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The design of temporary flood damage mitigating measures

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Colophon

Title
The design of temporary flood damage mitigating measures

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Preface

In front of you is my bachelor thesis “The design of temporary flood damage mitigating measures”, the crown jewel of my bachelor Civil Engineering at the University of Twente. In the last three months, I carried out my research at the Water Board Drents Overijselse Delta, as part of the “research and consultancy” team. However, I never met my team in person due to the COVID-19 restrictions. Nevertheless, I had a good time and had some instructive but also very fun online meetings with the team members.

The first person that I want to thank is Gerben Tromp. He was my supervisor and has given me an enjoyable time, despite working home. From the first time we met in November to the bitter end in June, you supported me by providing useful documents, insights, and feedback, as if you had all the time in the world. Furthermore, I want to thank Lieke Lokin from the University of Twente. You guaranteed a successful internship period by providing constructing feedback which raised my research to a scientific level.

Finally, to all the readers of this report, I hope that you will enjoy reading my Bachelor Thesis. Feel free to ask questions.

Joël Haase

Kampen, 18 June 2021

Summary

The standard approach to flood risk in the Netherlands consists of one strategy: keeping the water out. However, more strategies can be used to mitigate flood risk: spatial planning and evacuation. The Water Board Drents Overijselse Delta wants to gain insight in the action perspective there is in case of a dike breach, by taking temporary measures by using already existing infrastructure and other topographic elements. This study is about which temporary measures can be taken and what their effect is. These temporary measures are part of the spatial planning layer but also hit the evacuation layer because water arrival times can be increased or decreased by the measures.

The area between Zwolle and Dalfsen, south of the Vecht, is used as a pilot area for this research. In this area, there are topographic elements that may influence the flood pattern in combination with temporary measures. There are three types of intervention used: 1) Close openings in line-elements, 2) create new line-elements, 3) raise existing line-elements. Because the research is about the action perspective in case of a dike breach, the measures are not worked out in detail. Instead, the focus is on the effect of the temporary measures.

The results of the study show that there is an action perspective. However, this perspective is area and breach flow dependent. In the case of the pilot area, the economic damage was decreased by at least 60%. However, when the used methodology was verified to dike breaches in the Mastenbroekenpolder, or the water level was too high, or the measures worked counter effective. Therefore, side effects of temporary measures should be considered while trying to mitigate the flood risk.

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1. Introduction

HWBP

In 2014, the HoogwaterBeschermingsProgramma (HWBP) has started. The biggest dike reinforcement operation since the Delta works (HWBP, 2021). The alliance of the Water Boards and Rijkwaterstaat are working together to reinforce 1300 kilometres of dike and 500 other waterworks. The projects that are executed within the program are performed by individual Water Boards. However, the costs of the executed projects are shared with Rijkswaterstaat and the other Water Boards. Every Water Board determines whether and which of the dikes in their jurisdictional area need to be reinforced based on risk calculations (HWBP, 2021). Since 2017, the safety norms applicable to waterworks have been changed (Expertice-network waterveiligheid, 2016). Before 2017, each dike ring had a certain norm, based on the probability of flooding. Nowadays, the norms concern the probability of failure combined and the impact of the flood. This is called flood risk. Flood risk can be calculated by $chance \times impact$. Based on the acceptable risk, norms are derived. The probability that the hinterland of a primary dike may flood differs from 1/1000 to 1/1000,000 per year. Secondary dikes and other water barriers have lower safety standards.

WDOD

Dikes must be checked based on the safety norms laid down in the Waterwet. Currently, the flood risk calculations are updated, as is stated in the order description of Waterboard Drents Overijselse Delta (WDOD). When a part of a dike does not meet the legal norms, the dike is is deemed insufficient and has to be reinforced. A project financed by HWBP is started. First, a problem analysis is done, followed by a dike reinforcement. The reinforcements in the jurisdictional area of WDOD are planned for the period between 2016 and 2037 (WDOD, 2021). This reinforcement cost millions of euros. As an illustration, a rise of 75 cm cost between 4 and 10 M€ per kilometre, depending on the location of the dike (Deltares, 2011). The Water Board is looking for cheaper ways of guaranteeing the required safety norms.

One can think about ways to reduce the damage resulting from a dike breach by taking temporary mitigation measures. The waterboard has asked for the setup and execution of a method regarding the design of smart, temporary measures which can be taken while using the current infrastructure to reduce the flood impact, so the flood risk is reduced. When the flood risk is reduced, the dike norms can possibly be decreased proportionally.

Multi-layered safety

Reducing risk by taking other measures than preventing flooding is part of the so-called multi-layered safety approach (Hoss et al., 2011). This approach consists of 3 layers, as can be seen in Figure 1. Preventing flooding is the most important layer, but the other 2 layers cover a broader action perspective. Taking temporary measures can be located between the second and third layer. Temporary measures will namely reduce the flood risk due to the spatial adaptations that are made but can increase the time for emergency response as well. By ordering research like this, the Water Board shows that the traditional flood assessment is being extended to a more comprehensive one.

Figure 1 Multi-layered flood safety approach (Interreg VB North Sea Region Programme, 2021)

1.1. Research objective

The research objective is to set up a list of smart, temporary measures which reduce the flood risk within the jurisdictional area of WDOD. These measures are designed by using the already existing infrastructure, and other non-official flood pattern influencing barriers in the pilot area. These measures must reduce the flood risk, and should be easily implementable. The waterboard wants insight into the action perspective it has in case of an emergency, where a dike will fail almost certainly. When the flood risk can be reduced, the dike norms may be lowered, and reinforcement costs can be lowered as well.

1.2. Research questions

Four research questions follow from the research objective. These questions form the backbone of this research. Each question corresponds with a chapter, beginning at chapter 3.

1. **Which area is suitable as a pilot area for the research to the action perspective the Water Board has in case of an emergency?**

Assessing the whole jurisdictional of the Water Board at once will be too time-consuming and the scope of this research would be too broad. Therefore, a pilot area is chosen for which all the design steps are carried out. Moreover, an area analysis is done to get more insight into the pilot area for which the temporary measures are designed.

2. **What is the action perspective concerning temporary measures that can be taken to reduce flood risk?**

In this research question, a framework is set to delineate the temporary measures that are designed. In this way, the set of possible measures is reduced, and therefore, the scope of this research is narrowed done.

3. **Which temporary measures can be taken in the pilot area, and what is the impact of these measures on the caused economical damage?**

Based on the outcomes of the previous questions, temporary measures are designed for the pilot area.

4. **Can the used methodology for the pilot area be applied to other parts of the jurisdictional area of WDOD?**

The client, WDOD, strives for a methodology that applies to their whole jurisdictional area. Therefore, the used methodology is applied to another part of the jurisdictional area as a verification.

1.3. Short methodology

The measures are designed based on a study of the relevant area, (comparable) flood reducing projects in the Netherlands, flood patterns, and interviews with experts at WDOD. The testing is done in 3Di Water Management, a 1D-2D hydraulic model which can be used for flood simulations. The literature study forms a broad basis of diverse aspects regarding the design and testing of the temporary flood mitigation measures.

In Figure 2, the proposed methodology is presented. The four rows are an elaboration of the 4 research questions (RQ's). The iteration phases In RQ 3 and 4 are about design improvements after gained insights in the analye part.

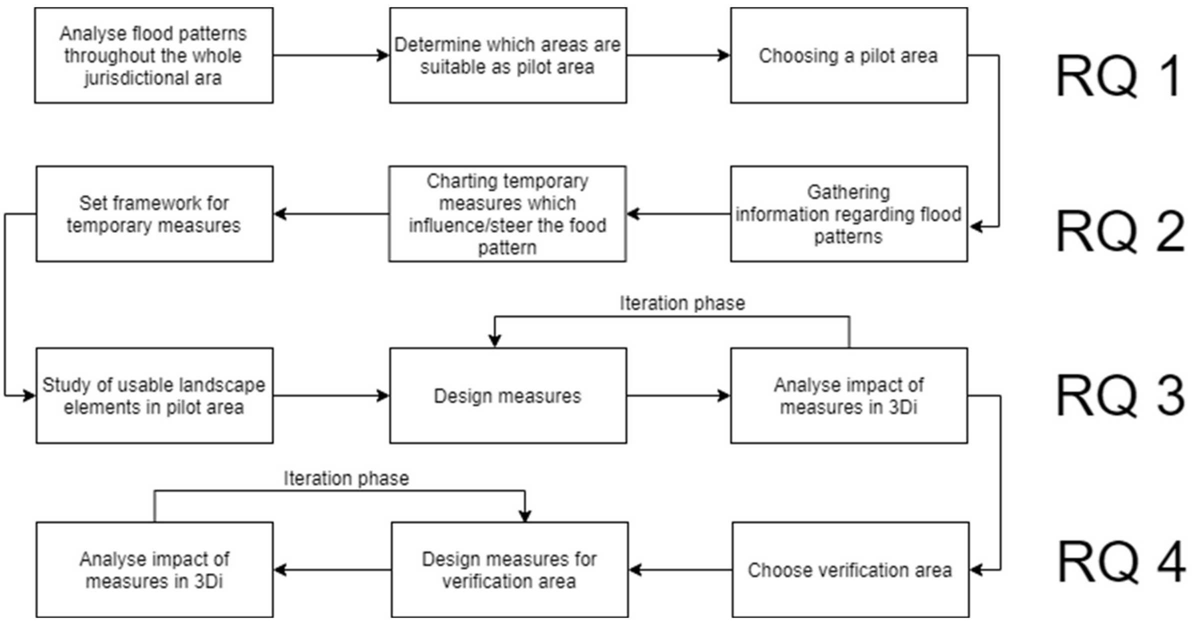


Figure 2 Schematic overview methodology

1.4. Models used

As already mentioned in the previous paragraph, 3Di Water Management is used for testing the temporary measures. Making changes to the model schematisation is done in QGIS. Here, dikes, orifices and other relevant elements can be added into the GIS files. When the GIS files are uploaded to the 3Di server, floods and other water-related events can be simulated. Afterwards, flood characteristics can be analysed. 3Di is a 1D-2D hydraulic model. In Appendix IV a brief elaboration can be found on how the 3Di model works.

1.5. Set-up of the report

The set-up of this report is as follows. In the second chapter, some background literature research is done. In the third chapter, a pilot area is chosen for which the research is conducted. In the next chapter, the action perspective concerning the measures that can be taken is studied. In the fifth chapter, measures are designed for the pilot area. Moreover, the feasibility, impact, and possible side effects are assessed. In the sixth chapter, the methodology used for designing measures in the pilot area is applied to another area to verify the method used. The report ends with a conclusion, discussion, and recommendations regarding the methodology and further research.

2. Literature

2.1. Introduction

In this chapter, a brief literature research is done concerning flood risk and multi-layered safety. In the remaining part of this research, more background literature is included, interwoven in the main text.

2.2. Flood risk

The Netherlands is densely populated. Especially around rivers and near the coast. In case of flooding, the impact will be large. Due to increasing weather extremes, the occurrence probability of flooding will increase (Verweij et al., 2010). More heavy rainfall events alternated with periods of drought will affect the flood risk in the Netherlands both. Heavy rainfalls will increase the discharge of the rivers and therefore the occurrence probability of dike failure which influences the risk will increase as well (Verweij et al., 2010). On the other hand, drought will increase the dike failure probability, due to peat shrink, and therefore impacts the flood risk as well (Siepman, 2021).

Since the flood of 1953, the safety norms regarding the primary water defence of the Netherlands are laid down in law, the Water law (*Waterwet*, 2021). Flood defence should be able to withstand a certain water level. However, in 2017 the policy changed. Instead of solely focussing on the chance of flooding, the impact of the flooding is considered as well. The equation $flood\ risk = chance \times impact$ combines the two mentioned aspects into flood risk by a multiplication. The report 'Grondslagen voor Hoogwaterbescherming' (Experticenetwork waterveiligheid, 2016) describes what the elements in the equation mean and how they are calculated.
The report distinguishes between three types of risks. Economic risk, group risk, and individual risk. Economic risk is the chance of damage in Euro or Euro per year. The group risk indicates the chances of high numbers of casualties. The impact on the public of the death of 30 people at once is much higher than the impact of several accidents with one or two casualties. Lastly, the local individual risk describes the chance that someone dies due to the flood. In the Netherlands, there is a threshold value of 1/100.000 per year. This means that the chance that someone will die due to the flood may not exceed the chance of 0,00001 per year (Experticenetwork waterveiligheid, 2016).
The second element in the equation is the chance of a flood. Here, several failure mechanisms of the dike are addressed. During the design and inspections of the dikes, attention should be paid to several ways a dike can fail. The four main failure mechanisms are: overtopping due to water level or waves, inner slope erosion, outer slope instability, and piping (van Kempen & van Baars, 2009). For each failure mechanism, the chance of occurrence must be determined.
The third element in the risk equation is the impact of the flood. Here, several flood scenarios are made, and the flood impact is determined. This is done by using the characteristics of a flood (inundation depth, flow rate, and climb rate), and the people and objects which are present. Depending on an eventual preventive evacuation, the number of casualties will be lower. The impact is used to determine the norms which apply to the primary water barriers. The higher the impact, the stricter the norms. Therefore, the flood risk is almost the same in the flood-prone area of the Netherlands (Experticenetwork waterveiligheid, 2016).

2.3. Multi-layered safety

Figure 3 Multi-layered flood safety approach (Interreg VB North Sea Region Programme, 2021)

As already mentioned in the introduction of this research, the traditional way of assessing flood safety is gradually being replaced by a multi-layered approach (Hoss et al., 2011). The traditional way of flood prevention by keeping the water out still exists but is supplemented with two new underlying layers: spatial adaptation and evacuation planning, see Figure 3

However, the first layer is still the most important one. Dikes and other water barriers are constantly in a reinforcement loop. Moreover, there are projects concerning the space which the river needs in case of high discharges (Ruimte Voor de Rivieren, 2021). The HWBP program, discussed in the introduction of the research, is part of the first layer as well.

The second layer is about spatial planning. Spatial planning is becoming a more important instrument to reduce flood risk (Neuvel & van den Brink, 2009). For example, valuable areas can be protected by secondary dikes which create compartments, or new residential or industrial areas can be raised with 1 or 1.5 meter to prevent the area from flooding in case of a dike breach. In the 4th chapter of this research, more possible interventions, and the execution thereof, are discussed.

The third layer concerns evacuation. In the US, the focus is on forecasting flood events and evacuate the area that will be hit (Wesselink, 2007). US citizens are aware of the possibilities there are in case of an emergency. In the Netherlands, less attention is paid to flood forecasting and evacuation, due to the strict primary water barrier norms.

3. Choice and study of a pilot area

3.1. Introduction

In this chapter, the pilot area which is used in this research is chosen and studied. A pilot area is chosen because the start of this research would be too complex and too extensive if the whole jurisdictional area of WDOD is assessed. Therefore, the area under research is set from the jurisdictional area of WDOD to a smaller pilot area for which the design steps of the temporary measures will be carried out. Once the measures are designed for the pilot area, the applicability of the methodology will be verified with another part of the jurisdictional area.

3.2. Pilot area requirements

The requirements for the choice of the pilot area are:

1. There are line-elements that influence the flood pattern.
2. There is time and space for the implementation of temporary measures.
3. The water reaches valuable area.

The first requirement stems from the client of this research, WDOD. The measures should be implemented by using the already existing infrastructure. Therefore, a brief flood pattern study of the whole jurisdictional area of WDOD will highlight which elements in the area have a (temporary) steering effect on the flood pattern.

The second requirement is set to guarantee circumstances for implementing measures successfully. The time component ensures that there is time available to react on a coming dike breach. When a dike fails upstream near Zwolle, almost nothing can be done due to time constraints. In case of a dike breach far upstream from Zwolle, there is time before the water reaches the city. Moreover, there is space between the breach location and high valuable area. During the time before the forecasting of a breach and the moment of the breach itself, measures can be taken in the area between Zwolle and the location of the dike breach.

The last criterium ensures the pilot area is a buffer zone between the location of the dike breach and high-value area. If more areas meet the first two requirements, a hierarchy between suitable pilot areas is created by comparing the areas where the water flows to. For example, when the water flows to urban area, industrial area, or farmland, the area where an intervention ensures the protection of people and money is preferred above another.

