%.

For the short and long duration of precipitation, the water level buffer is the most effective measure in reducing the maximum water level. Using this measure, the maximum water level is reduced with 4.35% for the short precipitation event and reduced with 2.4% for the long precipitation event. The second most effective measure for reducing the maximum water level is for both short and long duration of precipitation event the emergency pumps, which reduce the maximum water level with 0.51% and 1.02% respectively.

For short precipitation event, the water level buffer is most effective for a return period of 1/10 years. This measure reduces the maximum water level with 3.7%. For a return period of 1/100 years, the emergency pumps measure is most effective, which reduces the maximum water level with 5.0%. For the long duration precipitation events, the water level buffer is most effective. This reduces the maximum water level with 1.4% for a return period of 1/10 years and with 3.4 for a return period of 1/100 years.

In general, the water level buffer and the emergency pumps measures are most effective in reducing maximum water level. This is because the flood barriers do not contribute to the drainage of the area so the maximum water level is not reduced by this measure. In addition, the emergency pumps together have a higher capacity than the mills in the area. Therefore, these provide more drainage of the water resulting in a lower maximum water level.

### 4.5.3. Flood damage

When flood damage is considered to be the most important criteria by the decision makers, activating the old mills would be most effective on average. This measure reduces the flood damage by 0.82%. The temporary flood barriers measure comes second as this measure reduces the flood damage with 0.79% on average.

For short precipitation events, the water level buffer is most effective, which reduces the flood damage by 0.5%, followed by the emergency pumps, which reduce the flood damage by 0.3%. For long precipitation events, activating the old mills is most effective as this measure reduces the flood damage by 1.7% and the temporary flood barriers measure comes second as this measure reduces the flood damage by 1.6%. In reducing the flood damage, it can thus be concluded, based on the model results, that for the short precipitation event, the water level buffer measure and the emergency pumps measure are most effective, while for the long precipitation events the activating old mills and the temporary flood barriers measure are most effective. That the temporary flood barriers are only effective in reducing flood damage for long precipitation events and not for short precipitation events, is because during short precipitations, the maximum water level is higher than during long precipitations, as can be seen in Appendix L. Once the water level exceeds the height of the temporary flood barriers, they are no longer effective in reducing flood damage as the water will pass over it.

For short precipitation events, the water level buffer measure is most effective for both a return period of 1/10 years and 1/100 years, as it reduces the flood damage with 0.24% and 0.68% respectively. For long precipitation events, the temporary flood barriers measure is most effective in reducing flood damage for a return period of 1/10 years and the activating old mills is second most effective, since they reduce flood damage with 1.8% and 1.5% respectively. For a return period of 1/100 years, activating the old mills is most effective as it reduces flood damage with 1.9%.

### 4.5.4. Inundated area

In case the decision makers consider the inundated area as most important criteria, the emergency pumps measure is considered as most effective as this measure reduces the inundated area by 2.3% on average. The water level buffer comes second as this measure reduces the inundated area by 2.1% on average.

For short precipitation events, the water level buffer measure is on average most effective. This measure reduces the inundated area with 2.2%. Second in row is the emergency pumps measure, which reduces the inundated area with 0.5%. For long precipitation events, the emergency pumps measure score best, which reduces the inundated area with 4.2%. The second most effective measure for long precipitation events is activating the old mills. This measure reduces the inundated area with 3.7%.

For short precipitation events, the water level scores best for both a return period of 1/10 years and 1/100 years. This measure reduces the inundated area with 1.0% and 3.4% respectively. For long precipitation events, the water level buffer measure scores best for a return period of 1/10 years as it reduces the inundated area with 1.0%. For a long precipitation event and a return period of 1/100 years, the emergency pumps measure scores best as it reduces the inundated area with 8.4%.

For reducing the inundated area, the temporary flood barriers measure is the only measure which is not among the two most effective measures for any of the situations. This is because the inundated area increases when the temporary flood barriers measure is used, as can be seen in appendix N.

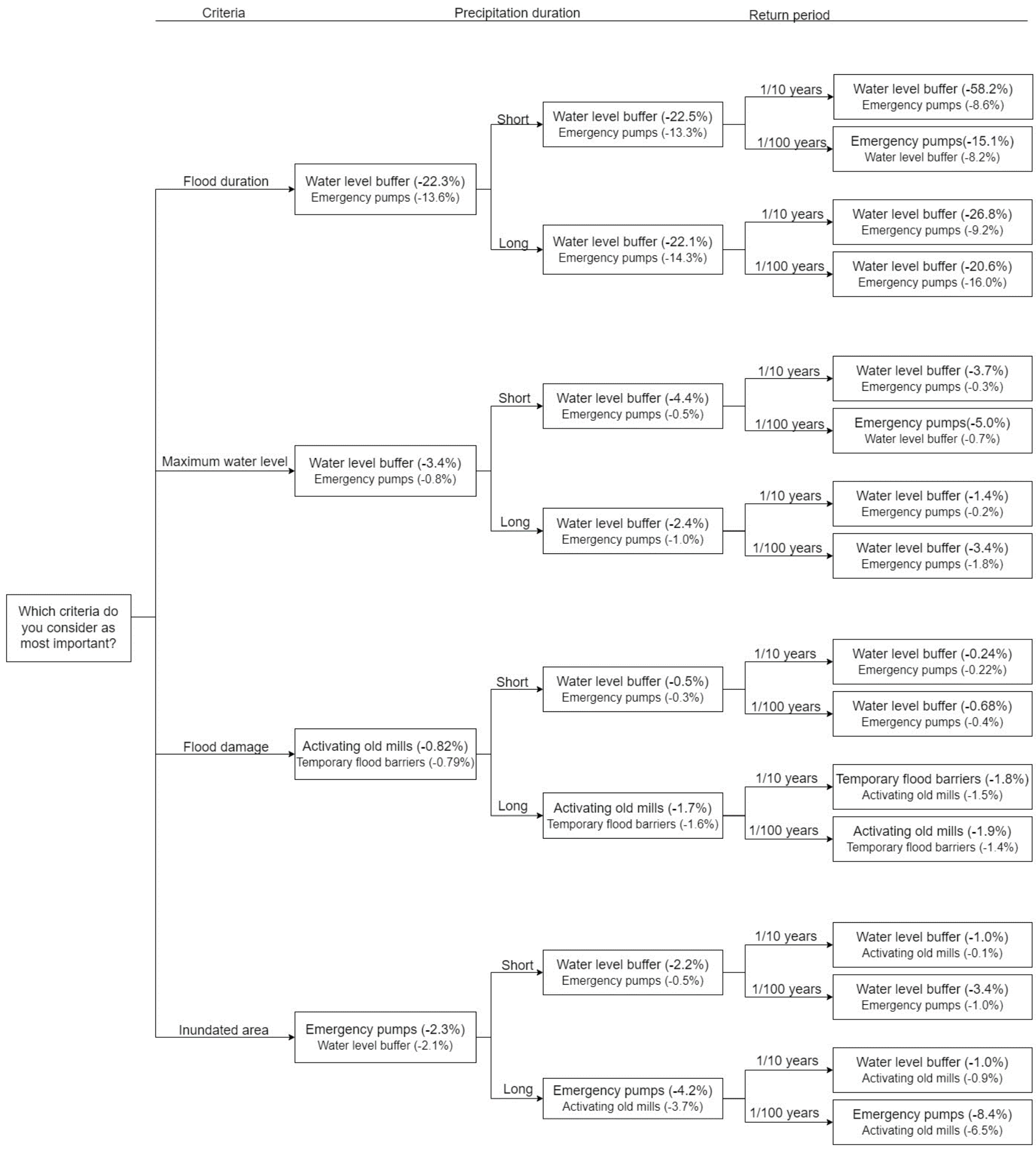


*Figure 18: Flowchart representing advice for the Zijpepolder dependent on criteria, precipitation duration and return period.*

## 4.6. Lessons learned from the Zijpepolder which can be applied to polders in general (RQ 3)

In general, the water level buffer measure is the most effective measure in reducing flooding according to the multi criteria decision analysis. In the section below, there will be discussed for each criteria which measures is most effective with some trade-offs.

### 4.6.1. Flood duration

In reducing of the flood duration, the water level buffer is most effective. However, some trade-offs for polders with different terrain characteristics compared to the Zijpepolder will be mentioned here.

Polders which have a lower infiltration rate than the Zijpepolder will experience a big decrease in effectivity of the water level buffer measure in reducing flood duration. An example is that polders with a 10% lower infiltration rate than the Zijpepolder experience a reduced effectiveness of water level buffer measure in reducing flood duration of 29.5%.

Polders with a lower storage capacity than the Zijpepolder will experience a decrease in effectivity of the water level buffer measure in reducing flood duration. If the storage capacity of a polder is 10% less than the storage capacity of the Zijpepolder, the flood duration will increase with 6.8% in case the water level buffer measure is applied. This can be explained by the fact that a smaller storage capacity allows less water to enter the ground and more water remains on the ground level. This water is then drained into the waterways, causing the water level in the waterways to remain above target level for longer period, because more water has to be drained away.

Despite the water level buffer appeared to be by far the most effective measure in reducing flood duration in the multi criteria decision analysis (0.56 for the water level buffer measure against 0.34 for the emergency pumps measure), it is advised to check for polders with a lower infiltration rate and a lower storage capacity than the Zijpepolder whether the results of reduction in flood duration of other measures are also this much affected by a change in infiltration rate or not.

For polders with different friction or interception capacities compared to the Zijpepolder, the water level is still most effective in reducing flood duration, as changes in these terrain characteristics did not majorly affect the flood duration.

### 4.6.2. Maximum water level

In reducing the maximum water level, the water level buffer is most effective. However, some trade-offs for polders with different terrain characteristics compared to the Zijpepolder will be discussed.

Polders which have a lower infiltration rate compared to the Zijpepolder, will experience a lower effectivity of the water level buffer in reducing the maximum water level. A decrease of 30% in infiltration rate will for example decrease the effectivity of the water level buffer measure in reducing the maximum water level with 24.3%.

For polders with a reduced infiltration rate compared to the Zijpepolder, it is advised to check whether the effectiveness of other measures is affected to a lesser extent by a reduction in infiltration rate, despite the fact that the water level buffer scored much better for reducing the maximum water level with a score of 0.80 compared to a score of 0.18 for the emergency pumps measure

For polders with different storage capacity, friction, or interception capacity, the water level buffer should still work best in reducing flood duration as a change in these terrain characteristics barely affected the reduction of the maximum water level by the water level buffer measure.

### 4.6.3. Flood damage

For reducing the flood damage, overall, activating the old mills is most effective. For polders which do not have old mills, the temporary flood barriers measure is most effective. How the activating old mills measure is affected by changes in terrain characteristics is unknown since it has not been tested. However, in figure 18, it can be seen that for short duration precipitation events, the water level buffer scores best. There are some trade-offs related to reducing flood damage in polders with different terrain characteristics. These are mentioned below.

Polders with a lower infiltration rate compared to the Zijpepolder will experience a decrease in effectivity of the water level buffer in reducing flood damage for short precipitation events. An example is that polders with a 30% lower infiltration rate, will experience a decrease in effectivity of 6.8%.

Also, polders which have a lower storage capacity than the Zijpepolder, will experience a decreased effectiveness of the water level buffer measure in reducing the flood damage of short precipitation events. For example, a decrease of 30% in storage capacity, results in a decrease in effectivity of the water level buffer measure in reducing flood damage of 7.8%.

As the differences in scores in the multi criteria decision analysis for the flood damage criteria are only minimal for the different measures, it is advised to check for polders with a lower infiltration rate and a lower storage capacity than the Zijpepolder, whether the results of reduction in flood damage of other measures are also affected by a change in infiltration rate or not.

For polders who have different friction and different interception capacities compared to the Zijpepolder, the water level buffer would still be most effective in reducing the flood damage for short precipitation events, as only minor changes in flood damage can be noticed when these terrain characteristics are varied.

### 4.6.4. Inundated area

Overall, the emergency pumps measure works best for reducing the inundated area. How this measure is affected by changes in terrain characteristics is unknown, since it has not been tested. However, for both short precipitation events, the water level buffer is most effective, as shown in figure 18. There are some trade-offs regarding the reduction of the inundated area in polders with different terrain characteristics. These are mentioned below.

For polders with a lower infiltration rate, and a lower storage capacity than the Zijpepolder, the effectivity of the water level buffer measure decreases. When the infiltration rate and the storage capacity decrease with 20%, the effectivity of the water level buffer measure will decrease with 26.6% and 7.6% respectively.

As the differences in scores in the multi criteria decision analysis for the inundated area criteria are only minimal for the different measures, it is advised to check for polders with a lower infiltration rate and a lower storage capacity than the Zijpepolder, whether the results of reduction in inundated area of other measures are also affected by a change in infiltration rate or not.

In case the friction and interception capacity of a polder are different compared to the Zijpepolder, the water level buffer measure would still be most effective in reducing the inundated area for short precipitation events, as the results of the inundated area do not change majorly when these terrain characteristics change.

# 5. Discussion

The objective of this research was ’to investigate how flooding of polders during the preparation phase preceding an extreme weather event can be reduced, taking climate change into account’. This chapter will critically discuss the results and how the methodology that has been used has affected the results of the research.

## 5.1. Investigating potentially effective measures to reduce flooding (RQ 1)

Investigating what measures would possibly reduce flooding, was done to achieve the first part of the research objective. This was done using literature research and performing two semi-structured interviews. Ideally, at least three to five interviews should have been conducted. However, due to limited availability of experts and limited time, only two interviews have been conducted. Therefore, it is important to recognize that the findings may have been influenced by an individual opinion and experience. An example illustrating this is that interviewee #1 says there is no time to properly consider which emergency pumps are best placed where when he thinks back to the June 2021 flood, which is his only frame of reference (For a full transcript of the interview, See Appendix G). This comment is thus based on a single individual's experience. The facto that only two interviews have been conducted also limits the possibility of comparing different responses and comparing their perspectives. If more interviews could have been conducted, the results would have been more robust. Moreover, the findings would then have been better representing the vision of the team of experts on this topic, instead of only two individuals.

## 5.2. Modelling flood reducing measures in 3Di (RQ 2a)

After the selection of the measures, the measures were implemented into 3Di. This was done differently for all measures. For the water level buffer there was chosen to lower the start and stop pumping level with 10 cm. This created there to be a buffer of 10 cm. However, there was not taken into account whether or not the receiving waterbody, to which the water is pumped, could handle these volumes of water. As a result, it is uncertain in reality whether this measure will cause flooding outside the boundaries of the polder. Moreover, the risks of lowering the water level during summer has not been studied yet. If the polder is drained but the rain falls in the adjacent polder, the polder may run dry. Therefore, this measure cannot yet be safely put into practice by the Hoogheemraadschap Hollands Noorderkwartier. However, if research is done into this, the risks and benefits can be weighed against each other to achieve safe implementation.

The mills are implemented as normal pumps in the model. However, in reality, they are pumps that depend on wind to function. This is not accounted for in the model. If this was included in the model, it would be easier to estimate whether the mills are really capable of draining the amount of water as currently assumed. In the results, the capability of the old mills might therefore be overestimated.

The temporary flood barriers are modelled as levees in 3Di. However, the levee might idealise the temporary flood barriers, because temporary flood barriers are in reality separate parts that are joined together. These can therefore come apart more easily than a levee would. Thus, the strength of the levee will actually be greater than the strength of the temporary flood barrier. The effectivity of the temporary flood barriers measure is therefore overestimated.

The emergency pumps are integrated in the model as being an extra capacity of the polder pumping stations. During flooding, emergency pumps regularly experience failures (Hoogheemraadschap Hollands Noorderkwartier, 2022). However, this is not accounted for in the model because they are modelled as polder mills that cannot fail. Also, there should be enough space next to the polder pumping station to accommodate an emergency pump. Using Google Street View, it was estimated that there is enough space for the chosen locations. However, this is not a scientific way of determining this. Therefore, it would be possible that estimation errors have been made here. As a result, it could be possible that there is not enough space to deploy additional pumping capacity for the chosen locations.

## 5.3. Selection of most effective measure in reducing flooding in the Zijpepolder (RQ 2b)

To select the most effective measure, a multi criteria analysis was used. In this multi criteria analysis, flood duration, maximum water level, flood damage, and inundation area were used to assess the alternatives. The assessment of the measures was done based on simulation results. To obtain these simulation results, precipitation scenarios for 2050 were used to account for climate change. However, the upper scenario for 2050 was used. This means that in reality, it may be the case that less extreme precipitation occurs in 2050 than the measures have been tested for. It may therefore be the case that, for example, the flood duration is over estimated. For the results, however, this will have limited impact as both the original situation without measures, and the scenarios with measures are tested for the same upper scenario of 2050. Moreover, relative differences have been used to determine the most effective measure.

To determine the flood duration and maximum water level, only five locations have been used. This means that the score of these two criteria are directly related to the choice of the test locations. It might be the case that if other test locations were used, the results would be different. However, these location are chosen based on the target level areas that experienced most inundation in the original situation. For these target level areas, a measurement location is chosen which represents the area and does not deviate much from the average of that target level area.

The flood damage is calculated by adding the direct and indirect damage. A disadvantage of the way that damage is calculated is that it takes a uniform inundation duration into account. This means that for the entire area only one inundation duration could be used. In reality, however, every location within the area has another duration of the inundation, and the longer a certain land use is inundated, the higher the damage becomes and vice versa.

For the inundated area it was assumed that the less area inundates the better. However, there could be argued that if less area inundates, some areas might experience a higher inundation depth. This would not automatically reduce flooding as in this way some people might experience high inundation depths while others do not experience any inundation at all.

In order to assign the measures a score for all criteria, a score of 1 was divided among the measures based on their performance for that specific criteria. However, when a measure did not improve or did worse on that criteria compared to the original situation, a score of 0 was assigned. This means that if one measure worsened for example the flood damage, and with another measure the flood damage stayed the same, they would both get a score of 0. Therefore, some measures might seem more effective than they are in reality. However, in this specific case, only the temporary flood barriers measure scored 0, and despite this measure did not receive a negative score, this measure still scored worse.

Finally, 'The 3Di model is not primarily intended to test water systems against a particular standard precipitation event, but it is intended to create understanding on how systems work and to visualise the effect of interventions to water systems including outdoor space' (van Luijtelaar, 2014). In this report normative values are mentioned, however, the multi criteria decision analysis only takes relative differences into account. Thus, the results on how flooding of polders can be reduced during the preparation phase preceding an extreme weather event, taking climate change into account, is based on a difference in performance of different measures, as the 3Di program is intended to be used for. Calculating with relative differences also has its drawbacks. Using these relative differences instead of normative differences make the results very dependent on the original situation. For example, the flood duration without applying a measure for the precipitation scenario with a return period of 1/10 years and a flood duration of 4 hours for the location Afdeling W is 7.6 hours. When applying the water-level buffer measure, the flood duration is 0 hours. Therefore, the relative difference is 100%. For another location where the flood duration also decrease with about 7 hours (from 71.9 hours to 65.4 hours), the relative difference is only -9%.

## 5.4. Uncertainties of the model results (RQ 2c)

To get insight into the influence of the area-specific properties of the case study the Zijpepolder on the results presented in the previous section, a sensitivity analysis is performed. For this sensitivity analysis the terrain characteristics were varied in a range from -30% to +30%. When the infiltration rate of Zijpe North is increased with 30%, the infiltration becomes 1300 mm/day for some places. This would be unrealistically high as normal sand has an infiltration rate of 720 mm/day (Brouwer, 1985).

Next to that, in the results section was mentioned that the test factors are not sensitive to a change in interception capacity. However, the values for the interception capacity are really small or even zero. When increasing zero with 30% nothing changes and when increasing a really small value with 30% almost nothing changes. Thus, there is not really tested what happens with the test factors for higher interception capacities. Therefore, in areas where the interception values are higher than tested in this multi criteria analysis, it possibly could affect one of the test factors.

## 5.5. Lessons learned from the Zijpepolder which can be applied to polders in general (RQ 3)

The guideline of the Zijpepolder and the sensitivity analysis were used to generalise the lessons learned from the Zijpepolder. However, this sensitivity analysis was only performed for the measure that appeared to be most effective in reducing flooding during the preparation phase of an extreme weather event, which was the water level buffer. Therefore, it was unknown how the other three measures would be affected by changing terrain characteristics. This made it impossible to make conclusions regarding whether there were measures that were less affected by changing terrain characteristics than the water level buffer measure was. Thus, it could only be stated for which change in terrain the water level buffer measure was sensitive to, but it could not be stated whether or not this would be also applicable for the other measures. If a sensitivity analysis was performed for the other three measures as well, better advice could be given in which measure would be most effective under the changing circumstances.

# 6. Conclusion and Recommendations

In this chapter, the conclusion of this research will be given. After that, recommendations will be given for future research into this topic.

## 6.1. Conclusion

This research is set out to answer the main research question: 'How can flooding of polders be reduced during the preparation phase preceding an extreme weather event, taking climate change into account?'.

Based on literature research and two expert interviews, four measures appeared to possibly reduce flooding in the preparation phase of an extreme weather event. These were, creating a water level buffer, activating the old mills in the area, installing temporary flood barriers, and installing emergency pumps.

After implementing these measures into 3Di, they were tested for different precipitation scenarios. They were tested for both a precipitation duration of 4 hours and 48 hours, and a return period of both 1/10 years and 1/100 years. The precipitation values that were used were estimations of the precipitation amount of 2050, in order to take climate change into account (Beersma et al., 2019). Based on a multi criteria decision analysis, in which the flood duration, maximum water level, flood damage, and inundated area were used as criteria, the water level buffer measure appeared to be most effective as it scored 1.86 compared to 1.08, 0.74, and 0.32 for emergency pumps, activating the old mills, and temporary flood barriers respectively.

The sensitivity analysis showed that the flood duration and the inundated area are especially sensitive to a reduction in infiltration rate in case the water level buffer measure is implemented. A decrease in infiltration rate of 30% led to an increase of 103.3% and 37.9% for flood duration and maximum water level respectively. For a decrease in storage capacities, the flood duration, the flood damage, and the inundated area were sensitive. A decrease of 30% in storage capacity led to an increase of 34.3% , 7.8%, and 14.1%, for flood duration, flood damage and inundated area respectively. There can thus be concluded that for polders with a significant lower infiltration rate or lower storage capacities than the Zijpepolder, the water level buffer measure is a lot less effective. There was also shown that an increase in terrain characteristics had only a minor effect on reducing the flood duration, maximum water level, flood damage, and inundated area. Therefore it can be concluded that polders with better, for example, infiltration rate, will experience equal, or only slightly better working of the water level buffer measure.

It can be concluded that overall the water level buffer is most effective in reducing flooding. More specifically, the water level buffer measure is most effective in reducing the flood duration and the maximum water level. However, under decreasing infiltration rates, and decreasing storage capacities, the water level buffer measure is significantly less effective. For reducing the flood damage, activating the old mills is most effective, and for reducing the inundated area, the emergency pumps measure is most effective.

## 6.2. Recommendations

Recommendations for future research will be done here.

Firstly, The number of locations for which the flood duration and maximum water level were tested could be expanded. In stead of choosing 5 target level areas for which 1 location has been tested, there could be chosen more target level areas for which more locations would have been tested. This research only used 5 target level areas, which obtains us with a first impression that the water level buffer measure is most effective. For validation, more target level areas and location within the target level areas should be tested to check if the water level buffer measure then still appears to be most effective.

Secondly, there is recommended to do an analysis in which the reliability of the measures is taken into account. For example, for the measure in which the old mills in the area are activated, there must be enough wind for them to function. However, this is not taken into account in this analysis. If this would be taken into account, decision makers could also base their considerations on reliability of the measure rather than only on the performance. There is thus recommended to do further research into the reliability of the measures.

Thirdly, a sensitivity analysis was performed to check the effect of the terrain characteristics on the performance of the water level buffer measure. It appeared that the water level buffer measure was highly sensitive for a change in infiltration rate and a change in storage capacities for multiple test factors. However, it could not be stated whether or not the other measures are also sensitive to a change in one or multiple of the terrain characteristics. Therefore, no conclusions could be drawn whether or not other measures would might be more effective under the changing terrain characteristics. Thus, for future research there is recommended to also perform a sensitivity analysis for the activating the old mills measure, the temporary flood barriers measure and for the emergency pumps measure.

Lastly, there is recommended to do further research into the effects of the water level buffer measure. As mentioned before, there are risks associated with draining the polder during the summer. If the precipitation then falls into the adjacent polder, the whole polder will be dry. Future research should critically weigh the risks of this measure against the benefits. In this way, it can be decided how and if this measure can be put into practice safely.

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# Appendix A: Test locations for flood duration and maximum water level

In figure 19 and figure 20, the inundation maps for the Zijpepolder are shown for a precipitation duration of 4 hours and 48 hours respectively in the case that no measures are implemented. The inundation maps show in dark blue what areas will inundate already during a precipitation event with a return period of 1/10 years. These areas are marked as ‘very vulnerable’. The maps show in light blue what areas will inundate during a precipitation scenario of 1/100 years but do not inundate during a precipitation event with a return period of 1/10 years. Therefore, these areas are considered to be ‘vulnerable’. The pink areas are the storage areas. These should be completely inundated, since they are areas where as much water as possible is stored in case of excessive water.