3.3. Test locations and circumstances

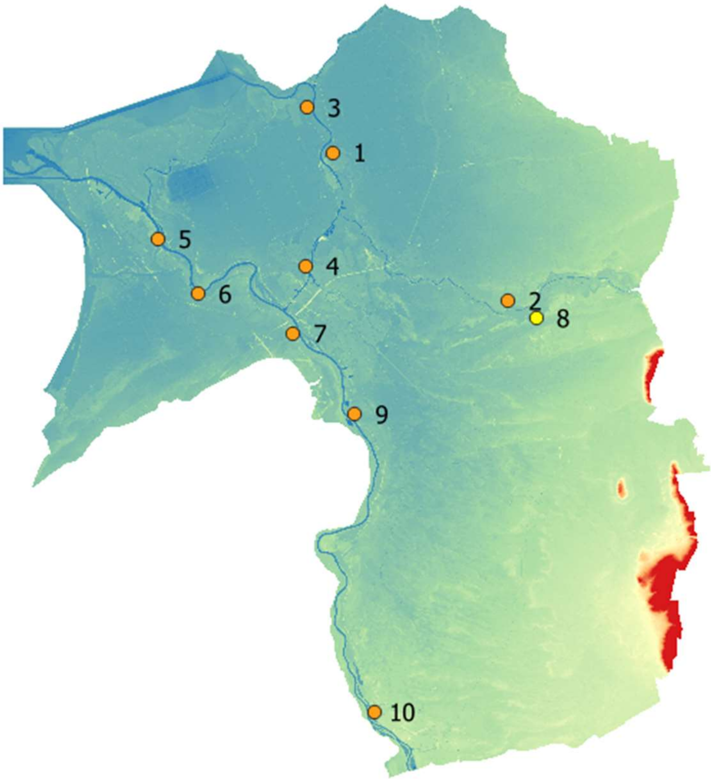
The pilot area choice is based on the outcomes of the modelling of dike breaches at several dike breach locations and the set requirements in the previous paragraph. In Figure 4, the used breach locations are presented. These locations are chosen based on the provided 3Di hydraulic model of the area. In this model, floods at 38 breach locations are modelled. Because several breach locations show similar flood patterns, a selection of 10 breach locations is made.

These locations can be found along the IJssel (5, 6, 7, 9, 10), the Vecht (2, 8), and the Zwartewater (1, 3). The discharges of these waterways differ. In Table 1, the average discharge, and the discharges corresponding to three recurrence times (T) can be found, based on (Rijkswaterstaat Waterinfo, 2021), (Houcine Chbab, 2017), and measurements of the waterboard during a period of 7 years.

Table 1 Discharges IJssel & Vecht

	Average	**T = 100**	**T = 1000**	**T = 10,000**
IJssel	330 m^3/s	1972 m^3/s	2423 m^3/s	2760 m^3/s
Vecht	30 m^3/s	419 m^3/s	~ 540 m^3/s	658 m^3/s

The average discharge of the Zwartewater is assumed to be approximately equal to the average discharge of the Vecht. These river discharges will increase in case of heavy rainfall and peak discharges will increase due to the impact of climate change (Hoogwater in Rivieren, 2018). When a dike fails during a high-water period, a large volume of water flows into the hinterland.



Legend:	**Dike track:**
1. Hasselt	9
2. Dalfsen	9
3. Genemuiden	10
4. Stadshagen	10
5. Kampen	11
6. de Zande	11
7. Hattem	11
8. Rechteren	53
9. Herxen	53
10. Deventer	53

Figure 4 Breach locations pilot area choice

The Water Board has a database where the results of flood simulations are stored. For each breach location, floods are modelled with river discharges of three different recurrence times (T). T = 100 years, 1000 years, and 10,000 years. For the pilot area choice, a recurrence time of 1000 years is chosen in dialogue with the Water Board. When measures are designed for a low recurrence time, the measures are possibly not applicable to higher recurrence times. On the other hand, when a high recurrence is chosen, the measures are not proportional to the volume of water that flows in. Therefore, the middle course is taken with T = 1000. The breach flow is determined by the water level of the river (derived from the river discharge with a recurrence time of 1000 years), the size the breach, and the water level in the inner dike area, which creates counter-pressure in some cases, depending on the topography of the area (Bates et al., 2009).

3.4. Pilot area choice

The analysis of the 10 breach locations and their floods pattern give insight in the line-elements which clearly (or temporarily) influence the flood pattern. In the next paragraph, the conclusions of the analysis considering the set of requirements are given. For additional insight in the done observations, Table 14, in Appendix I Pilot area study line-elements can be reviewed for the explication of the line-elements. Moreover,

Appendix V Flood pattern analysis gives insight in how the simulations are analysed by showing the progression of the water over time.

Figure 4 in the section above shows the breach locations and the corresponding dike tracks. The remaining part of this section describes the analysis of the flood pattern at these breach locations. The analysis is based on the stored flood simulations of the Water Board. These simulations are not accessible for people outside the Water Board. In Table 2 the results of the analysis can be found. The extended version is set out in the in Appendix I Pilot area study line-elements. The locations which do not meet all the three requirements are not considered in the damage ranking. This ranking is based on the size of the cities/neighbourhoods the water reaches.

Except for Kampen, each breach location fits the first two requirements. Therefore, the area with the most value is chosen. The water reaches several cities. Meppel, Hasselt, and Elburg are less valuable areas than Zwolle due to the difference in size and population. Therefore, a choice should be made between a dike breach south or east of Zwolle, which corresponds with locations 8 & 9. Because there is already a study done on the impact mitigation of a flood of the IJssel at the south of Zwolle ((Hydrologic, 2019), which is intern, not published report), the pilot area that is chosen is at the east of Zwolle: Rechteren.

Table 2 Summarised area flood pattern analysis

	Location	**Line-elements?**	**Implementation time?**	**Valuable area?**	**Damage ranking**
1	Hasselt	Yes	Yes	No	-
2	Dalfsen	Yes	Yes	No	-
3	Genemuiden	Yes	Yes	Yes	2
4	Stadshagen	Yes	Yes	Yes	2
5	Kampen	Yes	No	Yes	-
6	De Zande	Yes	Yes	Yes	3
7	Hattem	Yes	Yes	Yes	3
8	Rechteren	Yes	Yes	Yes	1
9	Herxen	Yes	Yes	Yes	1
10	Deventer	Yes	Yes	Yes	2

3.5. Pilot area analysis

Area description

In Figure 5, the delineated pilot area can be seen. The red lines indicate the main infrastructure. The elevation map shows that the area inclines from east to west. Moreover, some higher elevated areas are visible. Between Zwolle and Dalfsen, some small hamlets can be found. The dikes of the Overijsels Kanaal/Nieuwe Wetering forms the southern barrier of the flood pattern. The northern part of the pilot area are the dikes of the Vecht, which have a damming function.

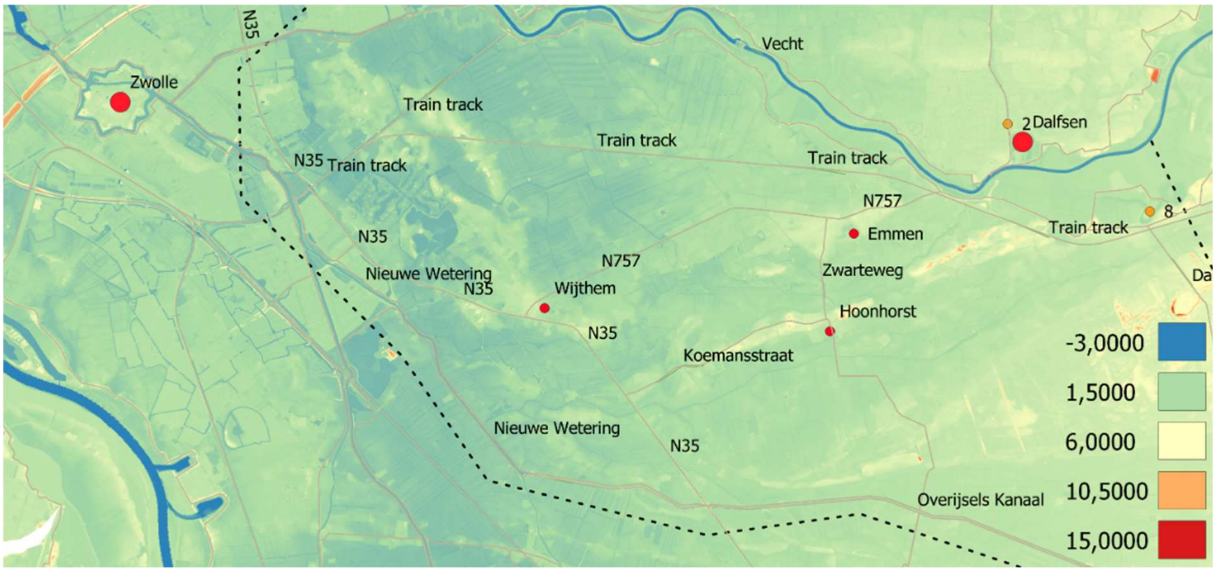


Figure 5 Pilot area

In Figure 6, the land use map of the pilot area is shown. The main part of the area is agricultural grass and maize. The agricultural land is interspersed by pine forest, buildings in the hamlets, and farms.

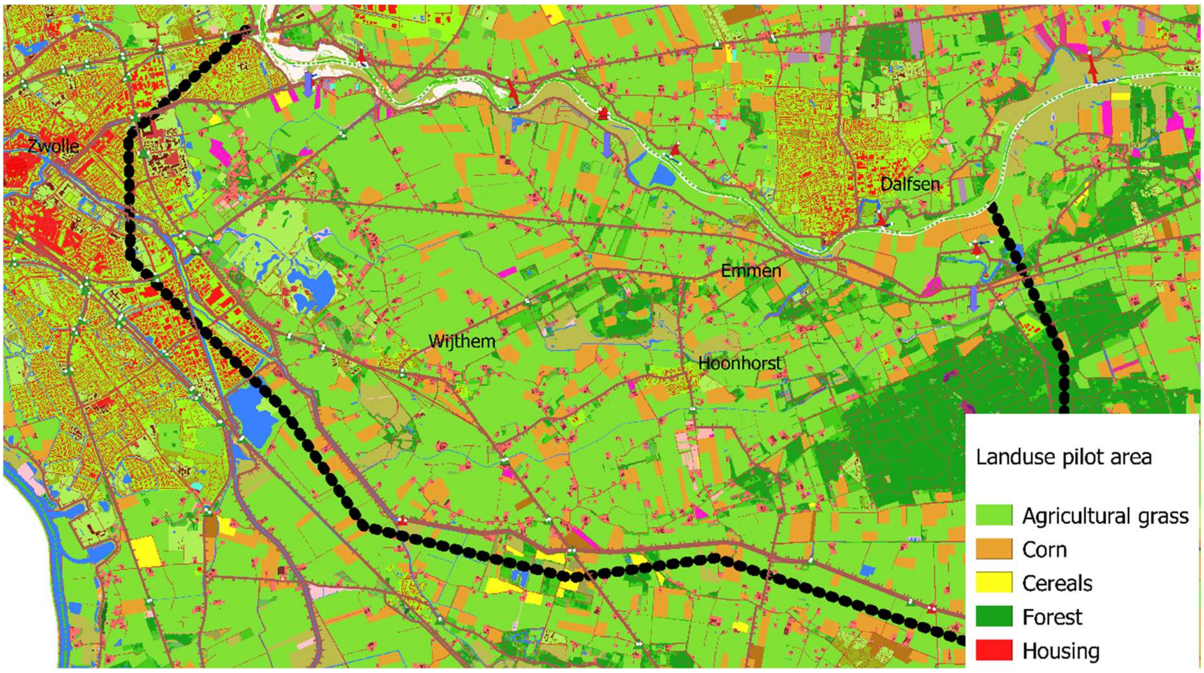


Figure 6 Land use pilot-area

In Figure 7 and Figure 8, impressions of the pilot area are shown. This image is taken during a field trip. The photo is a typical representation of the whole agricultural area. Stretches of grassland are separated from each other by rows of trees, roads, and train tracks.

Figure 7 Impression of the pilot area (Field trip)

Figure 8 Impression of the pilot area (Field trip)

Compartmentalising line-elements

The line-elements which can be used to create temporary measures are already charted, but the tunnels, culverts, and other passages in these line-elements are not yet mapped. These locations in the line-elements ensure that water can still pass through. An overview of these locations can be found in Table 3. The mentioned locations are passages that are modelled in the 3Di model of the pilot area.

Table 3 Overview passages line-elements pilot area

Line-element	**What**	**Where**
Train track	Tunnel	Ceintuurbaan
	Small railway bridge	Herfterwetering
	Bridge	Between Vecht and Ceintuurbaan
N35	Orifice	Emmertochsloot
	Bike tunnel	Hoekserflaan
	Orifice	Marswetering
	Orifice	Hagenweg

The roads, dikes, and train tracks are the main infrastructure elements in the area. Together with the elevation of the landscape, the course of the water is determined by these elements. As already mentioned, the N35 and N757 influence the flood pattern due to their compartmentalising function. The higher the line-element, the larger the compartmentalising effect. In Table 4, the elevation of the main line-elements is given. Moreover, the height compared to the surrounding area is estimated, based on the elevation map of the Netherlands (AHN) and a QGIS cross-section plugin.

Table 4 Elevation line-elements pilot area

Line-element	Height above sea-level (m)	Height from ground level (m)
Nieuwe Wetering	2.6 – 3.2	1.5 – 2.2
Overijsels Kanaal	2.6 – 3.1	0.6 – 1.5
Dike of Vecht	4.5	2.5 - 4
Train track 1	2. 8 – 3.0	1.8 – 2.8
Train track 2	2.2	1.0 - 1.5
Train track 3	3.0 - 4.0	1.5 – 3.5
N35	1.3 – 3.6	0.3 – 1.6
N757	2.0 – 3.0	0.8 – 1.8
Koemansstraat	2.1 – 4.7	1.3 – 3.3
Zwarteweg	2.2 – 4.0	0.2 – 0.5
Tibbensteeg	2.3 -2.9	0.3 – 1.5

Breach flow analysis

Roughly, there are 2 ways in which the water can spread. The first case is occurs when a the dike fails near or eastwards of Dalfsen. The second case from Dalfsen to Zwolle. The flood pattern develops in both cases from right to left, due to the elevation difference. Moreover, the higher elevated areas are not inundated by the water. In the first breach case, the N35 and N757 and the Overijsels Kanaal are the line-elements that form the temporary boundaries of the flood pattern. However, after some time, the water overtops both roads and spreads westwards to Zwolle. The water continues spreading westwards, even both train tracks are passed. This means that the water reaches the area where among others the office of WDOD, the hospital, and the stadium of PEC Zwolle can be found (*Google Maps*, 2021). The flood pattern for the second breach is comparable to the first one. The water first overtops the two train tracks, then it spreads over the area in the direction of Zwolle and the Nieuwe Wetering/Overijsels kanaal. Most of the water does not overtop the N35 and N757, which roughly form the northern and eastern barrier of the flood pattern.

3.6. Conclusion

The area that is chosen as pilot area is the area between Zwolle and Dalfsen, south of the Vecht. There are several line-elements which are influencing the flood pattern. However, none of these elements are completely ‘watertight’ due to the openings for water courses and roads. Due to these openings, the water reaches valuable parts of Zwolle, like the hospital, and areas with housing.

4. Action perspective for temporary measures

4.1. Introduction

In this chapter, attention is paid to the action perspective that the Waterboard has in case of a dike breach. First, a context is outlined concerning the development of flood patterns and regular methods to steer the flood pattern. This context is based on literature and report review. In addition, an interview with Wijnand Evers, a dike and safety expert, is interwoven as a practical view. The chapter will conclude with a framework which forms the basis of the design of the temporary measures. This framework concerns the time there is to come up with measures and the scope of these measures.

4.2. Development flood pattern

Flood risk is a combination of the occurrence probability and the impact of the flood. The impact is determined by the inundated area. The breach location and corresponding hinterland characteristics are influencing the flood pattern and the inundated area (Rijkswaterstaat Projectbureau VNK, 2014). Higher elevated areas like train tracks, raised roads, surface area, and regional waterworks are hinterland characteristics that influence the course of a flood and the time it takes for the area to fill up. In practice, there are several ‘types’ of floods, depending on the breach location and characteristics of the hinterland. 3 types: bathtub, inclined plane, and variable flood pattern, are described.