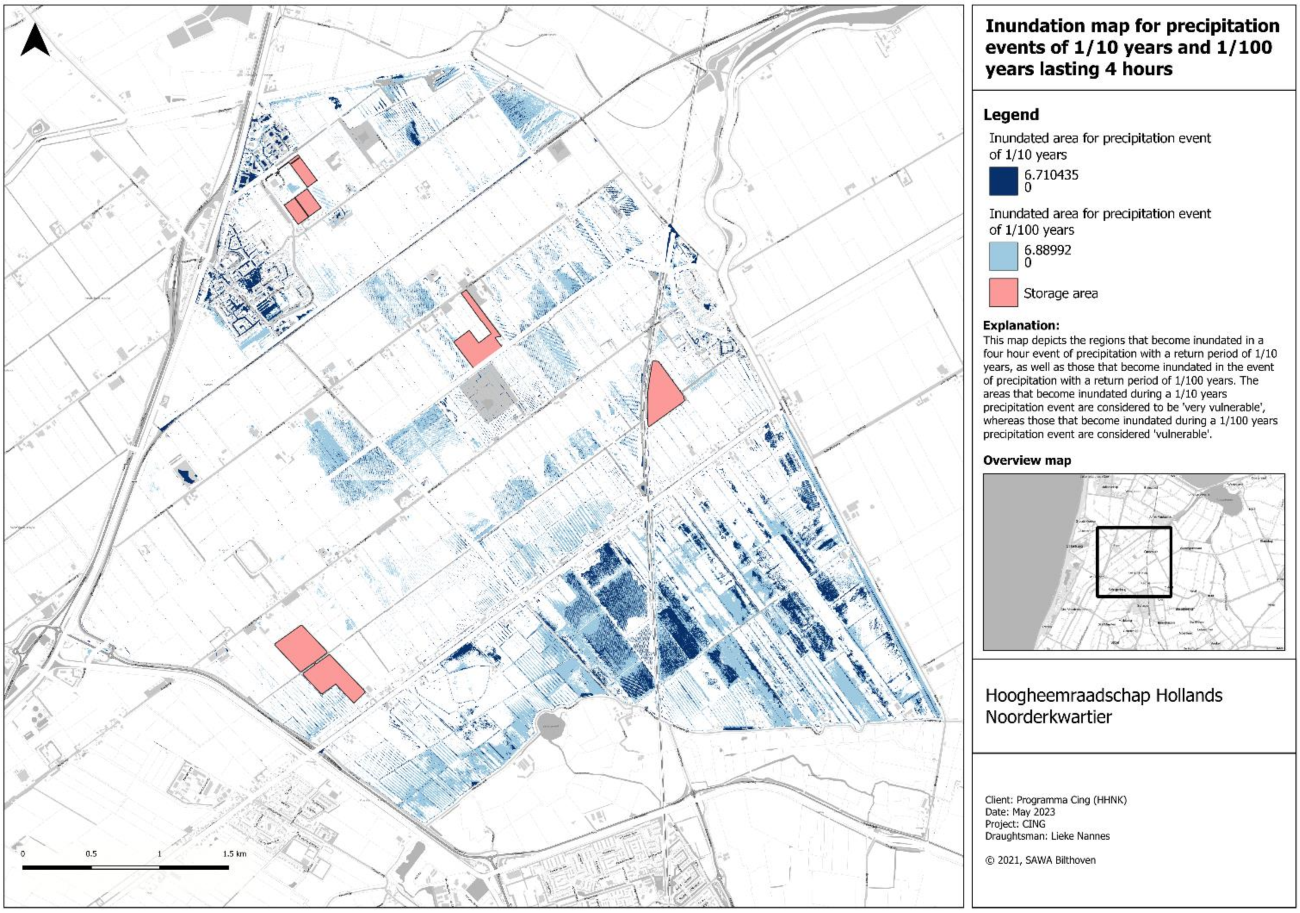


*Figure 19: Inundation map for precipitation events of 1/10 years and 1/100 years lasting 4 hours.*

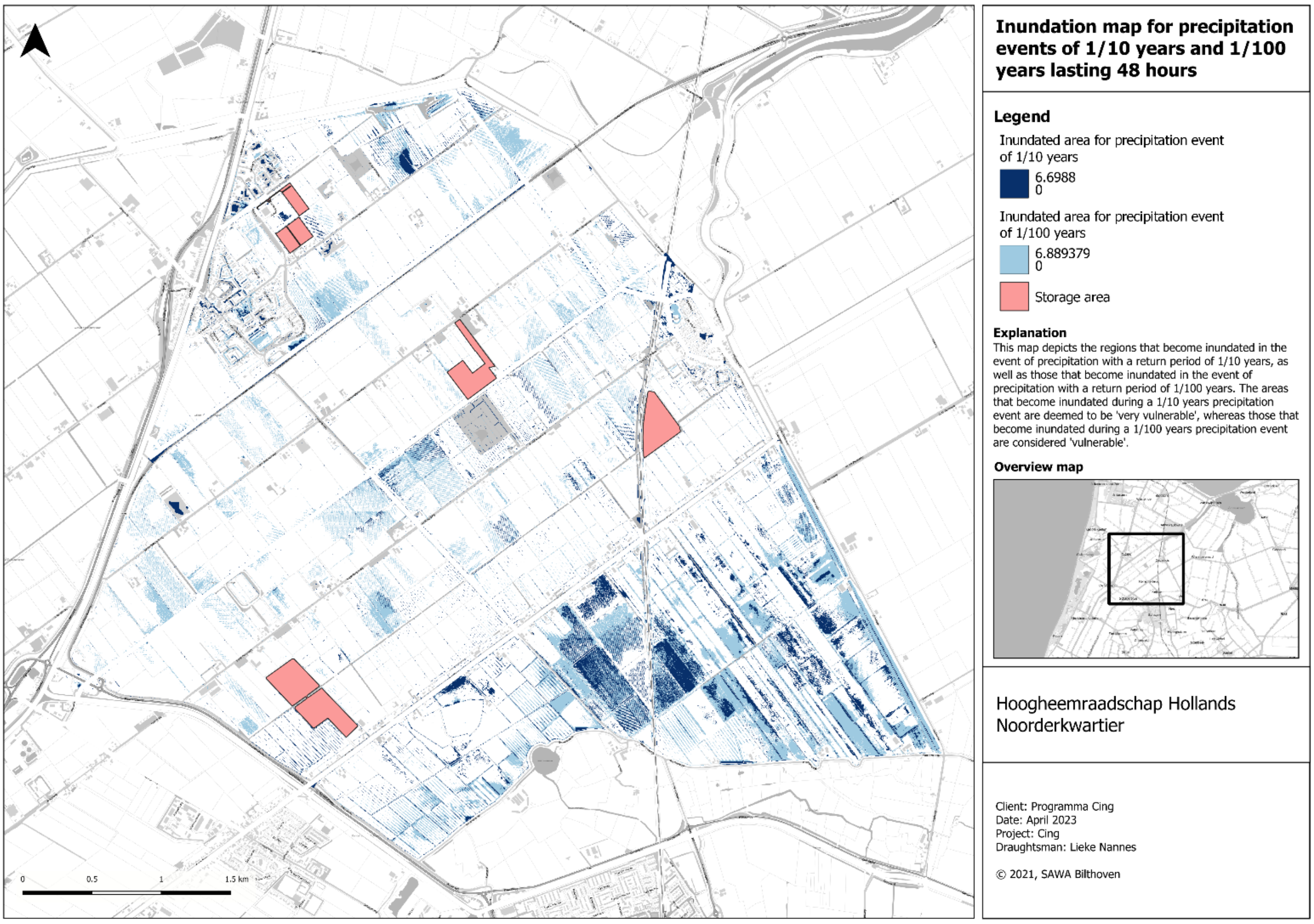


*Figure 20: Inundation map for precipitation events of 1/10 years and 1/100 years lasting 48 hours.*

As can be seen, especially the South Eastern part of the area suffers from flooding. This can be deduced from the fact that the elevation is lower in the Eastern part of the area than in the Western part of the area, as explained in the case study description in section 2.1. Also, the urban area in the North Western part of the area suffers from flooding during a four hour precipitation event. During the 48-hour precipitation events, the entire rural area suffers slightly from excess water at ground level. However, during the 4-hour precipitation events, this is centred towards the middle of the area This can be explained by more flooding of the main drain and receiving water bodies during long block precipitation and more flooding from the collector drains and sub-main drains during short peak precipitation. With short peak precipitation, it is thus localised and not yet extended to the major watercourses. With long block precipitation, there is more flooding along large watercourses (van Leeuwen, 2017).

Based on these maps, five locations have been chosen that experience flooding. These locations are shown in figure 21. Each location is in a different water level area, which means a different target level is used. Within each target level area, a measurement location, which is relatively close to the main drains have been chosen. This is done because all the water will be drained towards those main drains and therfore these locations will definitely experience an increase in water level during extreme precipitation events. The target level areas with their corresponding target levels are shown in figure 21.

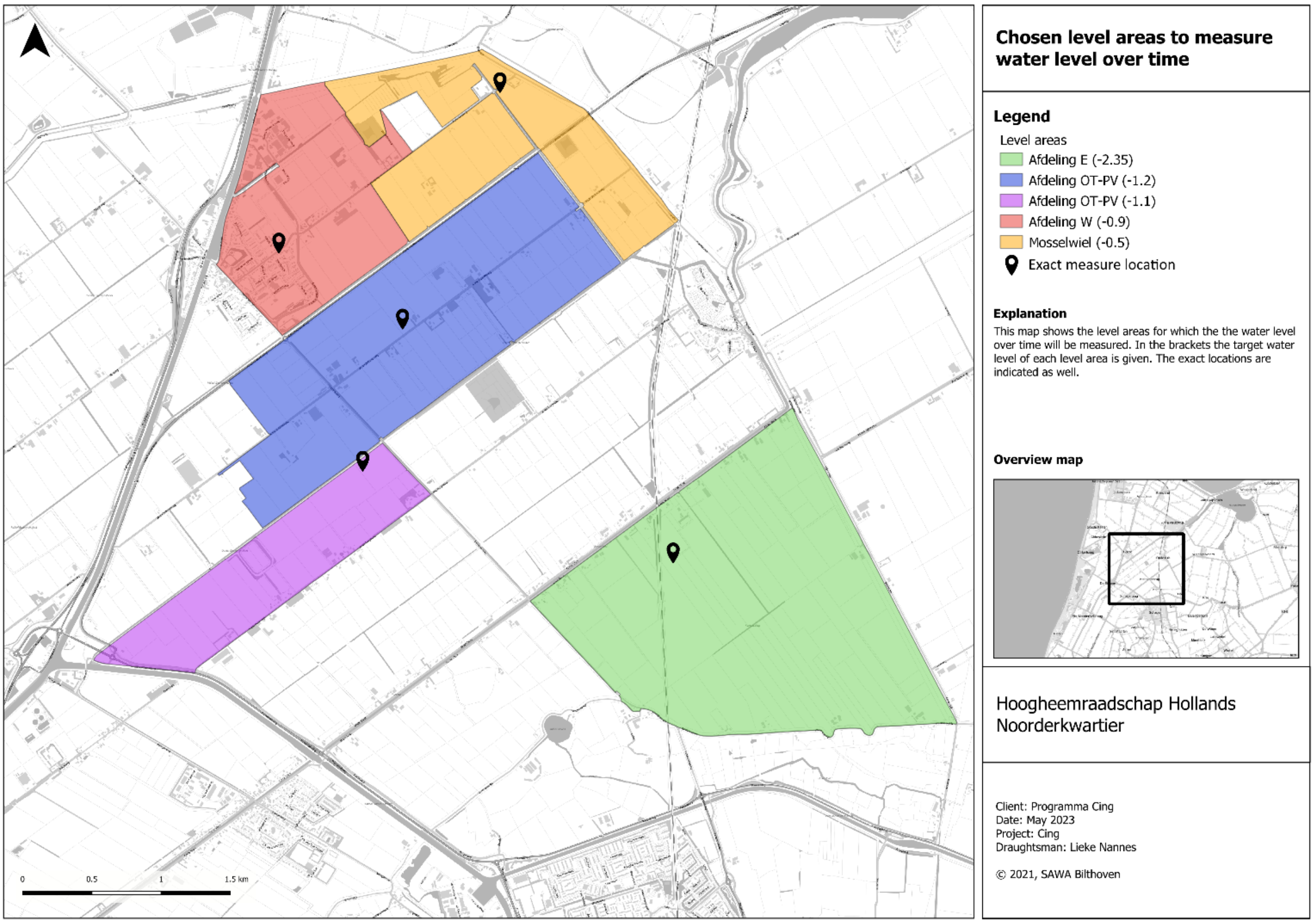


*Figure 21: Measurement locations for flood duration and maximum water level.*

## Appendix B: Damage calculation

This Appendix shows how the damage, which is used as criteria for the multi criteria decision analysis, is calculated. The formula to calculate the direct damage is as follows;

$$S_{direct} = D_{i,j} * \gamma_{depth} * \gamma_{duration\_direct} * \gamma_{season} \tag{1}$$

Where;

| | |
|---|---|
| $S_{direct}$ | = Direct damage. [Euros] |
| $D_{i,j}$ | = Amount of damage dependent on land use (i) and minimum, average or maximum scenario (j). [Euros] |
| $\gamma_{depth}$ | = Reduction factor dependent on the inundation depth. |
| $\gamma_{duration\_direct}$ | = Reduction factor dependent on the duration of flooding. |
| $\gamma_{season}$ | = Reduction factor dependent on the season |

The WaterSchadeSchatter uses a minimum, average or maximum scenario to quantify damage. For this research, the average scenarios were used. This choice is considered to be most realistic as it strikes a balance between avoiding underestimation and overestimation of the damage. The quantification of the damage is based on the price level of 2015 (Boomgaard, 2018).

The inundation depth is important because the damage for some land uses depends on this. Different reduction factors apply to each land use. The more damage something gets the smaller the reduction factor is. For instance, the damage reduction factor of residential function ranges from 0.016 to 0.76 at an inundation depth of 0.01 to 0.5 metres, respectively. From 1.5 meters onwards, reduction factor dependent on the inundation depth is equal to 1.0 for residential land use.

Also, the duration of the flooding impacts the damage. The longer it takes, the higher the damage. For example, flower bulbs have no damage at all after one and twelve hours of flooding, so the reduction factor is 0. However, from 24 hours they have some damage, with a reduction factor of 0.2. After three days, the state of the bulbs become irreversible, which causes much damage and a reduction factor of 1.0.

Finally, the season also influences the amount of damage. In this research the month June is used as the flooding in June 2021 was the reason for this research. For June, each land use has a reduction factor of one. This means that in June the damage is maximal compared to other months. In winter, reduction factors of 0.1 to 0.9 occur.

The indirect damage is calculated using equation 2.

$$S_{indirect} = D_{i,j} * \gamma_{duration\_direct} \tag{2}$$

Where;

| | |
|---|---|
| $S_{indirect}$ | = Indirect damage. [Euros] |
| $D_{i,j}$ | = Amount of damage dependent on type of building (i) and minimum, average or maximum scenario (j). [Euros] |
| $\gamma_{duration\_direct}$ | = Reduction factor dependent on the duration of flooding and the repairs. |

## Appendix C: Test setup for simulations

In table 7, the test setup is shown. It has been assumed in this setup that five measures would possibly reduce flooding in polders during the preparation phase of an extreme weather event. The simulated measure with number 0 represents the original situation in which no additional measures have been applied.

*Table 7: Test setup for different test scenarios.*

| **Measure that is simulated** | **Scenarios** | **Return period [years$^{-1}$]** | **Duration precipitation [hours]** |
|---|---|---|---|
| 0 | 1 | 1/10 | 4 hours |
| 0 | 2 | 1/10 | 48 hours |
| 0 | 3 | 1/100 | 4 hours |
| 0 | 4 | 1/100 | 48 hours |
| 1 | 1 | 1/10 | 4 hours |
| 1 | 2 | 1/10 | 48 hours |
| 1 | 3 | 1/100 | 4 hours |
| 1 | 4 | 1/100 | 48 hours |
| 2 | 1 | 1/10 | 4 hours |
| 2 | 2 | 1/10 | 48 hours |
| 2 | 3 | 1/100 | 4 hours |
| 2 | 4 | 1/100 | 48 hours |
| 3 | 1 | 1/10 | 4 hours |
| 3 | 2 | 1/10 | 48 hours |
| 3 | 3 | 1/100 | 4 hours |
| 3 | 4 | 1/100 | 48 hours |
| 4 | 1 | 1/10 | 4 hours |
| 4 | 2 | 1/10 | 48 hours |
| 4 | 3 | 1/100 | 4 hours |
| 4 | 4 | 1/100 | 48 hours |
| 5 | 1 | 1/10 | 4 hours |
| 5 | 2 | 1/10 | 48 hours |
| 5 | 3 | 1/100 | 4 hours |
| 5 | 4 | 1/100 | 48 hours |

## Appendix D: Sensitivity calculation

The sensitivity of the water level buffer measure were drawn in figures where the sensitivity was plotted as a percentage change in output on the y-axis versus a percentage change in input on the x-axis. The percentage change in output was calculated using equation (3).

$$y = \frac{final - initial}{initial} * 100\% \tag{3}$$

Where;

| | | |
|---|---|---|
| $y$ | = | sensitivity of flood damage/flood duration compare to initial parameter set. [%] |
| $initial$ | = | model parameter output after original default value. |
| $final$ | = | model parameter output after input value change. |

The original default value is in this case the situation in which the water level buffer measure is applied, but no changes have been made to the terrain characteristics. Below, a description on the terrain characteristics is provided.

# Appendix E: Infiltration rates in the Zijpepolder

In figure 22, it can be seen that the infiltration rate of the sand in the Western part of the Zijpepolder is higher than the infiltration rate of the clayey part in the East of the Zijpepolder.

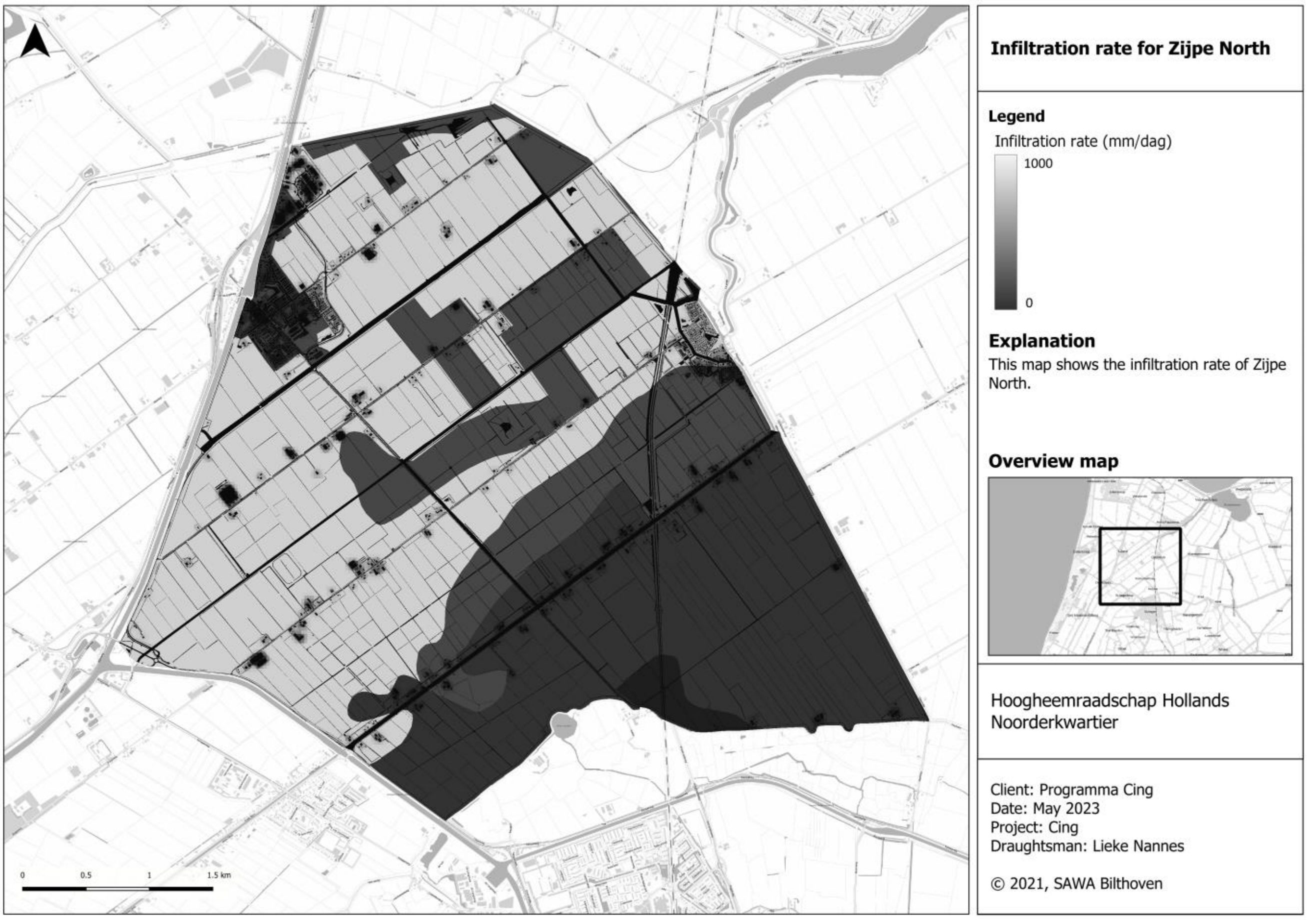


*Figure 22: Infiltration rates in the Zijpepolder.*

# Appendix F: Storage capacities in the Zijpepolder

In figure 23, the storage capacities of the Zijpepolder are shown. For the clayey part in the East, the storage capacities are obviously lower than for the sandy part in the West.

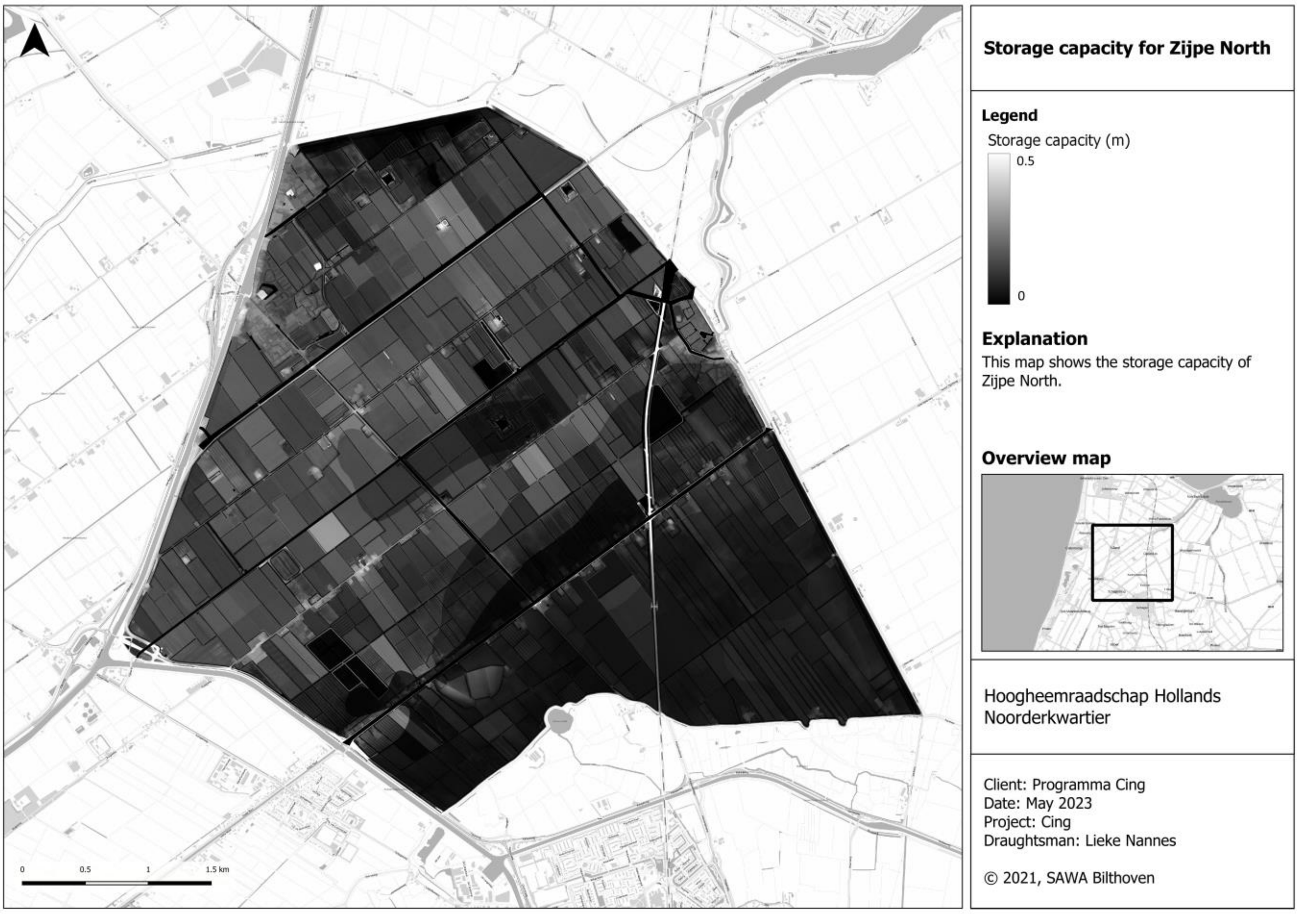


*Figure 23: Storage capacities of the Zijpepolder.*

# Appendix G: Interview transcripts

## Interview with interviewee #1

Interviewed: #1

Interviewer: Lieke Nannes (L)

Date: 5th May 2023, 9 A.M.

Location: Teams

Voorafgaand aan dit interview heb ik geïntroduceerd waar mijn onderzoek over gaat.

L: Bedankt dat je de tijd hebt genomen voor dit interview. Ik heb verschillende vragen voorbereid. Van te voren is het moeilijk om voor mij te beoordelen of je ze allemaal kan beantwoorden, maar als dat niet het geval is hoor ik graag. Ook als je nog andere interessante dingen doe te voegen hebt dan hoor ik het graag.