In Figure 9, two breach locations are modelled within the same area. In this area, the breach location does not influence the impact of the flood. Therefore, it is called a bathtub flood pattern.

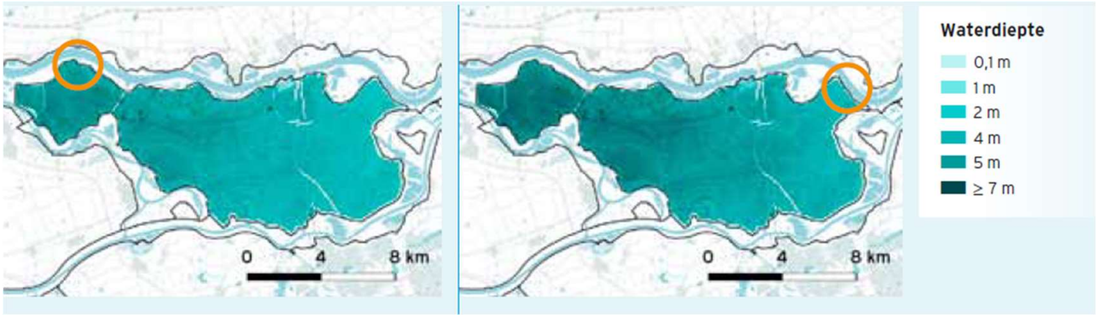


Figure 9 Bathtub flood pattern (Rijkswaterstaat Projectbureau VNK, 2014)

Figure 10 shows the inundated area after 1 and 12 days due to a breach at the marked location. This pattern is caused by the altitude of the hinterland. The elevation of the hinterland downstream is lower in this case, so the water will flow downstream. This is typical for a inclined plane flood pattern.

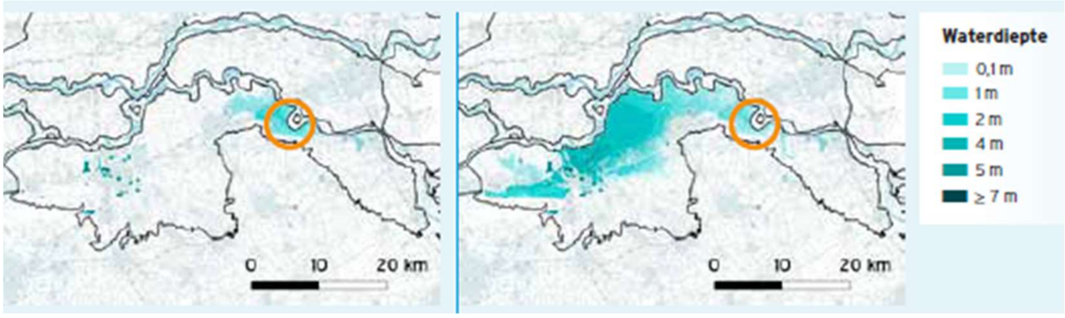


Figure 10 Inclined plane flood pattern (Rijkswaterstaat Projectbureau VNK, 2014)

The third and last described flood pattern type can be found in Figure 11. The term ‘variable’ fits perfectly due to the randomness the water is spread over the area. This randomness is determined by the elevation of the hinterland, regional water barriers or elevated line elements like train tracks.

Figure 11 Variable flood pattern (Rijkswaterstaat Projectbureau VNK, 2014)

4.3. Steering flood pattern

Compartmentalisation

The flood pattern, as result of a dike breach, causes damage due to the economic value of the area and the number of people that live in the area it inundates. Flood impact mitigating strategies should therefore include all opportunities of measures that are available (Traver, 2014). Several strategies can be used in the hinterland of a dike to steer or prevent the development of a flood pattern. In the paper (Alkema & Middelkoop, 2007), several strategies are mentioned. Creating retention areas in which the water is temporarily stored is one of these strategies. When the water is stored in such areas, water is kept out of more valuable adjacent areas. However, the volume of water that can be stored in a retention area is limited. Therefore, water can be led to other less vulnerable adjacent retention areas. Using spill-overs is one of the ways water can be steered to other locations. Spill-overs are locations where the dike is lowered, so the water will overtop these locations before it happens somewhere else. These floodable locations should be able to withstand the overtopping of large amounts of water.

Retention areas are created by surrounding the area with dikes or higher elevated infrastructure (Alkema & Middelkoop, 2007). This is called compartmentalisation: dividing the area in smaller compartments. These compartments can then be used to retain water and control the flood water by guiding them to the areas which are intended as retention areas.

In the report of Hydrologic (an intern WDOD document), additional measures strategies are proposed (Hydrologic, 2019). Increase the influence of already existing infrastructure by raising these line elements. It will therefore take longer before a road or train track floods. Moreover, more water can be retained. A second strategy that is offered is about creating a fast discharge channel. By creating such a channel, water can be transported controlled and fast to another location, where more room is to get rid of the water. The third strategy the report offers is taking compartmentalisation into account by raising roads while they are (re-)constructed. Fourthly, tunnels or other passages can be temporarily closed or filled up.

Implementation of temporary measures

In this research, the emphasis is on using the already existing infrastructure to influence the flood pattern. Therefore, temporary water barriers are needed to implement in the infrastructure. There are several types of temporary water barriers (WaterWindow, 2021). Using sandbags is one of the most common methods. Another way is implementing a NOAQ Tubewall. This barrier consists of interconnected PVC tubes which are inflated on the location where they are needed. The same method can be used, but then the tubes are filled with water: a mobile dike. A fourth temporary barrier is a BoxBarrier. A series of boxes filled with water can increase the height of a water barrier by at least 50 cm. An example of the usage of Boxbarriers is given in Figure 12.

Figure 12 Box barrier (WaterWindow, 2021)

In the conversation with Wijnand Evers (see Appendix II interview), more insight is gained into the arsenal of opportunities the waterboard has. The waterboard has material in stock for the prevention of a dike breach. However, this material is primary meant for dike reinforcement. Moreover, the available material is not enough for creating large scale measures, like the temporary dike in Figure 13. For large scale temporary measures in emergency situations, local contracters and/or defence can be deployed for assisting the realisation thereof by providing men and material. The problem can also be partly tackled at the source by reducing the inflow volume. This can be done by filling the breach with caissons or by manoeuvring a ship into the gap in the dike.

Figure 13 Temporary dike in Kampen (Destentor.nl, 2021)

4.4. Framework for temporary measures

Highwater periods and possible dike failure locations can be foreseen to some extent (See Appendix II interview Wijnand Evers). Therefore, there is some time in which temporary measures can be taken. The client, WDOD, has proposed a period of 2 or 3 days in which the measures can be implemented. For the implementation it is assumed that there are 2 days that can be used fully effectively. This means that there are 48 hours available if work continues day and night. Within these 48 hours several temporary measures can be taken:

1. Openings in line-elements are closed.
2. Existing line-elements are raised.
3. New line-elements are created.
4. The inflow volume is reduced.

In this research, there will not be paid much attention to feasibility, exact size, and technical details of the measures. The measures will be briefly verified with some experts within the Water Board. The fourth type of measures will not be considered in this research. The assumptions that have to be done are uncertainty. On forehand, it cannot be predicted how much water flows in before the ship or caissons arrive. The same applies for the breach growth.

The first type of measures is relatively easy achievable within several hours. The waterboard has sandbags and big bags in stock. These bags or other objects can be used to close tunnels or other openings.
The second and third measure concern the raising or creation of line-elements. On small scale, temporary barriers like big bags or box barriers can be used. On large scale, however, these barriers are insufficient. Creating temporary barriers with materials on-site involves enlargement of the action perspective the Water Board has in case of a dike breach.

4.5. Conclusion

The framework in which the measures are designed consists of three methods of action. 1. Filling gaps in line-elements, 2. Raise existing line-elements, 3. Create new line-elements. The way how these methods are conducted can be done in several ways, like the implementation of big bags, or creating a dike with on-site material. However, further research should be done to the materials and the script of the execution of the temporary measures. Moreover, research should be done to other ways or reducing the flood risk or steering the flood pattern by testing spill overs or high water discharge channels, for example.

5. Design of temporary measures

5.1. Introduction

In this chapter, the design of temporary measures which reduce the flood risk is described. The design is based on the prequisites described in the prevoius chapter and the pilot area study in the third chapter. The comparison is made by using the outcomes of the "WaterSchadeSchatter", a tool which estimates the flood damage in euros depending on the land-use of a certain area, and is a post processing function of the 3Di calculations. The WaterSchadeSchatter only estimates economic damage. Therefore, during the measure analysis, only economic damage is considered. The timeseries with inflow volumes that are used for modelling the floods can be found in Appendix IV inflow volumes.

5.2. Initial flood situation analysis

In Figure 14, the max water depth after a breach near Rechteren is shown. This is the situation without measures. The water reaches almost the centre of Zwolle. North of the train track (nr 1 and 3), the water inundates residential area, offices and even the hospital is reached by the water. The remaining part of the area that is flooded contains meadows, farms, and some small villages.

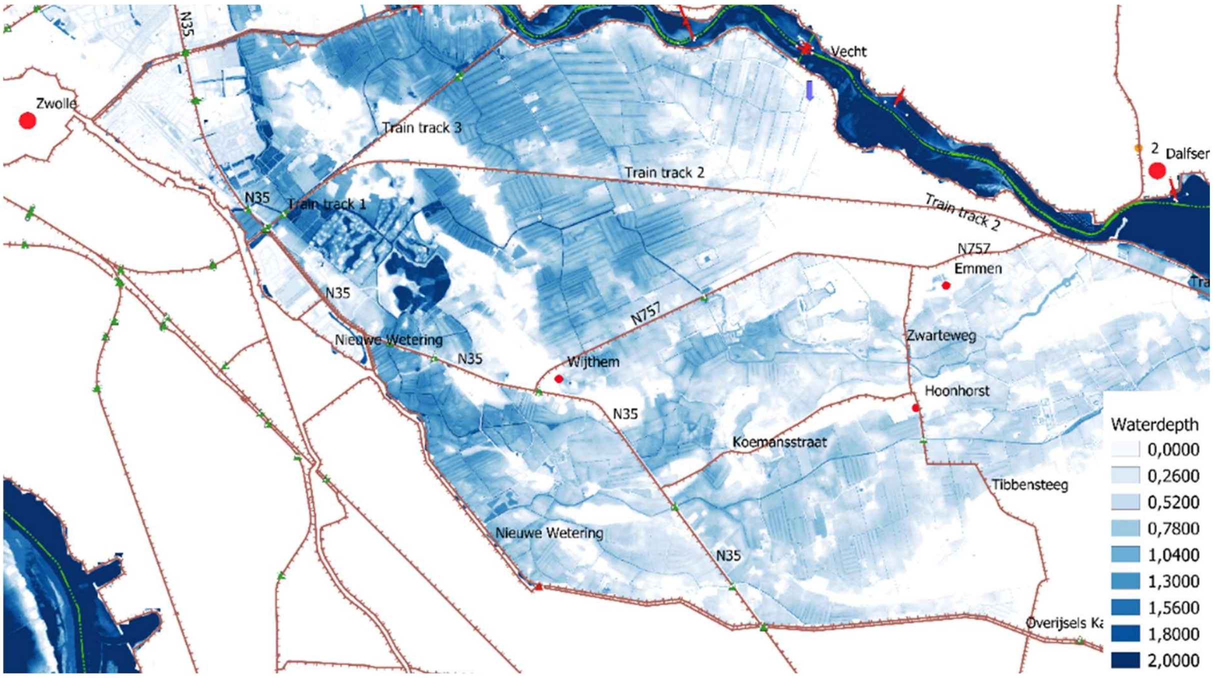


Figure 14 Max waterdepth after breach Rechteren (initial situation)

Table 4 in the pilot area analysis in Chapter 2 shows that the train tracks 1 and 3 together form a potential compartmentalising line-element due to the height compared to ground level. However, there are three openings which enable water throughflow. These locations are marked in Figure 15.

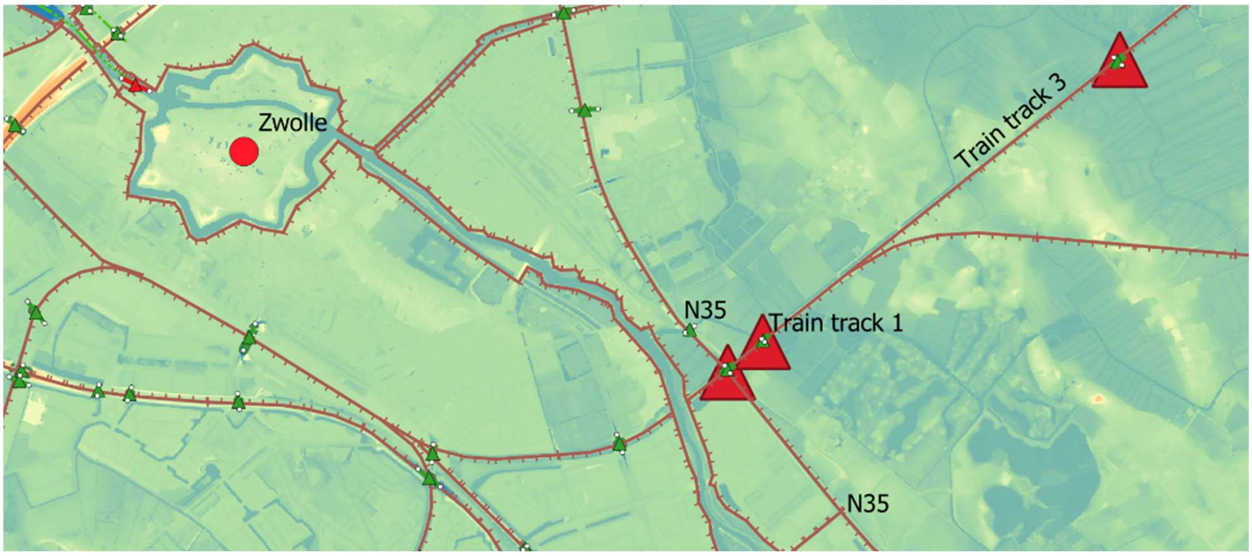


Figure 15 Openings in train track

The graph in Figure 16 shows the throughflow of these three openings. The total volume of water that flows through the train track in the model is more than 6 x 10^6 m^3 water. The hypothese is that closing these openings will save Zwolle for this volume of water (only if the water does not find another way over the train track, what has not happened in one of the simulations).