#1: Laat maar horen!

L: De eerste vraag is of het Hoogheemraadschap Hollands Noorderkwartier een specifieke strategie nastreeft tijdens een crisissituatie met hun beleid? Hier kun je denken aan of ze iets specifieks willen beschermen, dus bijvoorbeeld stedelijk gebied of landelijk gebied?

#1: Daar is wel over nagedacht en voor het Hoogheemraadschap kun je spreken over verschillende soorten scenario's van crisis. Het wateroverlast scenario wat we in Juni 2021 hadden, dan valt er heel veel regen en dan stijgt overal het water een beetje. Je kunt natuurlijk ook denken aan een hevige storm of aan een dijk die het niet houdt of een cyberaanval maar ook aan een water kwaliteit issue. Ze hebben dus allerlei scenario's van verschillende soorten waar ze dan weer plannen voor hebben gemaakt en ik denk dat ons interview voornamelijk over water overlast gaat.

L: Ja, het gaat voornamelijk over wateroverlast door overtollige neerslag.

#1: Het standaard beleid dat het Hoogheemraadschap heeft is het zo veel mogelijk afvoeren, want daar is natuurlijk het hele systeem op ingericht. Dus ze hebben voor zover ik weet geen gedifferentieerd beleid binnen het afvoergebied. Er is wel bijvoorbeeld opgeschreven wanneer er een maalstop moet komen. Dat is als de boezems zodanig hoog worden dat de boezem het niet dreigt te houden dan kunnen ze een maalstop aankondigen voor een aantal gemalen, maar dat betekent dat het gebied daarachter natuurlijk verder gaat oplopen in de waterstand. Dit is voornamelijk gebaseerd op het beschermen van de boezen en niet zozeer op wat er in die gebieden daarachter zit. Dus er is voor zover ik weet geen beleid om binnen dat gebied dingen beter of minder goed te beschermen, het is allemaal gebaseerd op afvoer.

L: Dus het beleid zegt eigenlijk dat alles binnen het gebied gelijk staat en dat het gezamenlijke doel is om zoveel mogelijk af te voeren zodat zoveel mogelijk water zo snel mogelijk weg is.

#1: Ja, en dat heeft er ook wel mee te maken denk ik dat er in deze overlast scenario's geen sprake is van mensenlevens, want we hebben het over het algemeen over waterstanden die niet extreem hoog zijn en die ook wel weer weglopen, waardoor het voornamelijk wateroverlast scenario's zijn en geen overstromingsscenario's.

L: Oké. De volgende vraag is welke crisismaatregelen past het HHNK momenteel toe specifiek op bestrijding van wateroverlast?

#1: Volgens mij zou je het op twee manieren kunnen beantwoorden; Wat hebben ze nou voor technische maatregelen voor het waterbeheer, dus wat doen ze in het veld om te zorgen dat het water beter afgevoerd wordt en wat hebben ze nou voor maatregelen in de crisisstructuur om te zorgen dat je een organisatie hebt waarbinnen je die werkzaamheden kunt uitvoeren. Die eerste, dus wat doen ze nou technisch allemaal in het veld, daar moet ik eerlijk op zeggen dat ik daar niet zoveel van weet. Ik weet dat ze allerlei mensen op gebiedsbeheer en op onderhoud hebben, die lopen de hele dag het veld in om inlaten open te zetten en de afvoeren te bekijken, enzovoort. Er zijn ook allerlei noodpompen die ingezet kunnen worden. Daar hebben ze er volgens mij 20 van ter beschikking. Er is niet van te voren nagedacht waar die moeten staan, dus er wordt op het moment zelf gekeken waar die moeten staan en daar zit wel een leerpunt uit 2021, want eigenlijk zou je per gebied, dus bijvoorbeeld de Zijpe, van te voren moeten nadenken waar je die pompen wilt hebben, dus wat zijn nou de beste plekken om die pompen neer te zetten als er zoveel water in het gebied staat. Datzelfde geldt voor de pompen van de agrariërs, want we merken ook dat bij wateroverlast er heel veel boeren zijn pompen inzetten en niet altijd de moeite nemen om te overleggen waar ze die neerzetten, dus die kunnen ook heel goed op plekken staan die eigenlijk helemaal niet handig zijn. Daar zit dus echt nog winst en ruimte voor verbetering in, in hoe gaan we nou de pompcapaciteit die er bijgezet wordt optimaliseren en wat is je plan daarvoor.
Het idee vanuit de crisisbeheersing is dat je een structuur hebt waarbij je een soort waterschap actie team hebt waar een voorzitter op zit en iemand die de informatie doet en die moet dan eigenlijk dat aansturen waar al die dingen gebeuren en dat is allemaal netjes opgeschreven in het calamiteitenbestrijdingsplan van het Hoogheemraadschap. Daarin staat dus beschreven wanneer zo'n team bij elkaar komt en wie er team zitten. Dat plan heeft ook niet helemaal goed gefunctioneerd maar die structuur staat er in principe wel.

L: Ja, je noemde een paar maatregelen zoals pompen neerzetten, inlaten dichtzetten en de afvoeren bekijken, denk je dat deze maatregelen allemaal effectief zijn om nog in werking te stellen tijdens zo'n situatie?

#1: Nou ik denk dat het inzetten van extra pompcapaciteit dat dat zeker zin heeft. Het is een beetje afhankelijk van waar ze het water naartoe kunnen pompen en hoe hoog het water daar staat, maar als er in de boezem nog ruimte is dan kun je gewoon water afvoeren, extra water. We zijn nu ook in overleg met de brandweer, die hebben weliswaar kleinere pompen, van 7 $M^3$, maar er zijn ook best wel heel veel kleinere poldertjes waar ook een gemaal op staat van 5-6 $M^3$, waar mee je met zo'n extra capaciteit van de brandweer toch zo'n poldertje sneller leeg krijgt. Het inzetten van noodpompcapaciteit tijdens wateroverlast is volgens mij dus gewoon een prima maatregel waarbij je het effect van de wateroverlast kunt verkorten. Je zou ook preventief natuurlijk een lagere waterstand kunnen organiseren in heel veel waterlopen alleen ik heb geen idee hoeveel het oplevert. Ik heb gewoon geen idee hoe dat in verhouding staat tot de regen die dan valt en de overlast, dus dat is wel interessant. Maar goed, hoe minder water er in het systeem zit hoe meer er bij kan en hoe meer je dan ook met noodcapaciteit kunt afvoeren hoe minder lang de overlast is. In principe, theoretisch lijkt dat een redelijk logisch verhaal.
De maatregelen van inlaten open zetten en dergelijke, ik heb gewoon geen idee in hoeverre dat effectief is en in hoeverre ze dat wel of niet al doen, ik weet gewoon niet in hoeverre die maatregelen heel veel toevoegen.
Wat ik wel begrijp is dat er af toe storingen zijn dat er veel vervuiling is, dan is het handig dat je die afvoeren openmaakt en dat je die storingen oplost. Dus om voldoende capaciteit in het veld te hebben om te zorgen dat alles wat je al geregeld hebt ook blijft functioneren, dat is wel belangrijk.

L: Zijn er ook maatregelen of dingen die volgens het plan of protocol gedaan moeten worden maar waar in de realiteit geen tijd voor is? Dus waar je eigenlijk niet aan toekomt?

#1: Het enige referentiekader wat ik heb is de inzet in Juni 2021, dus als we dat even als maatstaf nemen, waarbij ik natuurlijk niet kan zeggen of dat altijd zo gaat en meer voorbeelden hebben we zo ook niet direct, dan zien we wel dat er eigenlijk helemaal geen tijd is voor het afstemmen bijvoorbeeld van die noodpompen. Wat moet nou waar heen? En de pompen moeten weer opgehaald worden en kan het niet beter ergens anders staan? Dus die hele inzet van het noodpompen materieel is gewoon eigenlijk intuïtief gegaan. Je ziet dat mensen die dat zouden kunnen doen of dat bepalen dat die gewoon te druk waren. Er waren ook heel veel storingsmeldingen volgens mij vanuit die TMX meldingen, dus al die gebiedsbeheerders kregen allemaal meldingen over dat de waterstanden te hoog waren. Die gebiedsbeheerders werden dus helemaal overbeladen, waardoor ze helemaal niet meer goed konden communiceren. Hierdoor was het ook onvoldoende duidelijk welke afvoeren er nou wel of niet functioneerde omdat ze te veel moesten doen en bekijken. Dus om te kijken naar hoe de waterafvoer is zijn geheel nou functioneert, en eventueel probleem oplossen, daar is eigenlijk te weinig capaciteit voor op zon moment.

L: Het komt er dus op neer dat er een tekort aan mensen is die op dat moment in het veld bezig kunnen zijn.

#1: Ja, dat denk ik wel.

L: Zijn er ook maatregelen die volgens het protocol genomen moeten worden maar waarvan je denkt dat de effectiviteit laag is?

#1: Geen idee, dan zou je echt met iemand van waterveiligheid, of hoe heet die club, echt over de inhoud moeten praten die dat plan gemaakt heeft.

L: Dan gaan we door naar de volgende vraag. Op welke manier worden burgers geïnformeerd of betrokken bij de crisismaatregelen die genomen worden?

#1: De communicatie kanalen van het Hoogheemraadschap zijn vooral de website, maar ook een blog, de chat, en de mensen die bellen worden te woord gestaan via het KCC, het klanten contact centrum. Er worden volgens mij ook wel interviews gegeven, maar dat zijn de belangrijkst algemene kanalen, de website, de blog, en de chat die daarbij zit. Dat zijn dus concreet de belangrijkste kanalen.

L: Naast dan de boeren zelf noodpompen neerleggen, worden ze verder ook nog betrokken bij maatregelen die genomen worden?

#1: Ja, er is een algemene handelingskader gemaakt, waarin algemene dingen staan die mensen zelf kunnen doen bij hoogwater. Wat we nog niet doen, is specifiek geografisch bekeken aanwijzingen geven of advies geven over wat mensen of die locatie meemaken. We hebben gewoon geen goed beeld nog van wie er belt, waar die zit, in relatie tot wat daar precies gebeurt. Dat is wel een van de dingen die we graag zouden willen, dus dat je veel gerichter advies kunt geven.

L: Dus zodat je de burgers een duidelijker beeld kunt geven van wat ze het beste kunnen doen om de water overlast te verminderen?

#1: Ja om te kijken wat er op die plek precies gebeurt.

L: Zijn er maatregelen die nog niet doorgevoerd worden maar die wel van toegevoegde waarde kunnen zijn in de bestrijding van wateroverlast?

#1: Theoretisch zou je ook binnen een bepaald gebied, verschil kunnen hebben in de mate van ellende die hoog water veroorzaakt. Als je daar op zou kunnen sturen zou je natuurlijk schadebeperkend kunnen optreden. Dus in een gebied de Zijpe nog kunt variëren met waterhoogtes omdat je weet als dat onderloopt hebben we meer schade dan als dat onderloopt, dan zou je daar natuurlijk ook echt iets mee kunnen doen. Dit is vooral een theoretisch beeld en ik weet gewoon niet of dat in de praktijk ook werkt. Er wordt nu dus niet gestuurd binnen een poldergebied, behalve op gewoon maximaal afvoeren. Dus binnen het gebied zelf worden niet nog keuzes gemaakt. Het lijkt mij dus interessant om te onderzoeken of specifieke bescherming iets zou toevoegen.

L: Heb je een idee waarom dit nog niet gedaan wordt?

#1: Volgens mij omdat de kennis gewoon niet aanwezig is. De kennis is gewoon niet aanwezig hoe binnen die gebieden waarde zou kunnen worden toegekend aan verschillende deelgebieden. Er zijn dus ook geen afspraken, ook bestuurlijk niet en ik denk dat het ook voor het bestuur ook een ingewikkeld gesprek wordt, want nu kun je als waterschap zeggen we doen gewoon maximaal ons best en dit is wat we kunnen. Als je keuzes moet gaan maken binnen een gebied moet je dus sommige mensen bewust schade laten krijgen en sommige niet en dat is natuurlijk een heel lastig gesprek in zo’n bestuur.

L: Je kunt dan natuurlijk ook een geval hebben dat bepaalde mensen minder schade gaan krijgen maar dat andere mensen die nog geen schade hadden nu ineens wel schade krijgen dus hoe ga je ze dat dan ook uitleggen.

#1: Ja, ja en hoe ga je dan schade wegen, is dat alleen financieel of hoe weeg je dat dan tegen iemand wiens eeuwenoude boerderij nu schade heeft die al lang in de familie zit en allemaal emotionele schade heeft. Dat zijn allemaal ingewikkelde discussies. Maar goed, zolang we het niet weten hoeven we die discussie niet te voeren, maar ik denk dat het goed is dat we het in ieder geval wel weten en we bewust wel of niet de discussie voeren.

L: Ja dat klopt zeker. Dan is het tijd voor de volgende vraag; Wordt klimaatverandering meegenomen in de beslissing hoe het crisisplan wordt uitgevoerd of welke maatregelen er worden genomen?

#1: In 2018, en dat staat nu weer op de planning, kijken ze vanuit het Hoogheemraadschap naar welke scenario’s er nou relevant, waar moeten we ons nou op voorbereiden en daar zit ook wel in zoverre klimaatverandering in dat sommige scenario’s van wat extremere regenval of hoog water relevanter geworden zijn. Tegelijkertijd, klimaatverandering vindt niet acuut plaats van vandaag op morgen, dat is een langer lopend proces. We hebben het vooral over zeespiegelstijgingen die natuurlijk pas over jaren optreden en dat maakt niet uit voor de crisis van morgen of overmorgen.

L: Heb jij een idee welke scenario’s dan nu relevanter worden door klimaatverandering?

#1: Wat ik weet is dat we de stellingen hebben overgenomen dat het vaker droog is en dat het vaker nat is, dus dat er vaker droogte zal optreden, maar dat we ook veel vaker clusterbuien waarbij er kortdurende hevige wateroverlast zal zijn. Volgens mij is er in het kader van de zeespiegelstijging ook wel gekeken wat dat nou betekent voor de primaire keringen en lopen we daar nou groter risico of niet, maar volgens mij heeft dat niks acuuts opgeleverd. Het is vooral de wateroverlast en de droogte scenario’s dat het probleem zal vormen.

L: Oké. Dan zijn we bij de laatste vraag aangekomen. Wat is de rol van kosten in het maken van keuzes in het crisisplan en de crisismaatregelen?

#1: Nou op dit moment eigenlijk nog niets. Ook omdat het crisisbeheersingsplan gaat uit van de structuur van crisisbestrijding zoals die in het Hoogheemraadschap nu staat en daar zit eigenlijk heel weinig in over de daadwerkelijke uitvoering van bestrijding. Dus hoeveel mensen heb je nou in het veld lopen, dat staat er allemaal niet in, dat staat weer in hele andere plannen van de afdeling zelf. Daar zitten voornamelijk de kosten, ook als je het hebt over schade beperkende temporary flood barriers, dan worden kosten relevant, of hoeveel pompen heb je nou. Dat staat allemaal niet in het algmene calamiteiten bestrijdingsplan. Op dit moment worden kosten dus niet meegenomen, maar ook omdat er eigenlijk niet goed gekeken wordt naar wat nou de beste bestrijding strategieën en wat kun je daar nog aan doen. Als uit jouw onderzoek nou bijvoorbeeld zou blijken dat er een alternatieve strategie mogelijk is, dus niet alleen maximaal afvoeren, maar ook beperkt afvoeren van dat deel en maximaal afvoeren van dat deel, waardoor je extra instrumenten nodig hebt, dan wordt het interessant.

L: Kosten is dus wel iets wat voor het waterschap van belang is, maar wat nu nog niet gedaan wordt.

#1: Ja, dat denk ik wel.

L: Nou super bedankt voor je tijd en voor het beantwoorden van de vragen!

#1: Graag gedaan en ik hoor graag wat er uit het onderzoek komt! Ik zie graag je conclusies verschijnen.

L: Ja, ik zal het naar je toe sturen tegen de tijd dat het onderzoek af is.

## Interview with interviewee #2

Interviewed: #2

Interviewer: Lieke Nannes (L)

Date: 26th May 2023, 9 A.M.

Location: Teams

Voorafgaand aan dit interview heb ik geïntroduceerd waar mijn onderzoek over gaat.

L: Fijn dat je de tijd hebt om wat vragen te beantwoorden.

#2: Ja ik ben heel benieuwd.

L: Dan zal ik maar gelijk beginnen, is er een bepaalde strategie die het HHNK nastreeft in bescherming van het gebied tijdens een crisissituatie?

#2: Ja er is wel een strategie die nagestreefd wordt ja. Over het algemeen willen ze dat er zo min mogelijk schade optreedt. De schade in stedelijk gebied is over het algemeen groter dan de schade in landelijk gebied. Daarom is het idee vaak om stedelijk gebied beter te beschermen. In landelijk gebied heb je dingen als graan en mais die voor de economie niet belangrijk zijn, ook al is het natuurlijk wel het inkomen van de boeren. Dat is dan heel vervelend voor hen en dat is ook wat het nou juist een moeilijke situatie maakt. Het probleem is ook vaak dat boeren zelf aan de slag gaan met pompen die veel meer afvoeren dan dat ze mogen afvoeren. Hierdoor wordt hun eigen landje droog en kan hun oogst gered worden maar daardoor loopt ook het watersysteem helemaal vol waardoor boeren die aan de onderkant van het gebied zitten pech hebben omdat hun land dan vervolgens nog erger onderloopt.

L: Is het toegestaan dat boeren zo'n onderbemaling hebben?

#2: Ja, boeren mogen op basis van de grootte van hun land een bepaalde hoeveelheid water afvoeren. Maar wat het probleem is dat er pompen worden aangeboden in maar vier varianten. De kleinste variant is vaak al groter dan dat ze eigenlijk mogen hebben. Als ze meer mogen hebben dan de kleinste variant, ronden ze dat natuurlijk naar boven af en nemen ze de pomp die nog groter is. In de hele kop van Noord-Holland zijn wel zo'n 1500 boeren die dat nu hebben. Als we dat helemaal zouden willen verbieden zouden we naar de rechter moeten gaan die ons ongelijk zal geven omdat het al jaren mag dus het niet eerlijk zou zijn als dat nu ineens zou worden afgeschaft. Dat is wat dat vooral moeilijk maakt.

L: Welke maatregelen past het HHNK momenteel toe is bestrijding van wateroverlast tijdens een extreme neerslag event?

#2: Natuurlijk pompen neerzetten. Dat zorgt voor extra pompcapaciteit waardoor het water sneller afgevoerd wordt naar de boezem. Dat is natuurlijk altijd handig om het water sneller af te voeren. Inlaten dichtzetten is ook een belangrijke. Op die manier komt er geen water meer de polder in vanuit de boezem. Vooral in zomerperiodes staan deze vaak nog open dus het is dan heel belangrijk om deze dicht te zetten. Anders pomp je water het gebied uit met pompen terwijl er aan de andere kant nog water het gebied in komt door de inlaten. Ook kun je van te voren, als je zo'n bui aan ziet komen, al water de polder uitlaten zodat er uiteindelijk ruimte is om meer water op te vangen. Deze wordt alleen nog niet actief toegepast.

L: Van welke maatregel denk je dat deze het meest effectief is en waarom?

#2: Ik denk dat vooral de maatregel van het aflaten van het water voor een extreem neerslagevent effectief kan zijn. Het nadeel hiervan is wel dat het van te voren moeilijk te voorspellen is waar de neerslag exact zal vallen. Dat maakt het risicovol om in de zomer water alvast af te laten omdat je niet weet of het water ook precies in jouw stukje land gaat vallen. Als het water er niet gaat vallen dan heb je je gebied leeg gepompt zonder dat er nieuw water valt en als er dan nog een periode van droogte komt, komt het gebied in de problemen. Dat is dus wat het risicovol maakt om het gebied van te voren al af te laten, vooral in de zomer. Toch denk ik dat het uiteindelijk het meest effectief is omdat je er gewoon voor zorgt dat als het water dan valt het eerste gedeelte nog op normale wijze opgevangen kan worden door de watergangen tot ze weer op normaal peil zijn.

L: Als meerdere gebieden hun peil laten zakken om zo een buffer te creeeren, is dat dan een probleem voor de boezem?

#2: Nee, de boezem kan dat makkelijk aan. Die is zo groot en het loopt helemaal in de richting van Den Helder en Alkmaar dus dat is totaal geen probleem.

L: Op welke manier worden burgers geïnformeerd en betrokken bij de crisismaatregelen die genomen worden?

#2: Er zijn ongeveer 40 gebiedsbeheerders die ieder ongeveer 5 polders beheren. De ene wat meer dan de ander. Eentje heeft er bijvoorbeeld 8 of 6 en een andere maar 4. Maar dat doet er nu niet toe. Tijdens een crisissituatie hebben de gebiedsbeheerders niet direct contact met de burgers omdat daar veel te veel heisa voor is op dat moment. De burgers worden wel zo snel mogelijk op de hoogte gesteld door twitter, facebook en dat soort kanalen. Ook de site van het Hoogheemraadschap wordt daarvoor gebruikt. De burgers zetten vaak dus gewoon hun eigen pompen neer om hun eigen stuk grond te redden zonder te beseffen wat de gevolgen voor anderen zijn.

L: Beschikt het Hoogheemraadschap zelf ook over pompen die ingezet kunnen worden tijdens een extreme neerslagsituatie?

#2: Ja. Dit zijn er een stuk of 20 voor het hele gebied. Die kunnen dus echt alleen op de plekken neergezet worden waar het het allerergste is. Er worden in dit soort gevallen bedrijven gebeld die over dat soort pompen beschikken. Dat is dan een kort belletje en dan is dat geregeld en staan ze binnen anderhalf uur op plaats van bestemming.

L: Geldt het voor trekker pompen inderdaad dat ze zo snel opgezet kunnen worden?

#2: Ja als ze eenmaal aan de trekker zitten, liggen ze binnen twee minuten in het water. Het vervoeren en het op plaats van bestemming krijgen is vaak hetgeen wat het langst duurt. Als je dus al weet dat er extreme neerslag aan komt kun je je al voorbereiden, maar het probleem is juist vaak dat het heel lang onduidelijk is waar de bui precies gaat vallen. Ook is het pas laat te zien dat een bui zo extreem gaat worden. Vooral in deze gebieden aan de kust. Want het is vaak zo dat een bui veel extremer wordt in de overgang van zee naar land, dus dat maakt het ingewikkeld.

L: Zijn er ook strategieën waar je pompen het beste kunt plaatsen?

#2: Ja die zijn er zeker. Dit verschilt enorm per peilgebied. Je kunt niet één strategie maken die van toepassing is op allerlei verschillende gebieden. Er wordt dus ook gewerkt aan een overzicht voor alle peilgebieden waar pompen het beste geplaatst kunnen worden. Over het algemeen is extra pompcapaciteit plaatsen bij de poldergemalen altijd een goed idee. Dit zorgt er gewoon voor dat het water aan het einde van de polder sneller de boezem op kan dus dan kunnen de watergangen vanaf het maaiveld ook weer sneller gevuld worden.

L: Wordt er ook naar gekeken hoeveel ruimte een pomp nodig heeft, dus dat het op sommige plaatsen niet mogelijk is om in de werkelijkheid een pomp te plaatsen?

#2: Ik denk meer dat er naar de randvoorwaarden gekeken wordt. Vaak past een pomp wel. Het zijn vaak trekker pompen. Dat zijn pompen die worden aangedreven door trekkers. Als het net niet lekker past maak je de buis die aan de trekker zit wat langer en dan zet je de trekker wat verder weg. Boeren willen alleen niet altijd dat er bij hun op het land een pomp komt. Dan moet er over hun land gereden worden waardoor een gedeelte van de oogst beschadigd wordt en daar zijn ze zeker niet blij mee. Het is dus ook een beetje onderhandelen met de boeren.

L: Zijn er maatregelen die nog niet doorgevoerd werden, maar die wel van toegevoegde waarde kunnen zijn in het bestrijden van wateroverlast?

#2: Ja. Bijvoorbeeld het aflaten van water is nog niet eerder getest of actief toegepast maar ik denk wel dat het nuttig kan zijn in bescherming van gebieden zoals ik eerder heb verteld.

L: Hoe wordt klimaatverandering meegenomen bij het bedenken en testen van nieuwe maatregelen die genomen kunnen worden in de periode 2 tot 3 dagen voor een extreme neerslagsituatie

#2: Het hele watersysteem verandert over de jaren mee met de hoeveelheid water. De watergangen worden telkens een stukje groter en er komen meer bergingen bij. De buien waar het watersysteem over 20 jaar tegen bestemd moet zijn, zijn dan ook niet een relatief grotere last omdat het watersysteem groter is. Zo wordt er door provincies in samenwerking met gemeentes en waterschappen steeds meer ruimte vrij gemaakt voor water.

L: Hoe worden kosten meegenomen is de beslissing welke maatregelen toegepast worden bij de bestrijding van wateroverlast tijdens een crisissituatie?

#2: Kosten is niet direct het belangrijkste waar op zon moment aan gedacht wordt. Uiteindelijk is het allemaal belastinggeld dus je wilt niet dat de kosten de pan uit rijzen, maar verder wordt daar niet

aan gedacht. Verlagen van de waterstand door start level van pompen aan te passen is sowieso vrij van kosten en verder denk ik dat die paar pompen ook niet het verschil maken. De kosten baten wordt wel een beetje meegenomen in de keuze van maatregelen maar dat is zeker niet het enige en belangrijkste waar beslissingen op gemaakt worden binnen het HHNK.
Ik zie dat mijn volgende afspraak alweer voor de deur staat dus we moeten gaan afronden.