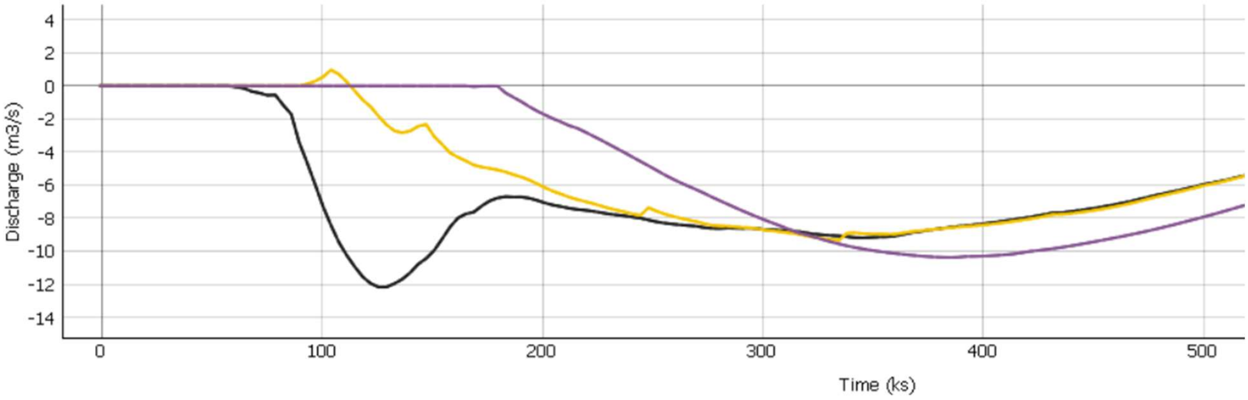


Figure 16 Throughflow openings in train track

5.3. Situation after closing openings

In Figure 17, the maximal water depth after a breach near Rechteren is shown. The openings in the train track are closed in this situation. The area north of train track 2 is safeguarded from the water in case of a breach near Rechteren. This is because the northern opening in the train track 3 apparently causes backflow of the water that was flown through the other two southern openings

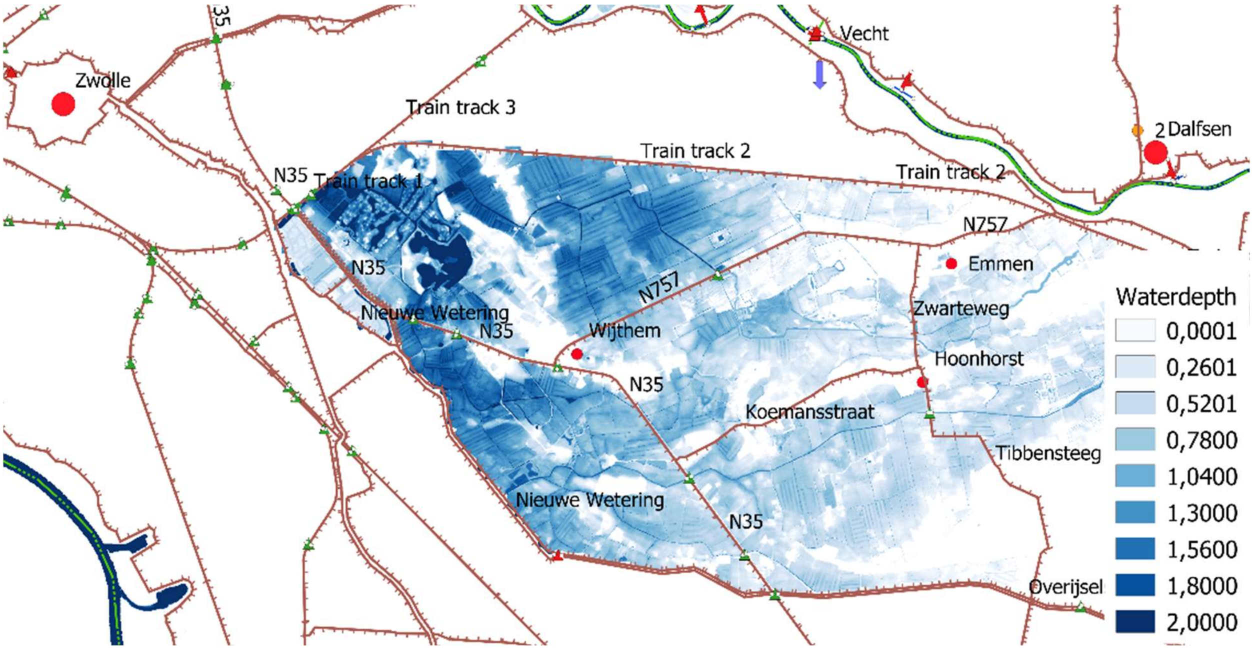


Figure 17 Max waterdepth after breach near Rechteren (openings in train track closed)

On the first sight, the situation has been improved by closing the openings in the train track. Less area is inundated. However, the output of the WaterSchadeSchatter shows the opposite, in case of a breach near Rechteren, as can be seen in Table 5. The damage has increased by almost 50%. In case the dike breached at the location of the purple arrow, the damage decreased with approximately €20,000,000.

Table 5 Monetary damge comparison (WaterSchadeSchatter)

	Breach near Rechteren	**Breach north of train track 2**
Initial situation	€176.000.000	€123.000.000
Openings in train track closed	€252.000.000	€106.000.000

Figure 18 clearly shows where the situation has improved, and where it has become worse. This figure has been created by subtracting the damage situation with measures by the initial damage situation without measures. Green colored buildings indicate less economic damage, red colored buildings indicate more economic damage. The area left of train track 1 and 3 benefits from the situation, but the main problem shifts to the industrial area left of the N35. The buildings in this area all all colored red, orange or yellow. To improve the current scenario, the industrial area should be protected against water inflow.

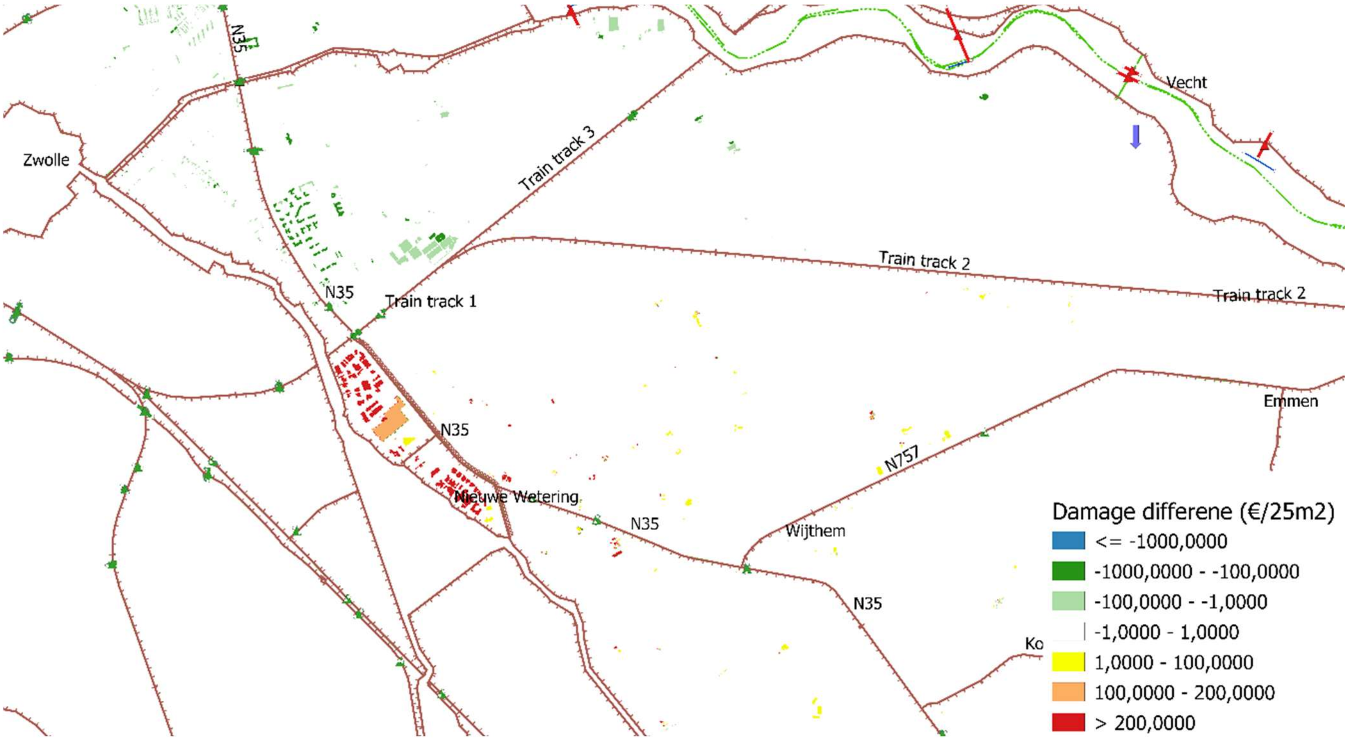


Figure 18 Damage difference due to closure openings after a breach near Rechteren.

5.4. Situation after protecting industrial area

Closing the openings in the train track leads to a side effect. The volume of water that overtops the N35 tot he industrial area is larger than in the initial situation. Therefore, the caused damage is increased. So, further measures should be taken to reduce the economic damage. A temporary dike is supposed around the industrial area.

In Figure 19, the industrial area is highlighted. The orange line indicates where the temporary dike is drawn in the model schematisation. The length of this dike is 1889.4 meter. The main part of the temporary dike can be built on the N35, which has an elevation of around 1 meter above sea level. The height of the temporary dike is set to 2.5 meter above sea level, a crest level which will not be exceeded by water according to the model, assuming that this dike will not cause a too large water level rise. In the next paragraph, a optimisation of the crest level will be done during the feasibility check of the proposed measures.

Figure 19 Temporary dike around industrial area

Figure 20 shows the impact of the temporary dike. The industrial area is free of water. Compared to the previous situation in Figure 17, nothing else is changed on the first sight.

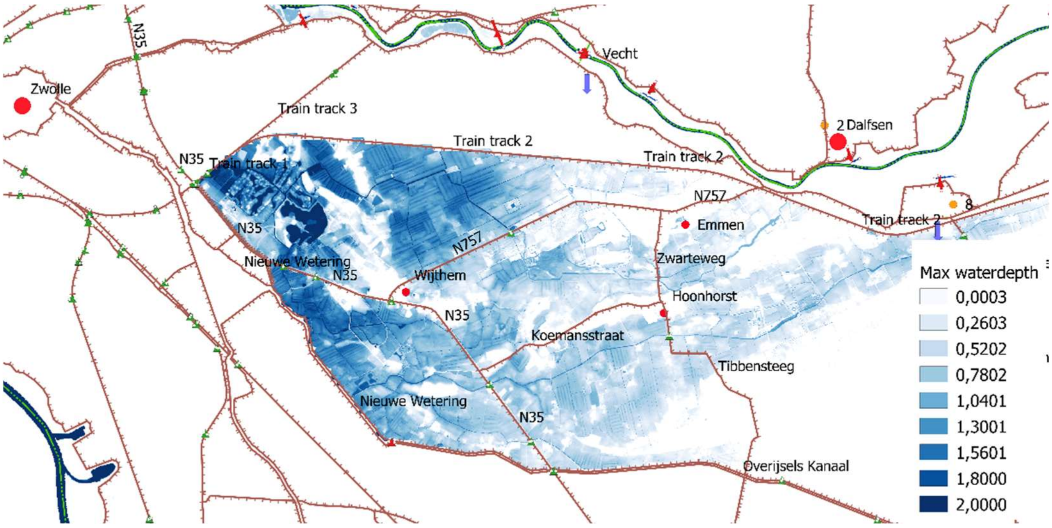


Figure 20 Max water depth after a breach near Rechteren (industrial area protected)

The impact on the monetary damage of these temporary dike is significant, as can be seen in Table 6. The damage due to a breach near Rechteren in the new situation with two measures is 20% of the initial damage. In case the dike breaches closer to Zwolle, the damage is 40% of the damage in the initial situation.

Table 6 Monetary damage comparison

	Breach near Rechteren	**Breach north of train track 2**
Initial situation	€176.000.000	€123.000.000
Openings in train track closed	€252.000.000	€106.000.000
Openings in train track closed & industrial area protected	€36.000.000	€48.000.000

5.5. Feasibility of measures

In this paragraph the feasibility of the designed measures is discussed. Moreover, the measures that are taken will be fine-tuned. The measures that are currently used are:

1. Closing the three openings in the train track
2. Fencing the industrial area with a temporary dike

The dimensions that are used for modelling the openings in the QGIS schematisation are presented in Table 7. It is important that the throughflow of the water is reduced to (almost) zero. Seeping water is not a problem, as long as the volume stays limited. The traffic tunnel of the Ceintuurbaan can easily be accessed because it is part of the infrastructure. Moreover, big bags can be placed around the entrance of the tunnel, so no water will flow through. The two bridges towards the Vecht are less accessible, but there is enough time for closing the gaps in the train track by placing bulkheads or using another method. There will not be further elaborated on details of closing these openings because it falls out of the scope of this research.

Table 7 Openings train track

What	Where	Dimensions	Distance to infrastructure
Traffic tunnel	Ceintuurbaan	5 m x 3 m	0 m
Small railway bridge	Herfterwetering	10 m x 3 m	200 m
Bridge	Between Vecht and Ceintuurbaan	1,5 m x 3 m	500 m

The temporary dike that is created is built mainly on the N35. In Figure 21, the green line is the longitudinal profile of the relevant part of the N35 (100 m – 1500 m). The remaining 500 meter is a higher elevated connection between the N35 and the Nieuwe Wetering. The blue line indicates the maximal water level that occurs next to the temporary dike due to the dike breach. The first 1100 meter needs the most attention. The N35 is approximately 1 meter high, and the max waterlevel is 2 meters. The N35 should therefore temporarily be raised with approximately 1 meter.

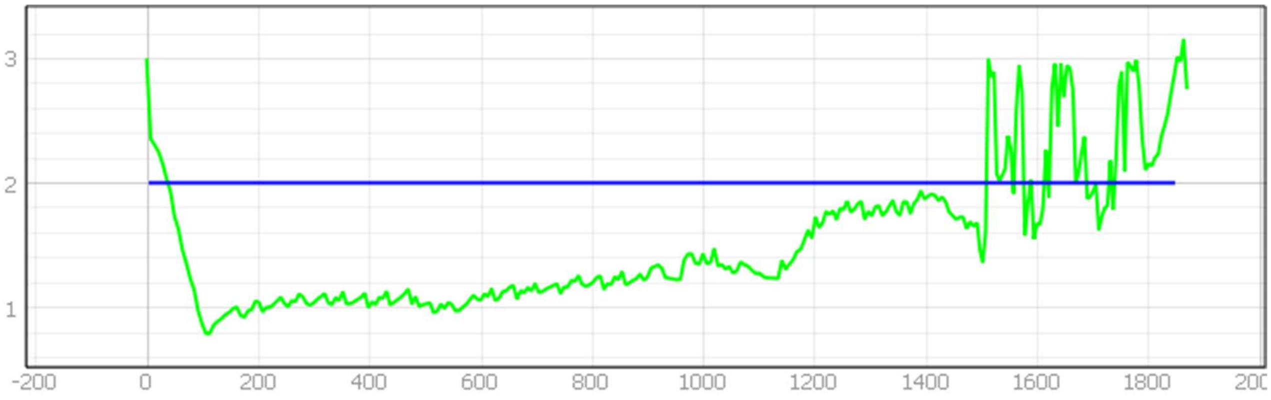
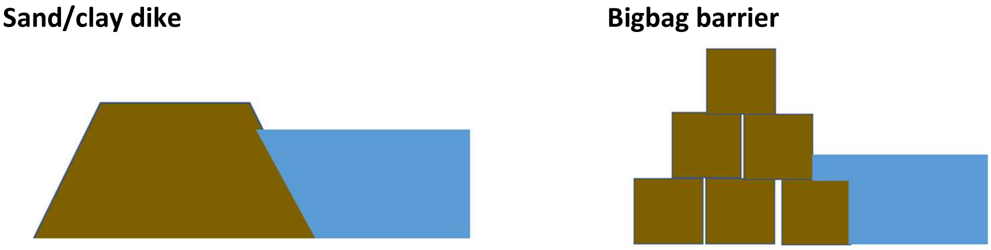


Figure 21 Elevation of underground temporary dike

This raising can be done in several ways. In Figure 22, two possible designs are shown. The stability of these measures has and will not been calculated. The first proposed dike is a dike made of sand or clay. The outside of the dike has to be covered with plastic or a comparable material, according to specialist in the Water Board. In the second option, bigbags are used. The size of a bigbag is approximately 1 x 1 x 1 m^3. In the figure, a cross section is proposed with three big bags on the bottom. This means that the total height is 3 m . According to Wijnand Evers, this set up will be able to withstand a water level of 1 meter. The temporary barrier should be placed over a stretch of approximately 1 km. Including the part where the raising is less than 1 meter, apprimately 7000 bigbags are needed for keeping the water out (estimation based on the big barrier setup below).