L: Oké. Ik wil je heel erg bedanken voor je tijd!

#2: Als je nog vragen hebt mag je altijd bij me terecht. Ik hoor ook graag wat er uit je onderzoek komt.

L: Is goed. Ik zal je meer laten weten als ik klaar ben.

# Appendix H: Locations of old mills in the Zijpepolder

Figure 24 shows the location of the old mills located in the Zijpepolder.

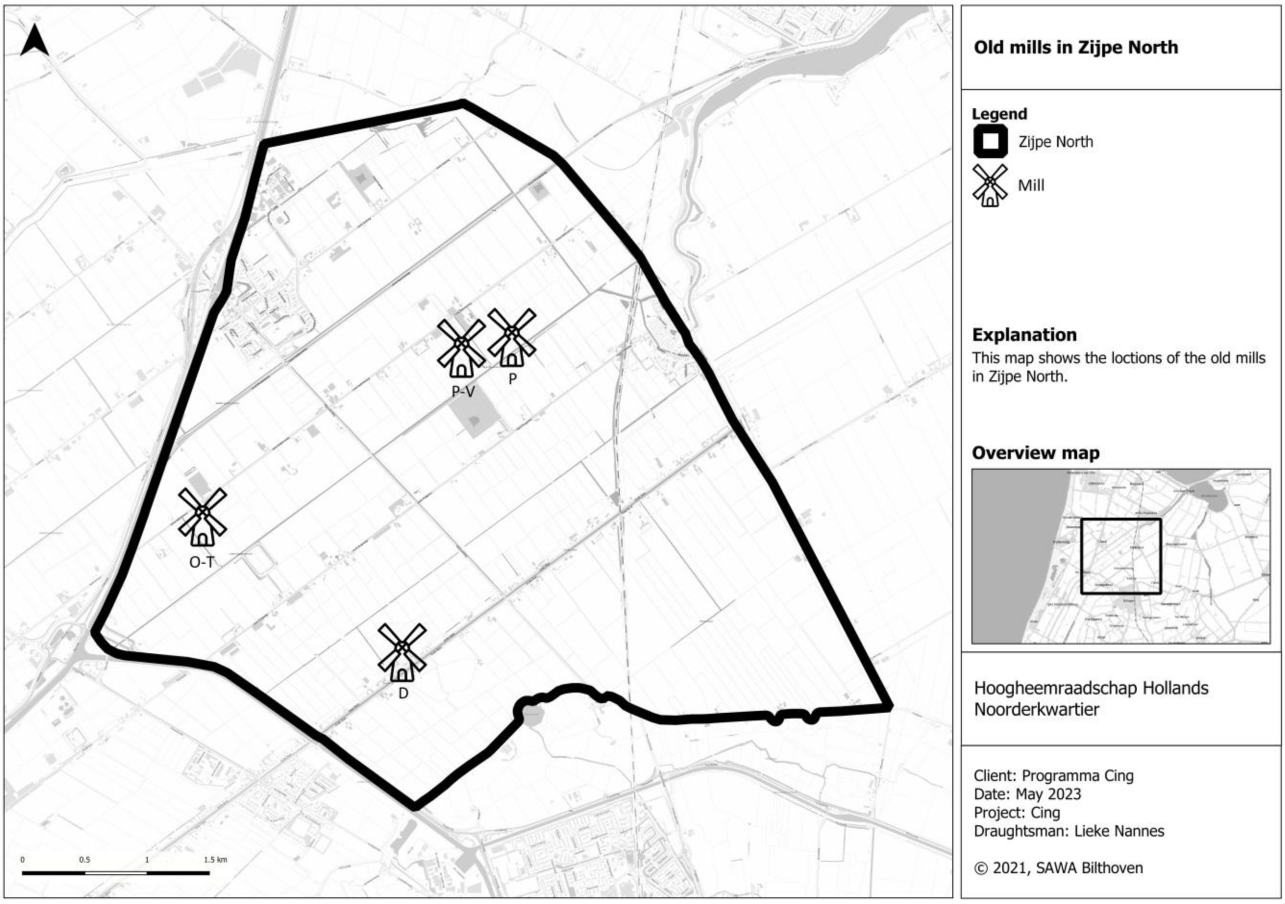


*Figure 24: Locations of old mills within the Zijpepolder.*

# Appendix I: Capacity calculation mills

Below, an explanation is given on how the capacity of the mills are calculated. The mills are dimensioned to handle a 14.4 mm precipitation event in 24 hours (Molenfederatie, 2019). Draining 14.4 mm/day is equivalent to draining 1.6 *10^-7 m/sec. From this, the capacity can be determined using equation 4.

$$Capacity\left[\frac{L}{sec}\right] = Capacity\left[\frac{m}{sec}\right] * Drainage\ area * 1000 \tag{4}$$

The drainage area is the size of the area where the mill provides drainage, this is equal to the size of the target level area.

*Table 8: Calculation of mills capacity.*

| | Capacity [m/sec] | Drainage area [$m^2$] | Capacity [L/sec] |
|---|---|---|---|
| Mill P | $1.6 *10^{-7}$ | 1167887 | 194.65 |
| Mill P-V | $1.6 *10^{-7}$ | 2964276 | 494.05 |
| Mill O-T | $1.6 *10^{-7}$ | 1676954 | 279.49 |
| Mill D | $1.6 *10^{-7}$ | 1122603 | 187.1 |

# Appendix J: Emergency pump locations

The placements for the emergency pumps were based on the inundation map of the polder. As explained in section 3.2.4, the emergency pumps are usually placed next to polder pumping stations. There are eight of these located in the study area, three of them have been chosen. This choice is based on inundation maps from the 4-hour precipitation scenarios were, because they contain more concentrated inundation and show which of the areas experience more problems than with the 48 hours precipitation scenarios. These areas also inundate during a 48-hour precipitation scenario, but then the inundation is more spread across the entire polder. Since there are limited pumps available, a decision for pump placement was therefore made based on the scenario where it can be clearly seen which areas experience severe flooding and which are less affected. Three locations were selected, these can be seen, together with the inundation, in figure 25.

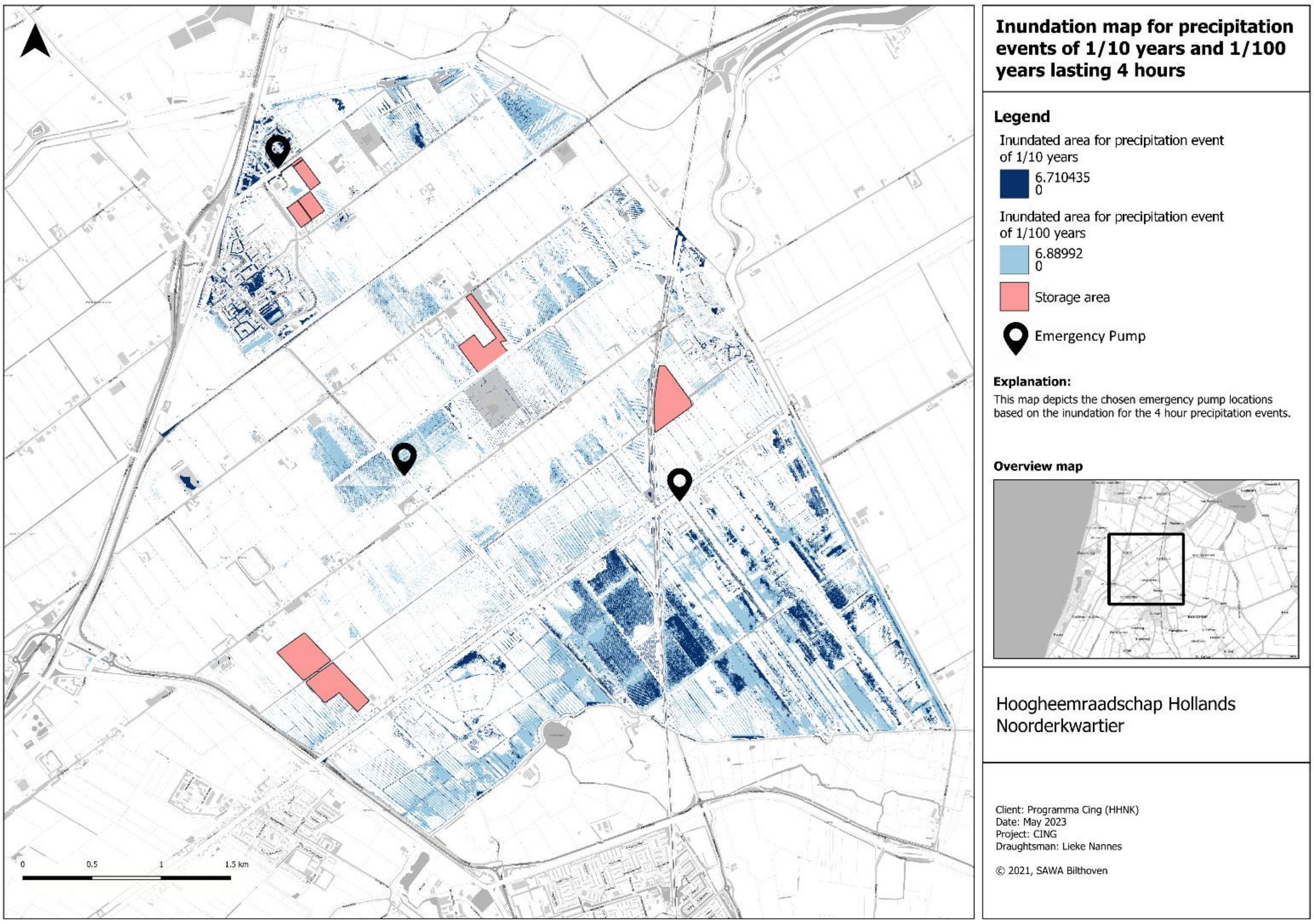


*Figure 25: Locations of emergency pumps.*

# Appendix K: Normative and relative results for flood duration

## Normative results

In table 9, the normative results of the flood duration are shown. The flood duration is shown in hours for each test scenario for every measurement location.

*Table 9: Normative flood duration for the different measures, for all scenarios and all locations in hours.*

| **Flood duration [Hours]** | **Afd W** | **Afd OT-PV (-1.1)** | **Afd OT-PV (-1.2)** | **Mosselwiel** | **Afd E** |
|---|---|---|---|---|---|
| **Test scenario** | Original situation | | | | |
| **1/10 years, 4 hours** | 7.66 | 0.00 | 0.00 | 0.00 | 26.50 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 71.91 |
| **1/100 years, 4 hours** | 29.42 | 24.92 | 23.50 | 19.17 | 89.50 |
| **1/100 years, 48 hours** | 28.92 | 0.00 | 39.25 | 0.00 | 136.00 |
| | | | | | |
| | Water level buffer | | | | |
| **1/10 years, 4 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 22.17 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 52.67 |
| **1/100 years, 4 hours** | 22.67 | 24.83 | 23.08 | 16.75 | 86.50 |
| **1/100 years, 48 hours** | 15.67 | 0.00 | 37.00 | 0.00 | 122.25 |
| | | | | | |
| | Activating old mills | | | | |
| **1/10 years, 4 hours** | 7.67 | 0.00 | 0.00 | 0.00 | 24.75 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 65.41 |
| **1/100 years, 4 hours** | 29.41 | 25.00 | 23.50 | 19.17 | 76.67 |
| **1/100 years, 48 hours** | 28.92 | 0.00 | 39.42 | 0.00 | 115.33 |
| | | | | | |
| | Temporary flood barriers | | | | |
| **1/10 years, 4 hours** | 7.67 | 0.00 | 0.00 | 0.00 | 26.50 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 71.91 |
| **1/100 years, 4 hours** | 29.42 | 25.00 | 23.50 | 19.17 | 89.58 |
| **1/100 years, 48 hours** | 29.00 | 0.00 | 39.25 | 0.00 | 136.00 |
| | | | | | |
| | Emergency pumps | | | | |
| **1/10 years, 4 hours** | 7.33 | 0.00 | 0.00 | 0.00 | 23.08 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 65.33 |
| **1/100 years, 4 hours** | 16.92 | 25.00 | 23.50 | 19.17 | 59.58 |
| **1/100 years, 48 hours** | 23.50 | 0.00 | 39.25 | 0.00 | 96.42 |

## Relative results

In table 10, the relative results of the flood duration are shown. The relative flood duration is shown in a percentage change compared to the original situation. The average of the percentage change per measure is used to assign the measures a score in the multi criteria decision analysis.