Sand/clay dike

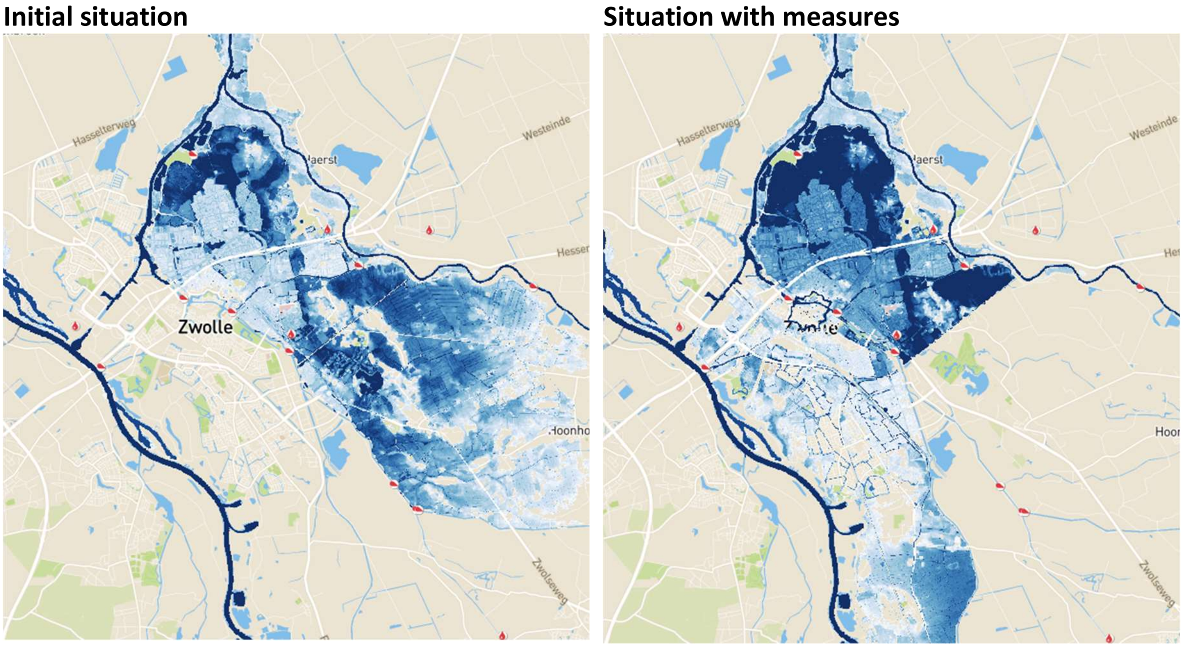
Bigbag barrier

Figure 22 Potential temporary dike design

It can be concluded that the openings in the train track can be closed relatively easily. However, creating a temporary dike requires more effort and preparation. It became clear from the interview with Wijnand Evers (Appendix II Interview) that this preparation not necessariliy means that 7000 bigbags should be filled and put ready on several locations throughout the jurisidictional area of the WDOD. However, when the Water Board does want to invest in the multi-layered safety, the current stock should be extended. The implementation of the measures can be done by local contractors, or even defence can be engaged in case of high need. On forehand, scripts can be created and even emergency situations can be simulated.
On the first sight, the proposed measures are feasible. However, the stability of the measures needs further research to ensure success.

5.6. Side-effects of measures

The measures are designed based on breaches east of Zwolle. The train track from Zwolle to Meppel forms the compartimentalising line-element that can prevent the water from flowing further to Zwolle if the openings in this line-element are closed. However, when the dike does not fail east of the train track but at the west side, the taken temporary measures can work countereffective. In Figure 23 the max waterdepth can be seen after a breach at Berkum. The influence of the implemented measures is clear. The area east of the train track is free of water. However, now the water spreads southwards along the Soestwetering to Wijhe.


Initial situation

Situation with measures

Figure 23 Comparison breach at Berkum

In Table 8, the damage outcomes of the two simulations are presented. It can clearly be seen that the caused damage by the water is much higher in case the openings in the train track are closed. When the two damage situations are compared, Figure 24 is created by substracting the initial situation with the situation with the openings in the train track closed (green is damage decrease, red is damage increase). The figure shows clearly where the situation has become better and worse. The situation right from train track (nr 1 and 3) has become better, because it is indemnified from water. The remaining part of the area must suffer from a larger volume of water. To make sure this situation does not happen, the closure of the openings in the train track must be easy to be undo.

Table 8 Comparison damage after breach at Berkum

Initial situation	€1,865,000,000
Sitation with train track closed	€4,302,000,000

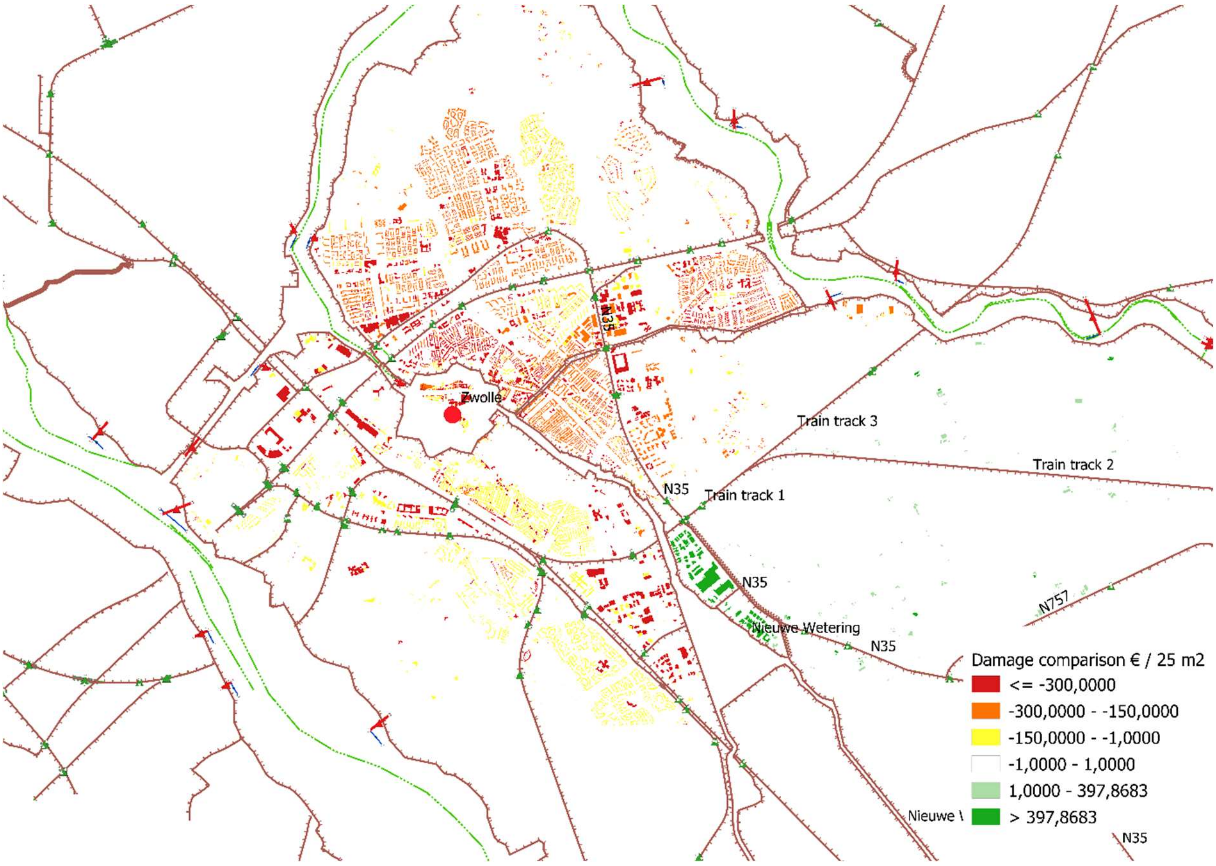


Figure 24 Damge comparison after breach at Berkum

5.7. Conclusion

It can be concluded that there are temporary measures that can be taken in the pilot area, which have a positive effect on the economic damage caused by the water. These measures reduce the economic damage with 60 or even 80%, depending on where the dike breach occurs. A note should be made because the measures may be counterproductive if the breach occurs at another location. Therefore, during the design phase of the measures, attention should be paid to possible side effects. These side effects can be negative, as can be seen in the case of Berkum. However, positive new insights can be gained, as can be seen in the case of the industrial area. When designers take these effects into account, input is created for design improvement interation loops.

6. Verification of method

6.1. Introduction

In this chapter, the used method is verified by applying it to another area in the jurisdictional area of WDOD. In consultation with the Waterboard, the Mastenbroekenpolder is chosen as verification area. The polder is an completely different area than the used pilot area. The verification will not be as expended as all the steps taken in the chapters above. From the already existing breach locations in this area, a breach is modelled at Veecaten, left of Stadshagen, as can be seen in Figure 25.

6.2. Short area analysis

In Figure 25, the lay-out of the Mastenbroekenpolder can be found. The rectangular pattern of roads and watercourses in the middle the figure shows a typical polder lay-out. 3 important places in this area are Genemuiden, IJsselmuiden and the suburb of Zwolle, Stadshagen. The Koekoekspolder is a compartment in the polder with several greenhouses, an area with a high economic value, located at the lowest point in the area. Three N-roads are located around the Mastenbroekenpolder. The train track from Kampen to Zwolle crosses the area.

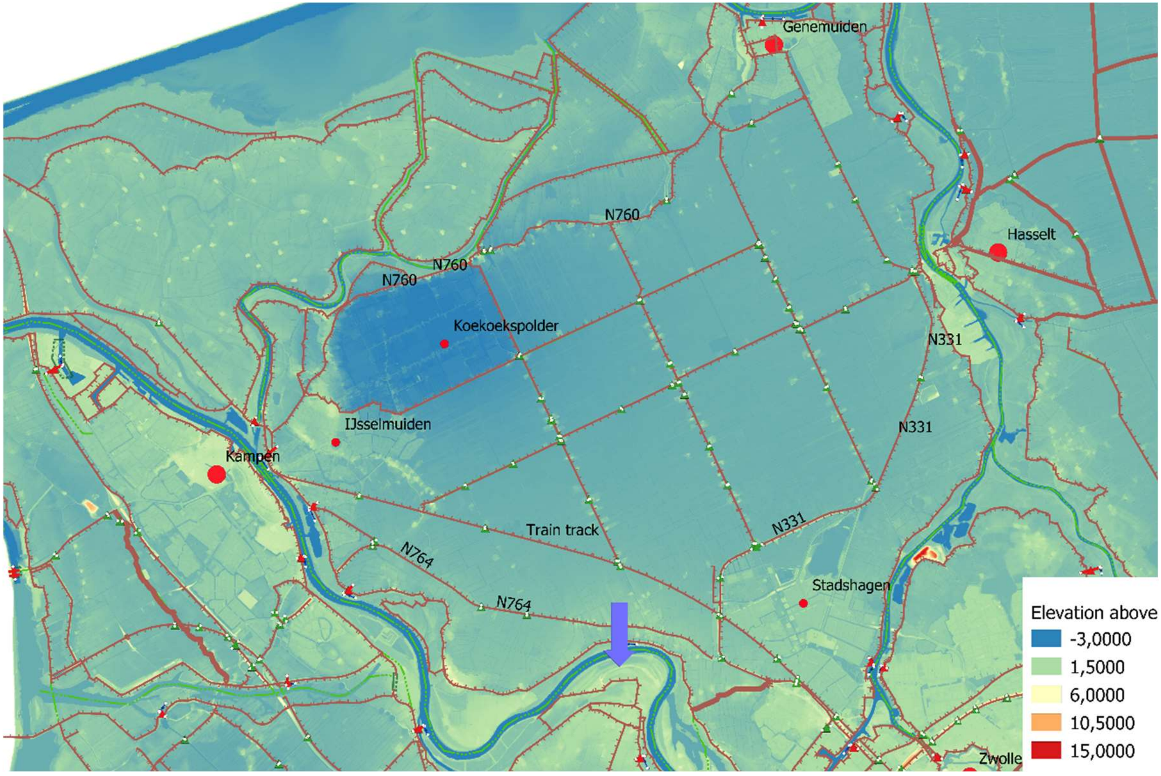


Figure 25 Lay-out Mastenbroekenpolder

6.3. Design of temporary measures

A breach in a dike of the IJssel will cause a higher inflow volume than a breach in a dike of the Vecht due to the discharge differences between both rivers, the width of the breach and the differences in water level between river and hinterland, as can be seen in Table 1. The breachflow that is used is taken from an already existing simulation with a river discharge recurrence time (T) of 1000 year. The used time series can be found in Appendix IV inflow volumes (nr.4 Veecaten). When the inflow time series for Veecaten is compared with the other 3 time series used in this research, a significant difference can be found. The inflow volume at Veecaten is much higher than at the other three locations. By assuming there is a linear relation between all the steps in the time-series, an total inflow volume can be estimated by calculating the area under the graph. The surface area can be calculated by using a QGIS function. Based on the inflow volume and surface area, an average water depth can be estimated by dividing the volume by the surface area. The results are presented in Table 9.

Table 9 Comparison pilot area & Mastenbroekenpolder

	Surface area	**Inflow volume**	**Average water depth**
Pilot area	6042 ha	1,7 x 10^7 m^3	0,28 m
Mastenbroekenpolder	8665 ha	3,2 x 10^8 m^3	3, 69 m

Based on the average water depth in the area, it can be concluded that there should be high-elevated line-elements to influence the flood pattern. In Table 10, the line-elements in the Mastenbroekenpolder are presented. The three N-roads are surrounding the polder, so these roads are not considered. Given that the calculated average water depth of 3.69 meter, only the sound barrier around Stadshagen is suitable to consider in this research to temporary measures.

Table 10 Elevation line-elements Mastenbroekenpolder

Line-element	**Elevation above ground level**
N764	0.2 – 0.6
N331	0.5 m – 2 m
N760	2 m – 2.5 m
Train track	0.5 m – 1 m
Sound barrier Stadshagen	2.5 m – 4 m
Roads along watercourses	0.5 m – 2 m

Figure 26 shows the water level in the Mastenbroekenpolder. It can clearly be seen that the area is filled up like a bathtub. The water level of 2.95 m above sealevel occurs everywhere inside the dikes. Figure 27 shows the water depth. The water depth differs from 1.20 m in Stadshagen to 5.80 meter in the Koekoekspolder. Based on the outputs of the 3Di calculations can again be concluded that only the sound barrier around Stadshagen can maybe be used as temporary barrier. All the crest levels of the line-elements are overtopped by the water, except for the sound barrier around Stadshagen.

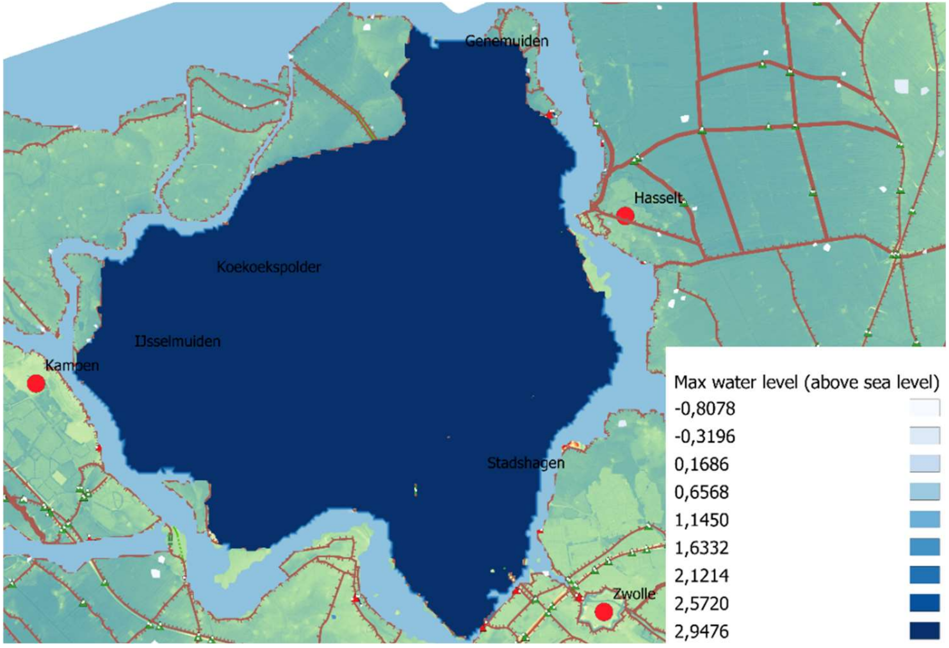


Figure 26 Water level Mastenbroekenpolder

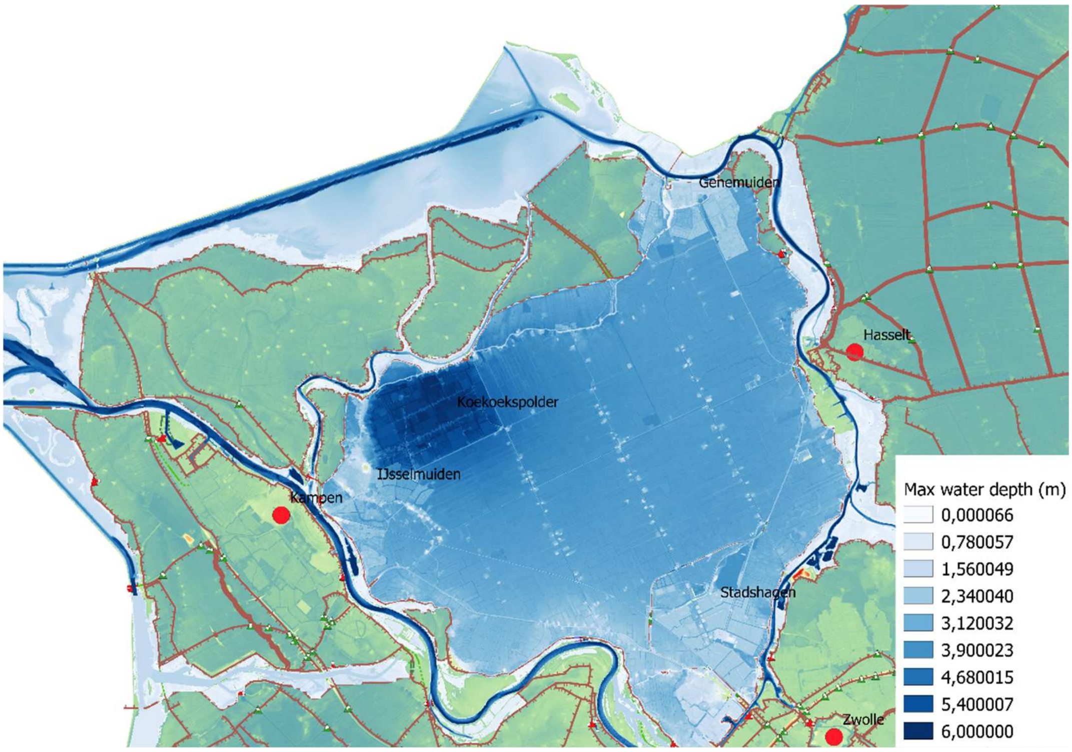


Figure 27 Water depth Mastenbroekenpolder

Because the sound barrier around Stadshagen is the only line-element which is high enough to function as water barrier, the temporary measures will be designed for Stadshagen. The start of this design is about to inventory which locations should be closed, and what the scale of the measures is. Then, the results are analysed.

6.4. Impact of temporary measures on dike breach of IJssel

Prevention of inundation

Closing Stadshagen is easier said than done. In Figure 28, the locations, according to several simulations in 3Di, where water can enter Stadshagen are shown.

Figure 28 Locations where water enters Stadshagen

Most of the locations can be made waterproof by placing big bags or bulkheads. If this succeeds, the biggest problem comes to light. The unprotected part at the north and southside of Stadshagen are low-lying and water will enter Stadshagen in case the other openings are closed. Figure 29 shows the difference between ground level and the maximal water level that occurs in case of the northern unprotected side. The average height that a temporary barrier should have at that location is 3 meters, over a stretch of 1 km.

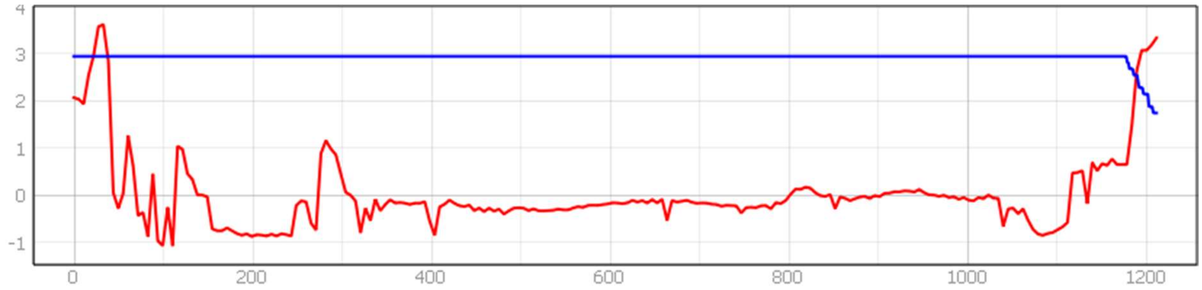


Figure 29 Cross-section unprotected side of Stadshagen

In Table 11, the temporary measure that should be taken to protect Stadshagen for the water of the IJssel are summarized. The size of this dimensions is determined by combining the inundation depth with the length over which the measures are to be taken. Compared to the measures which are designed for the pilot area, significant more time and resources are required due to the scale of measures. The sound barrier around Stadshagen is therefore not suitable for keeping the water out in case of a breach of the IJssel. Damming the northern unprotected part of Stadshagen is not realistic, by using the scale of measures used in this research.

Table 11 Measures to protect Stadshagen for Ijssel

Location	Length of measure	Height of measure
Unprotected (south)	500 m	3 m
Car entrance	100 m	1.75
Train tunnel	20 m	2 m
Car entrance	65	2 m
Bike tunnel	30	3.5 m
Water and road passage	300 m	3.5 m
Unprotected (north)	1000 m	3 m

Increase evacuation time

Keeping the water out of Stadshagen is not realistic in case a dike of the IJssel fails and 3.2 x 10^8 m^3 of water flows in. By assuming that all the openings in the sound barrier are closed, except for the unprotected parts, the evacuation time can be increased. In Figure 30, the difference in arrival time of the water is shown. This map is created by subtracting the arrival map of the situation with temporary measures from the initial situation. The greener, the higher the difference in arrival time. The measures have clearly an impact on the arrival time of the water after a breach near Veecaten. Depending on the location, the gained evacuation time varies between 2 and 20 hours for areas with housing.

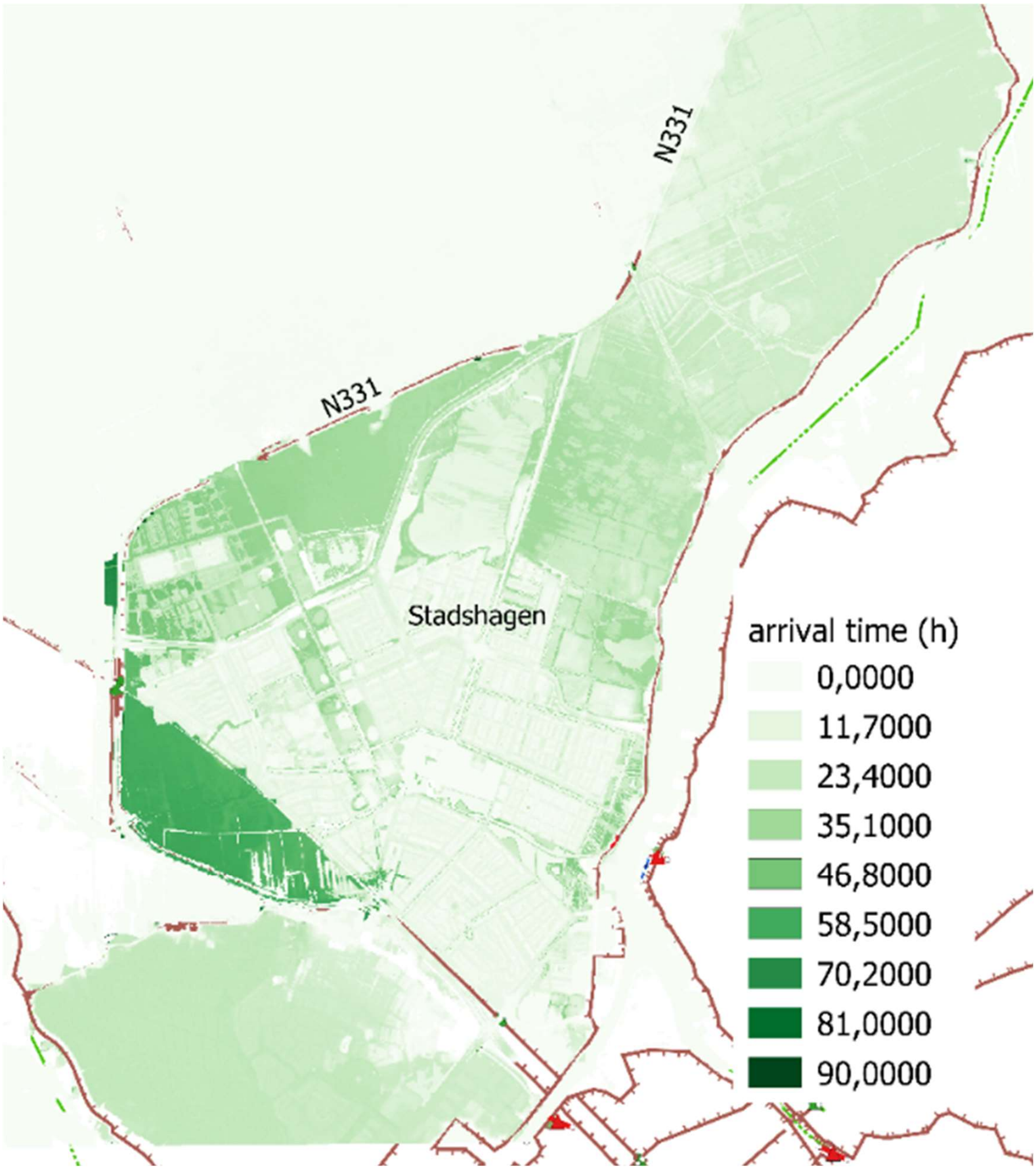


Figure 30 Impact measures on arrival time water in Stadshagen

6.5. Impact measures on breach Zwarte Water

Several news articles like (Plantinga, 2013), and intern documents of WDOD mention the sound barrier around Stadshagen as a possible water barrier. However, when a large volume of water enters the Mastenbroekenpolder, there is no action perspective for keeping Stadshagen dry. Therefore, another breach location is chosen, near Genemuiden: Roebolligerhoek.

The measures that are needed to keep Stadshagen dry in case of a breach south of Genemuiden with a water level with a recurrence time (T) of 1000 years are presented in Table 12. The size of the measures is significantly smaller than the measures that discussed in the previous section. The size of this dimensions is determined by combining the inundation depth with the length over which the measures are to be taken.

Table 12 Measures to protect Stadshagen for Zwarte Water

Location	**Length of measure**	**Height of measure**
Unprotected (south)	100 m	1 m
Car entrance	30 m	1.5
Train tunnel	20 m	1 m
Car entrance	65	0.5 m
Bike tunnel	30	1.5 m
Water and road passage	300 m	1.5 m
Unprotected (north)	400 m	2 m

In the initial situation, Stadshagen inundates because the water flows through the openings in the sound barrier. In Figure 31, the situation with temporary measures is shown. There is no water in the neighbourhood itself. The water depths that occur around Stadshagen are varying between 0.4 at the southern side and 1.6 at the northern side of Stadshagen. The model schematisation in QGIS is changed according to the values in the table above. However, the damage that arises in case the measures are implemented is €20,000,000 higher than in the initial situation, as can be seen in Table 13.

Table 13 Damage in Mastenbroekenpolder

Location	**Inflow volume**	**Economic damage**
Veecaten	3.2 x 10^8 m^3	€ 9,800,000,000
Roebolligerhoek	1.5 x 10^8 m^3	€4,480,000,000
Roebolligerhoek (Stadshagen closed)	1.5 x 10^8 m^3	€4,500,000,000

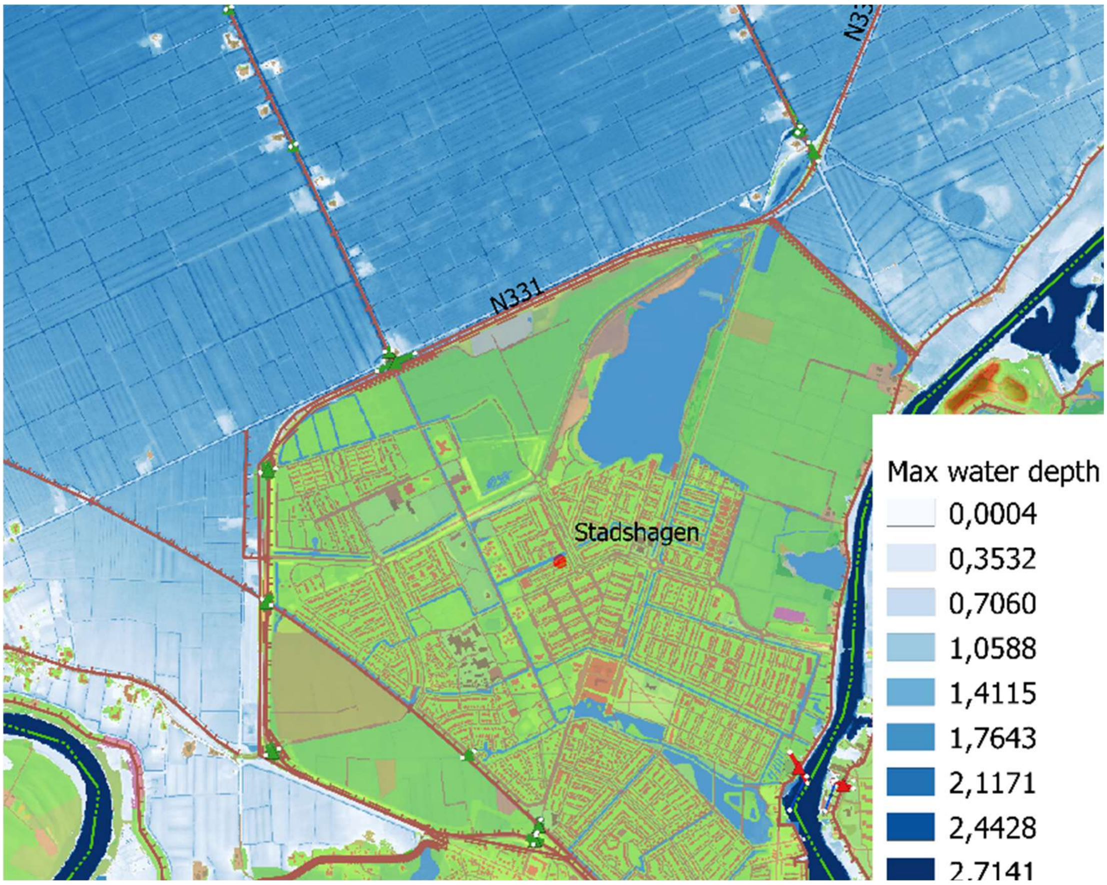


Figure 31 Stadshagen free of water

Figure 32 shows the locations where the damage difference due to the measures is positive (green), and where the situation has become worse (yellow, orange, red). The situation in Stadshagen has clearly been improved. However, the situation in Genemuiden and in IJsselmuiden has become worse. This is because the water that flowed into the area is now distributed over the remaining part of the Mastenbroekenpolder. Results of the 3Di simulation show that the water depth increases with approximately 8 cm.