*Table 10: Relative flood duration for the different measures, for all scenarios and all locations in percentage change.*

| **Flood duration [%]** | **Afd W** | **Afd OT-PV (-1.1)** | **Afd OT-PV(-1.2)** | **Mosselwiel** | **Afd E** |
|---|---|---|---|---|---|
| **Test scenario** | Water level buffer | | | | |
| **1/10 years, 4 hours** | -100 | NaN | NaN | NaN | -16.34 |
| **1/10 years, 48 hours** | NaN | NaN | NaN | NaN | -26.76 |
| **1/100 years, 4 hours** | -22.94 | -0.36 | -1.79 | -12.62 | -3.35 |
| **1/100 years, 48 hours** | -45.82 | NaN | -5.73 | NaN | -10.11 |
| | | | | | |
| | Activating old mills | | | | |
| **1/10 years, 4 hours** | 0.13 | NaN | NaN | NaN | -6.60 |
| **1/10 years, 48 hours** | NaN | NaN | NaN | NaN | -9.04 |
| **1/100 years, 4 hours** | -0.03 | 0.32 | 0.00 | 0.00 | -14.34 |
| **1/100 years, 48 hours** | 0.00 | NaN | 0.43 | NaN | -15.20 |
| | | | | | |
| | Temporary flood barriers | | | | |
| **1/10 years, 4 hours** | 0.13 | NaN | NaN | NaN | 0.00 |
| **1/10 years, 48 hours** | NaN | NaN | NaN | NaN | 0.00 |
| **1/100 years, 4 hours** | 0.00 | 0.32 | 0.00 | 0.00 | 0.09 |
| **1/100 years, 48 hours** | 0.28 | NaN | 0.00 | NaN | 0.00 |
| | | | | | |
| | Emergency pumps | | | | |
| **1/10 years, 4 hours** | -4.31 | NaN | NaN | NaN | -12.91 |
| **1/10 years, 48 hours** | NaN | NaN | NaN | NaN | -9.15 |
| **1/100 years, 4 hours** | -42.49 | 0.32 | 0.00 | 0.00 | -33.43 |
| **1/100 years, 48 hours** | -18.74 | NaN | 0.00 | NaN | -29.10 |

# Appendix L: Normative and relative results for maximum water level

## Normative results

In table 11, the normative results of the maximum water level are shown. The maximum water level is shown in meters for each test scenario for every measurement location.

*Table 11: Normative maximum water level for the different measures, for all scenarios and all locations in m+NAP.*

| **Maximum water level [m]** | **Afd W** | **Afd OT-PV (-1.1)** | **Afd OT-PV(-1.2)** | **Mosselwiel** | **Afd E** |
|---|---|---|---|---|---|
| **Test scenario** | Original situation | | | | |
| **1/10 years, 4 hours** | -0.80 | -1.17 | -1.33 | -1.11 | -1.77 |
| **1/10 years, 48 hours** | -0.88 | -1.36 | -1.33 | -1.15 | -1.84 |
| **1/100 years, 4 hours** | -0.52 | -0.25 | -0.33 | -0.21 | -1.38 |
| **1/100 years, 48 hours** | -0.73 | -1.36 | -0.35 | -0.98 | -1.41 |
| | | | | | |
| | Water level buffer | | | | |
| **1/10 years, 4 hours** | -0.88 | -1.17 | -1.35 | -1.16 | -1.81 |
| **1/10 years, 48 hours** | -0.90 | -1.38 | -1.35 | -1.16 | -1.86 |
| **1/100 years, 4 hours** | -0.57 | -0.25 | -0.33 | -0.25 | -1.39 |
| **1/100 years, 48 hours** | -0.78 | -1.38 | -0.36 | -1.04 | -1.42 |
| | | | | | |
| | Activating old mills | | | | |
| **1/10 years, 4 hours** | -0.80 | -1.17 | -1.33 | -1.11 | -1.78 |
| **1/10 years, 48 hours** | -0.88 | -1.36 | -1.33 | -1.15 | -1.86 |
| **1/100 years, 4 hours** | -0.52 | -0.25 | -0.33 | -0.21 | -1.38 |
| **1/100 years, 48 hours** | -0.73 | -1.36 | -0.35 | -0.98 | -1.43 |
| | | | | | |
| | Temporary flood barriers | | | | |
| **1/10 years, 4 hours** | -0.80 | -1.17 | -1.33 | -1.11 | -1.78 |
| **1/10 years, 48 hours** | -0.88 | -1.36 | -1.33 | -1.15 | -1.84 |
| **1/100 years, 4 hours** | -0.52 | -0.25 | -0.33 | -0.21 | -1.38 |
| **1/100 years, 48 hours** | -0.73 | -1.36 | -0.35 | -0.98 | -1.41 |
| | | | | | |
| | Emergency pumps | | | | |
| **1/10 years, 4 hours** | -0.80 | -1.19 | -1.33 | -1.11 | -1.78 |
| **1/10 years, 48 hours** | -0.88 | -1.36 | -1.33 | -1.15 | -1.86 |
| **1/100 years, 4 hours** | -0.54 | -0.25 | -0.33 | -0.21 | -1.38 |
| **1/100 years, 48 hours** | -0.77 | -1.36 | -0.35 | -0.98 | -1.46 |

## Relative results

In table 12, the relative results of the flood duration are shown. The relative flood duration is shown in a percentage change compared to the original situation. The average of the percentage change per measure is used to assign the measures a score in the multi criteria decision analysis.

*Table 12: Relative maximum water level  for the different measures, for all scenarios and all locations in percentage change.*

| <u>Maximum water level [%]</u> | Afd W[%] | Afd OT-PV (-1.1)[%] | Afd OT-PV(-1.2)[%] | Mosselwiel[%] | Afd E[%] |
|---|---|---|---|---|---|
| **Test scenario** | Water level buffer | | | | |
| **1/10 years, 4 hours** | -10.45 | 0.14 | -1.54 | -4.31 | -2.27 |
| **1/10 years, 48 hours** | -2.08 | -1.44 | -1.50 | -0.93 | -0.84 |
| **1/100 years, 4 hours** | -9.80 | 0.21 | -0.05 | -14.97 | -0.48 |
| **1/100 years, 48 hours** | -7.20 | -1.45 | -1.90 | -5.94 | -0.42 |
| | | | | | |
| | Activating old mills | | | | |
| **1/10 years, 4 hours** | 0.01 | 0.33 | 0.00 | 0.09 | -0.27 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | -0.94 |
| **1/100 years, 4 hours** | 0.04 | 0.44 | 0.03 | -0.11 | -0.02 |
| **1/100 years, 48 hours** | -0.01 | 0.00 | 0.16 | 0.00 | -1.06 |
| | | | | | |
| | Temporary flood barriers | | | | |
| **1/10 years, 4 hours** | 0.00 | 0.31 | 0.00 | 0.06 | -0.24 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 |
| **1/100 years, 4 hours** | 0.04 | 0.48 | 0.03 | -0.07 | -0.01 |
| **1/100 years, 48 hours** | -0.02 | 0.00 | 0.02 | 0.06 | -0.07 |
| | | | | | |
| | Emergency pumps | | | | |
| **1/10 years, 4 hours** | -0.22 | -1.21 | 0.00 | 0.07 | -0.20 |
| **1/10 years, 48 hours** | 0.00 | 0.00 | 0.00 | 0.00 | -1.05 |
| **1/100 years, 4 hours** | -3.91 | 0.48 | 0.02 | -0.04 | -0.11 |
| **1/100 years, 48 hours** | -5.55 | 0.00 | 0.02 | 0.10 | -3.68 |

# Appendix M: Normative and relative results for flood damage

## Normative results

In table 13, the normative results of the flood damage are shown. The flood damage is shown in euros for each test scenario for every measurement location.

*Table 13: Normative flood damage for the different measures, for all scenarios and all locations in euros.*

| **Damage [Euros]** | **Damage[euros]** |
|---|---|
| **Test scenario** | Original situation |
| **1/10 years, 4 hours** | 5080641 |
| **1/10 years, 48 hours** | 5316806 |
| **1/100 years, 4 hours** | 6992347 |
| **1/100 years, 48 hours** | 6295193 |
| | |
| | Water level buffer |
| **1/10 years, 4 hours** | 5068548 |
| **1/10 years, 48 hours** | 5299510 |
| **1/100 years, 4 hours** | 6945110 |
| **1/100 years, 48 hours** | 6267493 |
| | |
| | Activating old mills |
| **1/10 years, 4 hours** | 5081351 |
| **1/10 years, 48 hours** | 5235883 |
| **1/100 years, 4 hours** | 7003990 |
| **1/100 years, 48 hours** | 6173884 |
| | |
| | Temporary flood barriers |
| **1/10 years, 4 hours** | 5069773 |
| **1/10 years, 48 hours** | 5223486 |
| **1/100 years, 4 hours** | 7005497 |
| **1/100 years, 48 hours** | 6208582 |
| | |
| | Emergency pumps |
| **1/10 years, 4 hours** | 5069402 |
| **1/10 years, 48 hours** | 5304271 |
| **1/100 years, 4 hours** | 6962658 |
| **1/100 years, 48 hours** | 6232744 |

## Relative results

In table 14, the relative results of the flood damage are shown. The relative flood damage is shown in a percentage change compared to the original situation. The average of the percentage change per measure is used to assign the measures a score in the multi criteria decision analysis.

*Table 14: Relative flood damage for the different measures, for all scenarios and all locations in percentage change.*

| | **Damage [%]** |
|---|---|
| **Test scenario** | Water level buffer |
| **1/10 years, 4 hours** | -0.24 |
| **1/10 years, 48 hours** | -0.33 |
| **1/100 years, 4 hours** | -0.68 |
| **1/100 years, 48 hours** | -0.44 |
| | |
| | Activating old mills |
| **1/10 years, 4 hours** | 0.01 |
| **1/10 years, 48 hours** | -1.52 |
| **1/100 years, 4 hours** | 0.17 |
| **1/100 years, 48 hours** | -1.93 |
| | |
| | Temporary flood barriers |
| **1/10 years, 4 hours** | -0.21 |
| **1/10 years, 48 hours** | -1.76 |
| **1/100 years, 4 hours** | 0.19 |
| **1/100 years, 48 hours** | -1.38 |
| | |
| | Emergency pumps |
| **1/10 years, 4 hours** | -0.22 |
| **1/10 years, 48 hours** | -0.24 |
| **1/100 years, 4 hours** | -0.42 |
| **1/100 years, 48 hours** | -0.99 |

# Appendix N: Normative and relative results for inundated area

## Normative results

In table 15, the normative results of the inundated area are shown. The inundated area is shown in $m^2$ for each test scenario for every measurement location.

*Table 15: Normative inundated area  for the different measures, for all scenarios and all locations in squared meters.*

| | **Inundated area[m^2]** |
|---|---|
| **Test scenario** | Original situation |
| **1/10 years, 4 hours** | 918239 |
| **1/10 years, 48 hours** | 781618 |
| **1/100 years, 4 hours** | 2800811 |
| **1/100 years, 48 hours** | 2340179 |
| | |
| | Water level buffer |
| **1/10 years, 4 hours** | 908763 |
| **1/10 years, 48 hours** | 773580 |
| **1/100 years, 4 hours** | 2706969 |
| **1/100 years, 48 hours** | 2270147 |
| | |
| | Activating old mills |
| **1/10 years, 4 hours** | 916928 |
| **1/10 years, 48 hours** | 774731 |
| **1/100 years, 4 hours** | 2806261 |
| **1/100 years, 48 hours** | 2187432 |
| | |
| | Temporary flood barriers |
| **1/10 years, 4 hours** | 918537 |
| **1/10 years, 48 hours** | 782628 |
| **1/100 years, 4 hours** | 2822457 |
| **1/100 years, 48 hours** | 2344288 |
| | |
| | Emergency pumps |
| **1/10 years, 4 hours** | 918550 |
| **1/10 years, 48 hours** | 781787 |
| **1/100 years, 4 hours** | 2772755 |
| **1/100 years, 48 hours** | 2143719 |

## Relative results

In table, the relative results of the inundated area are shown. The relative inundated area is shown in a percentage change compared to the original situation. The average of the percentage change per measure is used to assign the measures a score in the multi criteria decision analysis.

*Table 16: Relative inundated area for the different measures, for all scenarios and all locations in percentage change.*

| | **Total inundated area[%]** |
|---|---|
| **Test scenario** | Water level buffer |
| **1/10 years, 4 hours** | -1.03 |
| **1/10 years, 48 hours** | -1.03 |
| **1/100 years, 4 hours** | -3.35 |
| **1/100 years, 48 hours** | -2.99 |
| | |
| | Activating old mills |
| **1/10 years, 4 hours** | -0.14 |
| **1/10 years, 48 hours** | -0.88 |
| **1/100 years, 4 hours** | 0.19 |
| **1/100 years, 48 hours** | -6.53 |
| | |
| | Temporary flood barriers |
| **1/10 years, 4 hours** | 0.03 |
| **1/10 years, 48 hours** | 0.13 |
| **1/100 years, 4 hours** | 0.77 |
| **1/100 years, 48 hours** | 0.18 |
| | |
| | Emergency pumps |
| **1/10 years, 4 hours** | 0.03 |
| **1/10 years, 48 hours** | 0.02 |
| **1/100 years, 4 hours** | -1.00 |
| **1/100 years, 48 hours** | -8.40 |