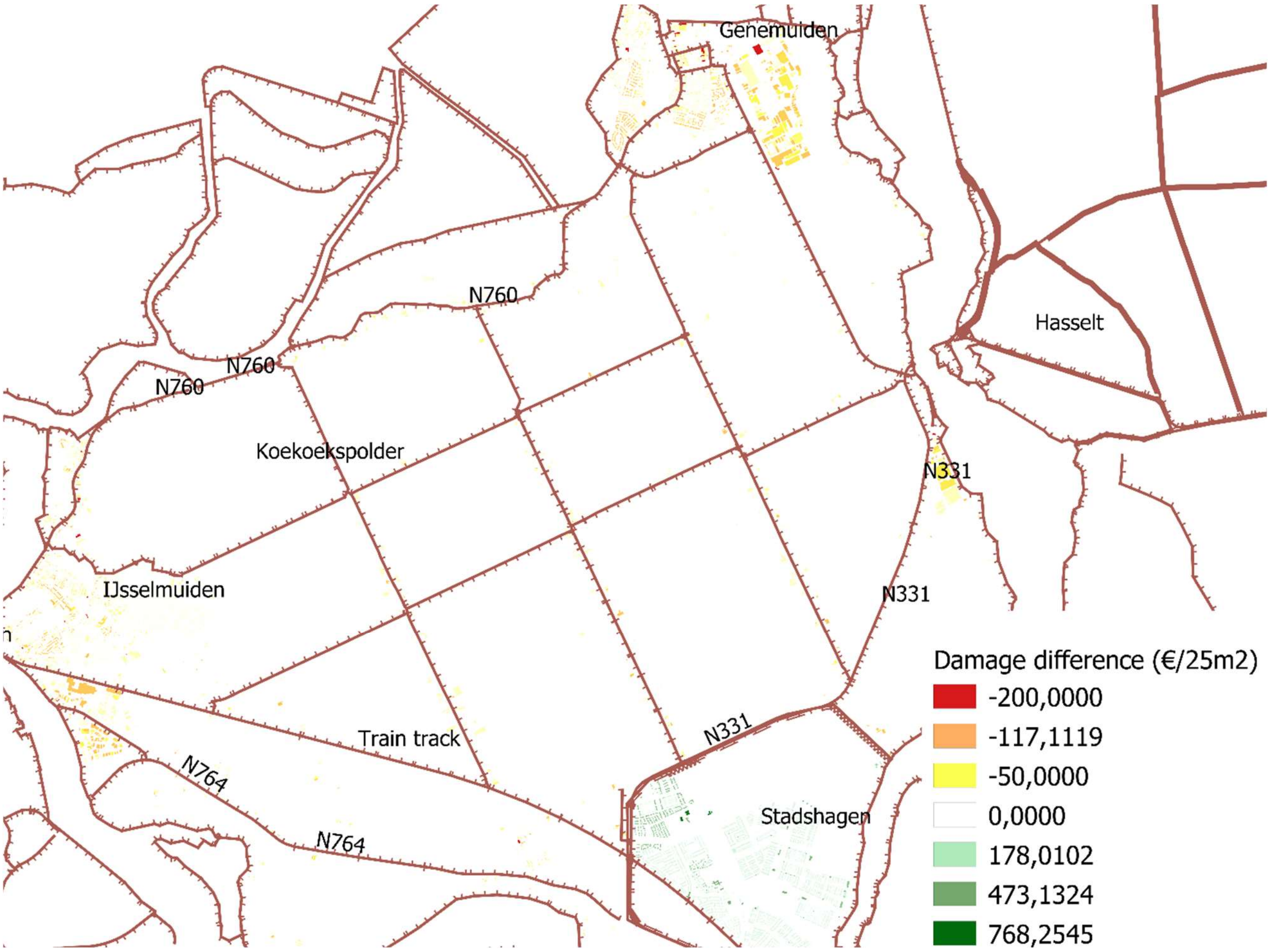


Figure 32 Damage difference due measures Stadshagen

6.6. Conclusion

It can be concluded that the line-elements and other landscape characteristics in the Mastenbroekenpolder are not suitable for the design of temporary measures, which are comparable to the size of the measures in the pilot area. This is for several reasons. Firstly, the inflow volume that occurs due to a breach in the dike of the IJssel is higher than a breach in the dike of the Vecht. Moreover, the line-elements in the area can be neglected regarding their damming function due to this high inflow volume. Therefore, the water cannot be steered to another location with a lower economical value. Even the sound barrier around Stadshagen cannot withhold the water from inundating this neighbourhood. Temporary measures around Stadshagen increase the evacuation time in case of breach of an IJssel dike. When a breach occurs along the Zwarte Water, the damage 50% of the damage in case of a breach along the IJssel. However, the situation becomes worse if measures around Stadshagen are implemented. As in the previous chapter, it can be concluded that temporary measures can have side effects or make the situation even worse. In the case of the Mastenbroekenpolder the problem shifts to another place and causes €20,000,000 extra damage.

7. Discussion

In this section, be results of this research will be discussed.

Throughout this research, the obtained results are an output of the calculations of 3Di. Models are never a 100% representation of reality. In the case of this hydraulic model, the hinterland behind the breach is divided into cells. The smaller these cells, the more accurate the simulation is. However, accuracy was not a problem in this study. Around all line-elements in the model schematisation, the cell size is already smaller than at other locations in the model. Moreover, the developers of the model have used a method that considers elevation differences within the cell. Sometimes cell sizes of 300 x 300 meters occur. However, at these locations in the model schematisation, the cell size is not influencing to the flood pattern.

Small openings in line-elements are not present in the model schemtatisation. In reality, small volumes of water will flow through these openings. Therefore, it will not influence the flood pattern significantly enough. Moreover, the more model elements, the more time consuming the calculations will be.

During the done simulations, external conditions like wind or rainfall are not considered. Moreover, it is assumed that the size of the measures is feasible, and the measures are reliable and will not fail during the time the water stands against them. These things do influence the flood pattern and are relevant in reality. However, this would go too far for an exploratory study like this.

The breach flow depends on the water level in the river, the water level and the elevation of the hinterland, and the size of the breach. However, the taken temporary measures may lead to higher water levels in the area around the bike breach. In that case, the counter-pressure of the water ensures that less water enters the area. The breach flow used for the first breach location in the area (see Appendix IV inflow volumes) is the same as for a breach at the second location: Rechteren. The breach flow at Rechteren corresponds with the characteristics of its location. This could lead to a difference in inflow volume at breach location 1. This is, however, not likely because the area characteristics look reasonably comparable.

The post-processing function of 3Di estimates the economic damage caused by the water. Each type of building, infrastructure element, or agriculture has a certain damage value, which is stored in tables. However, the caused damage will always be an estimation due to the uncertainty about the actual value of the inundated area. The Waterschadeschatter estimates the economic damage. However, it does not take human life into account. This includes the number of people that will be evacuated. This will influence the impact of a flood. For example, in chapter 6, floods in the Mastenbroekenpolder are assessed in combination with measures around Stadshagen. In section 6.5, the damage increase is around €20,000,000 in case Stadshagen is kept dry. But it takes longer for the water to reach IJsselmuiden than Stadshagen, so in this time, lives may be saved. Moreover, the situation with and without measures is compared with the same damage model, so the outcomes can be compared as well.

All these points do influence the results of this research. However, the main objective of this research was to get insight into the action perspective the Water Board has in case of a coming dike failure. To get these insights, no detailed results are necessary. Therefore, the results of this research are suitable for the objective and give the Water Board a good starting point for further investigation.

8. Conclusion

The goal of this research was to design temporary measures for the jurisdictional area of WDOD. By doing this, the Water Board gains insight into the action perspective there is in case of a flood. In this conclusion, the results of the research are presented. Extensive recommendations regarding the methodology for the Water Board can be found in the next chapter. Four conclusions will be drawn and substantiated with cases out of this research.

1. The water board has action perspective for temporary measures in case of a coming dike breach.

This conclusion is based on the design of measures in the pilot area of this research. The pilot area is the area between Zwolle and Dalfsen, south of the Vecht. This area was chosen as a pilot area because there seemed to be opportunities, due to the topography, to prevent the water to reach Zwolle.
There were indeed opportunities. By closing the three openings in the train track between Zwolle and Meppel and the laying of a temporary dike of one meter high around valuable industrial area, the economic damage is decreased by 60 or 80%, depending on the location of the dike breach. The framework that is used is to design the measures is limited by an implementation time of 48 hours. Within this time, openings in line-elements can be closed, line-elements are created, or raised. In this area, by using some measures which fall within this framework, useful results can be achieved. However, this is not always the case. This leads us to the second conclusion.

2. The feasibility of measures is situationally dependent.

When the used measure design methodology was verified to the Mastenbroekenpolder, no temporary measures could be designed due to the high water level in the area. This water level was a result of a breach in the dike of the IJssel with a high inflow volume. The line-elements in the area were all overtopped, except for the sound barrier around Stadshagen. The measures that were needed to protect Stadshagen from the water were not feasible due to the size, in contrast to the pilot area.

3. Consider side effects of the designed temporary measures.

This conclusion can be supported by using the results of the above-described cases. In the case of the pilot area, the analysis after the first design round showed a damage increase. However, this could be tackled easily, so this was a positive side effect for the process. Next to the breach locations for which the measures were designed in the pilot area, another breach location was used to chart negative side-effects after the first iteration round. Results: damage increase of €2,500,000,000.

In the case of the Mastenbroekenpolder, a breach along the Zwarte Water was simulated as well. There appeared to be more scope for action by using the sound barrier around Stadshagen than in case of a breach of the IJssel due to the lower inflow volume. However, the impact of closing Stadshagen to water was a €20,000,000 economic damage increase.

4. Temporary measures buy time for action.

In the case of the Mastenbroekenpolder, the line-elements were too low to be used as a water barrier. However, these line-elements can function as a temporary buffer, so the people behind that line-elements have more time to evacuate, especially when the damming function of these lines is increased.

9. Recommendations

Based on the results of this study, recommendations are done for the design of temporary measures to reduce flood risk. Moreover, a few suggestions are done for further research. These recommendations are based on the used methodology in a pilot area and the verification of this methodology in another area.

Almost every design phase is an iterative process. The suggested methodology is developed by repeating the design phase 2 times. This resulted in clear and useful results. However, when this methodology is applied, more iterations are proposed, because unexpected problems, due to neglected details or hidden snags, may arise.

The design of temporary measures starts with an extensive study of the area which is under research. First, a general impression of how the area looks like is needed to form a basis that enables the designer to use it later in the process. This impression can be created by charting the land-use types and identifying areas with housing or industry. Next to land-use, the main line-element in the area should be listed, together with the height above ground level. A field trip enlarges the affinity with the area as well.
The next step is running and/or analysing flood simulations for a certain recurrence time. In this research, a recurrence time of 1000 years is used. Depending on the purpose of the design, another recurrence time can be chosen. By analysing flood simulations, insight is gained in the way the water develops, which area is flooded, which line-elements influence the flood-pattern, and which inundation depths are caused by the water. Postprocessing functions of hydraulic models can even estimate the caused economic damage.
The third step is about the type of measures that will be used to design temporary measures. In this research, three types of measures are used: 1) filling openings in line-elements, 2) raising existing line-element, and 3) creating new line-elements. More research should be done to the extension of the measure arsenal, by, for example, considering spill-overs or closing the breach. Furthermore, the stability of all the proposed and new measures should be investigated by barrier specialists. Another key element that should be investigated is the size of the measures. How large can a temporary dike be? Or how many big bags can be installed within a certain time?

When the above steps are gone through, the iterative design process starts.
The first step is about finding the line-elements which can be used as temporary barrier. In the case of this research, the maximal inundation depth is compared with the elevation of the line-elements. By doing this, the area is divided into compartments, which are already closed or contain still smaller or larger openings.
Then, the designer should decide which parts of the area should be protected, by focussing on areas with high economic value. By using the type and size of the proposed measures, temporary measures can be designed by using line-elements or other topographical aspects of the area.
Once the measures are designed, the testing phase begins. In this research, 3Di Watermanagement is used to simulate floods. However, other hydraulic models can be used as well, with the note that detailed calculations around line-elements and other important locations of a hydraulic perspective are necessary to obtain the right results. In some cases, the inundation pattern is breach location bound. A breach 500 meters upstream can lead to a different course of the water. Therefore, running floods from multiple breach locations is suggested. This way, possible side effects of the temporary measures will come to light. Often, when water is kept from a place, it increases the water depth at other locations, so damage is caused somewhere else.

At this point, the designer has three options: 1) try other measures, or the same type of measure at another location, 2) improve the current set of measures due to gained insights, 3) stop designing because the desired result is obtained, or there is no action perspective in the area.

Lastly, a general recommendation with respect to spatial planning, evacuation, and successful implementation. The described temporary measures are part of the so-called new multi-layered flood safety approach. In the future, Water Boards should be more included in the design process of the landscape. This research shows that adjustments in the hinterland of a dike can lead to significant damage reduction. When new roads, train tracks, or neighborhoods are built, attention should be paid to permanent measures. Roads or train tracks can be raised, so the damming function is increased. Neighbourhoods can be arranged tactically, so evacuation is simplified. Next to having good emergency plans, whether it is about temporary measures or evacuation, high-water practices should be done. Practicing will increase the chance of success and will raise awareness for the fact that it is not obvious that we live safely behind our dikes.

Bibliography

Alkema, D., & Middelkoop, H. (2007). The influence of floodplain compartmentalization on flood risk within the Rhine-Meuse delta*. In *Advances in Natural and Technological Hazards Research* (Vol. 25, pp. 21–42). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4200-3_2

Bates, P., Woodhead, S., Fewtrell, T., Soares-Frazão, S., Zech, Y., Velickovic, M., de Wit, A., ter Maat, J., Verhoeven, G., & Lhomme, J. (2009). *Flood Inundation Modelling-Model Choice and Proper Application Lead Author Nathalie Asselman DOCUMENT HISTORY*.

Deltares. (2011). *Kosten van maatregelen Informatie ten behoeve van het project Waterveiligheid 21e eeuw*.

Dijkgraaf Albert leefde in een roes: 'Ik had nooit mediatraining gehad' | Foto | destentor.nl. (2021, May 4). https://www.destentor.nl/kampen/dijkgraaf-albert-leefde-in-een-roes-ik-had-nooit-mediatraining-gehad~af8390d2/164966218/

Experticenetwork waterveiligheid. (2016). *Grondslagen voor hoogwater-bescherming*.

FRAMES, Interreg VB North Sea Region Programme. (2021, May 1). https://northsearegion.eu/frames/

Hoss, F., Jonkman, S. N., & Maaskant, B. (2011). *A COMPREHENISVE ASSESSMENT OF MULTILAYERED SAFETY IN FLOOD RISK MANAGEMENT-THE DORDRECHT CASE STUDY*.

Houcine Chbab. (2017). *Basisstochasten WTI-2017*. http://publications.deltares.nl/1209433_012.pdf

HWBP. (2021, February 25). *Wie we zijn en wat we doen*. Https://Www.Hwbp.Nl/over-Hwbp/Wie-We-Zijn-En-Wat-We-Doen.

Hydrologic. (2019). *Gevolgenbeperking overstromingen dijkring 9*.

Kandiah, V. (2016). *Connecting 1D and 2D Domains*. https://www.youtube.com/watch?v=bwI5nSHHU2M&ab_channel=XPSolutionsMediabyInnovyze

Neuvel, J. M. M., & van den Brink, A. (2009). Flood risk management in dutch local spatial planning practices. *Journal of Environmental Planning and Management*, *52*(7), 865–880. https://doi.org/10.1080/09640560903180909

Plantinga, H. (2013, October 31). *Geluidswal beschermt Stadshagen tegen water | Weblog Zwolle - Nieuws*. https://www.weblogzwolle.nl/nieuws/37586/geluidswal-beschermt-stadshagen-tegen-water.html

Rijkswaterstaat Projectbureau VNK. (2014). *De veiligheid van Nederland in kaart*.

Ruimte voor de rivieren | Rijkswaterstaat. (2021, June 1). https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/ruimte-voor-de-rivieren

Siepman, S. (2021). *Drought in the Netherlands and its impact on groundwater resources*. Https://Www.Un-Igrac.Org/Stories/Drought-Netherlands-and-Its-Impact-Groundwater-Resources.

Temporary flood barriers | WaterWindow. (2021). https://waterwindow.nl/themas/tijdelijke-waterkeringen

Traver, R. (2014). Flood risk management: Call for a national strategy. In *Flood Risk Management: Call for a National Strategy*. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/9780784478585

van Kempen, I. M., & van Baars, S. (2009). *Official Publication of the European Water Association (EWA)*.

Verweij, W., van der Wiele, | J, van Moorselaar, | I, & van der Grinten, | E. (2010). *Impact of climate change on water quality in the Netherlands*. www.rivm.com

Volp, N. D., van Prooijen, B. C., & Stelling, G. S. (2013). A finite volume approach for shallow water flow accounting for high-resolution bathymetry and roughness data. *Water Resources Research*, *49*(7), 4126–4135. https://doi.org/10.1002/wrcr.20324

Waterwet. (2021, February 25). Https://Wetten.Overheid.Nl/BWBR0025458/2021-01-01#Hoofdstuk2.

WDOD. (2021). *HWBP Trajecten*. https://wdodelta.maps.arcgis.com/apps/Embed/index.html?webmap=96a29a7daaea40f3a9c8326547b5e3ce&extent=5.612,52.2929,6.6262,52.6438&home=true&zoom=true&scale=true&disable_scroll=false&theme=dark

Wesselink, A. J. (2007). Flood safety in the Netherlands: The Dutch response to Hurricane Katrina. *Technology in Society*, *29*(2), 239–247. https://doi.org/10.1016/j.techsoc.2007.01.010

Wicks, J. (2015). What is 1D and 2D flood modelling. In *https://www.youtube.com/watch?v=GIAqQDs5Gjc&ab_channel=FloodModeller*.

Appendix

Appendix I Pilot area study line-elements

In this Appendix, the line-elements which form (temporary) barriers are listed per breach location, which can be found in Figure 4. Using Google maps, these line-elements can be found. Moreover, a description is added in below the table.

Table 14 Breach locations analysis - line-elements

Breach location	**Dike nr**	**Influencing elements**
Hasselt	9	Dedemsvaart Zomerdijk Meppellerdiep Hoogeveensche vaart Rijksparallelweg
Dalfsen (to the north)	9	Train track Zwolle -Meppel A28 Zwolle Meppel After a long time, the N377, perpendicular on A28
East Genemuiden	10	First the Nieuwe Weg. Then Nieuwe Weg and Wolfshagenweg. After fill up, Kamperzeedijk. Polder compartments are slowly filling up.
Stadshagen	10	The roads in the polder form small barriers, but no influence at all. Kamperzeedijk is obvious! First 10 hours between Bisschopswetering Kerkwetering and Nieuwe Wetering. Before it enters the Koekoekspolder, Hagedoornerweg and Bisschopswetering. The train track from Zwolle to Kampen is barrier after 30 hours. Lastly, the train track overflows and the Koekoekspolder as well.
Kampen, Molenbrug	11	Its like a bathtub N50 and train track form barrier. Reevediep dike as well
Hattem	11	Kamperstraatweg holds it at some point. Water flows Between n50 and IJssel, stops at dike of Reevediep After 10 a 15 hours, water overtops kamperstraatweg. Water between Zwarteweg and Zuiderzeestraatweg to Elburg Grachtenweg is a barrier Grote Woldweg Area fills up from reevediep to the south.
De zande	11	The Reevediep dike and N50/traintrack. The kamperstraatweg. The roads like grote woldweg Zomerdijk Drontermeer Water between Zwarte weg, zuiderzeestraatweg It approaches Elburg, overtops rondweg.
Dalfsen (rechteren)	53	Traintrack Zwolle ommem Heinoseweg/zwolseweg then Overijselse kanaal/nieuwe wetering who lays behind these roads
Above Deventer	53	Train track (however it flows over at some point) Soesterwetering to some extent (Hamelweg, Boerhaar) Stops at Zuthermer weg windesheim
Herxen	53	Spoorlijn naar bovenstrooms, Soesterwetetering overal. Benedenstrooms de ijsseldijk. Eindigt in Zwolle WIjhseweg/ IJsselAllee

Simulation description
Breaches in dike track 9 cause little damage, because the water does not reach vulnerable urban areas, except for the urban areas near the breach. It is impossible to prevent this kind of damage due to space and time constraints. The water has plenty of space to spread between the dikes of some watercourses and elevated roads in the area. In case of a large inflow volume at a breach near Dalfsen, the water can reach Hasselt and the borders of Meppel and Staphorst. There are some opportunities for temporary measures due to the presence of some higher elevated line-elements.
Breaches in dike track 10 look comparable to each other. Due to the watercourses, roads, and train track with a compartmentalising effect in the polder landscape, water flows to adjacent compartments when a compartment is full of water. A characterizing rectangular flood pattern is visible. In case of a breach at Stadshagen, this district will flood. The sound barrier which surrounds the district partially functions as a flood barrier. Therefore, water can be kept out in case a dike fails outside Stadshagen.
Kampen, in dike track 11, is on forehand not a good choice as a pilot area. No matter where a breach occurs along the IJssel, the area fills up like a bathtub. The city is surrounded by dikes and water since the construction of the Reevediep. A breach at De Zande, on the other side of the Reevediep, will mainly cause damage for farmers which live in this area. The area between the IJssel and the Drontermeer will fill up southwards as time goes by. The borders of Elburg are even reached when the flood holds on for a longer time. Almost the same pattern is found after modelling a breach near Hattem.
Breaches in dike track 53 along the IJssel cause similar patterns to each other. The water stays between the dikes of a watercourse and the river. After a certain period, the water inundates the south of Zwolle. If the inflow volume of water and the inflow time are high, Zwolle can inundate. In case of a breach in dike track 53 along the Vecht, the water flows to Zwolle as well. Due to a south-facing watercourse, the water does not spread south and reaches the eastern part of Zwolle. When the flood holds on without any interventions, the remaining part of Zwolle can flood as well.

Appendix II interview Wijnand Evers

In this appendix, the ‘interview’ with Wijnand Evers, a dike supervisor, is described. During his career, Wijnand has gained experience all over the world in high water calamity situations. The conversation we had lasted longer than an hour. The notes took during the interview have been converted into a good running story.

What are emergency measures that WDOD is currently using?
Emergency measures are the same as management measures, but then in case of an emergency. The current measures that are taken are management measures. Think of cramming, supporting berms, placing sandbags, big bags, or other types of temporary water barriers. The waterboard has stored the needed materials for temporary measures in stocks, like sandbags, bigbags and foil. However, the materials available are mainly meant for reinforcing the primary defence system.

What are suitable ways to mitigate the flood risk if a dike is failed or will fail certainly?
First, have good emergency plans. Then, vulnerable areas should be protected. This can be done by creating compartments or steering the water in the desired direction. The infrastructure in the area can be used to create these compartments. Gaps in line-elements can be filled or whole roads or train tracks can be raised. Roads can be reached easily by loaders or cranes. Train tracks are less accessible for heavy-duty machinery. Meadows can be used as well. There is space enough to create a temporary barrier with clay and sand that can be dug on site. This temporary barrier does not have to be high immediately. The first 0.5 meter will stop the water for some time. In this time the barrier can be raised, or there is more time to evacuate and to create somewhere else a barrier.
When it is possible to steer water to less vulnerable areas, this opportunity should be taken. Most of the time this is agricultural land. I do not know which areas are suitable for sacrificing. It is therefore important to make sure dikes will nevers fail. And if it fails, the gap should be closed as soon as possible. This can be done by dragging ships in the gap, placing caissons, or by pouring all kinds of materials and objects in the gap.

How much time do we have after a dike breaches, and how much time does it cost to implement temporary measures?
That depends on the location of the breach and the inflow volume. The waterboard knows when high-water is coming and how long the dikes should withstand a certain water level. Most of the time, dikes can withstand the water, but in some cases a part of a dike is weakened by animals or other types of failure. Because the waterboard is monitoring the dikes, these locations are known, especially in case of high water, the monitoring of the dikes is intensified, and possible failures can be detected in an early stage.
When a dike fails, there is time enough to take some measures. Depending on the location and the inflow volume, a distinction can be made between measures that can be taken. The closing of a tunnel or culvert does not take that much time compared to the raising or creation of a line-element. The machinery and materials that are needed can be claimed by local contractors. Agreements can be made on forehand, but in case of an emergency, goodwill is always there. Money is no issue during calamities. Returning to the question, I estimate the time that you have between 5 and 10 hours. This can be more, or less, depending on the location. It is therefore wise to set up a list for small periods of time < 5 and between 5 and 10 hours. Filling gaps and creating small temporary barriers can be done within 5 hours. As the time increases, larger measures can be taken. Do not think complete new dikes can be created, but several hector meters can be addressed. Keep always in mind that stability of the measures is important. A small clay barrier on asphalt will enable more seepage than a temporary barrier next to the road on the soil for example.

Appendix III 1D-2D modelling

Model set up

Currently, there are three types of hydraulic models. 1D, 2D and 1D-2D. When an 1D- and 2D-model are combined, an optimal interplay between the 1D and 2D hydraulic modelling is achieved. A clear example can be seen in Figure 33. All the elements in a certain area which can be modelled best in 1D, rivers, pipes, and culvers, are modelled in 1D. The remaining part is modelled in 2D. One essential step when combining 1D- and 2D-models is getting rid of overlap. This is done by removing a part of the 2D grid on the locations where a 1D model is used. Afterwards, the 1D and 2D elements must be coupled to get an optimal synergy (Wicks, 2015). This coupling is not always made due to practical issues. It can be imagined that not each brook and creek will be removed out of the 2D grid and will be replaced by a 1D element (as described above), due to time constraints. In that case, the 1D lines and the 2D grid will overlap. In case of a flood, this will lead to a duplication of the volume of water that is present in the 1D line and the 2D grid at that location.

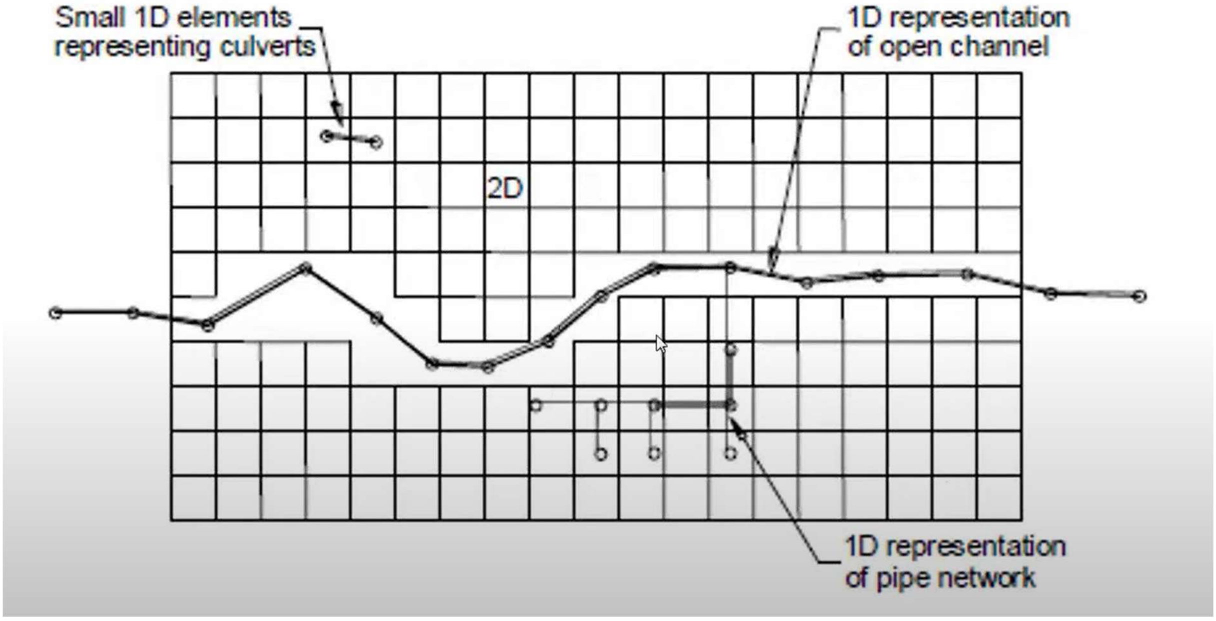


Figure 33 Optimal interplay between 1D-2D hydraulic modelling (Kandiah, 2016)

In Table 15, the characteristics of a 1D, 2D, and 1D-2D coupled hydraulic model are summarized, based on a comparison of(Kandiah, 2016). A 1D hydraulic model has a low computation time. Moreover, rivers and hydraulic structures can be modelled easily. However, a complex floodplain cannot be modelled accurately. The computation time of a 2D model is high, a river and hydraulic structures cannot be modelled accurate (or it will be time-consuming). The floodplain modelling is done accurately. The coupling of a 1D and 2D model is therefore the most realistic option because the 1D components in the model decrease the computation time.

Table 15 Comparison 1D, 2D, 1D-2D hydraulic models

	1D- model	**2D- model**	**1D-2D coupled model**
Computation time	Low	High	High
River modelling	Fast	Inaccurate or time consuming	Fast
Complex floodplain modelling	Inaccurate	Accurate	Accurate
Hydraulic structures	Accurate	Time-consuming	Accurate

Model calculations

3Di is a 1D-2D model. In Table 15, in the section above, some general characteristics of a 1D-2D model can be found. The computation time is high. This is because the number of equations that have to be solved is large. In general, the more detailed the model is, the higher the computation time. However, the the creators of 3Di found a way to tackle this. The way 3Di calculates the water flows in a 2D domain is mainly based on a paper of (Volp et al., 2013). The core of this method is that the model can calculate with a high resolution, without a large increase in computation time. This is done by creating a subgrid in the coarse grid of the model, so changes in roughness and bedlevel are acurater, see Figure 34. The waterlevel in a course cell applies to the whole cell. However, the model determines which cells in the subgrid of the course cell is considered by solving the momentum and continuity equations applicable to that specific situation. Users of 3Di can determine which cells in the grid need high resolution. The model used in this research uses these grid refinements as well. All the cells where dikes, roads and train tracks are modelled have a higher resolution, so 3Di estimates the water flow around those elements better due to the grid refinement. Moreover, the roads and dikes are 1D elements as well. This means that the water only passes in case the crest level is overtopped. In this way, the grid refinement around these line-elements do not require high detailed refinement.

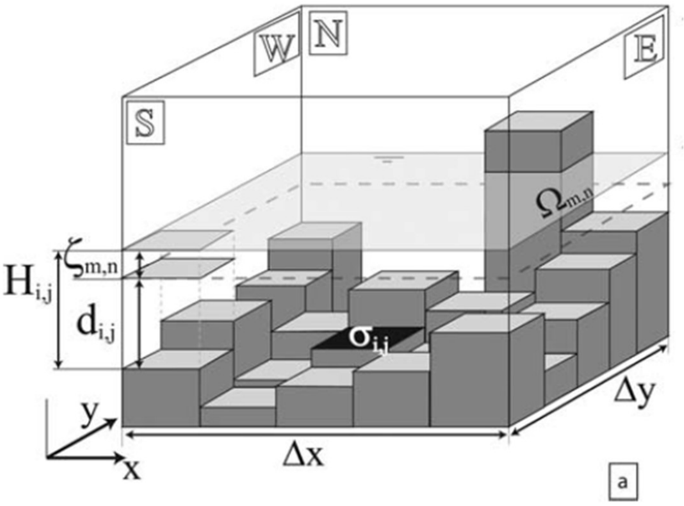
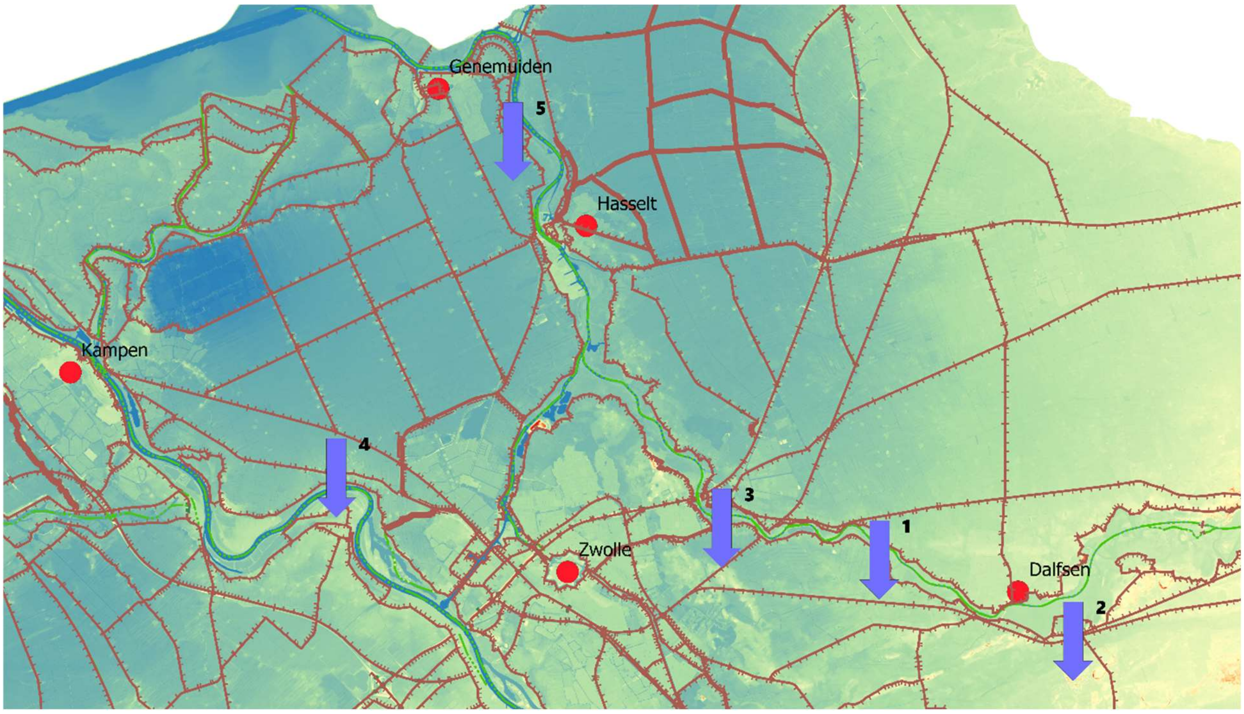


Figure 34 Subgrid used by 3Di 2D calculations (Volp et al., 2013)

Appendix IV inflow volumes

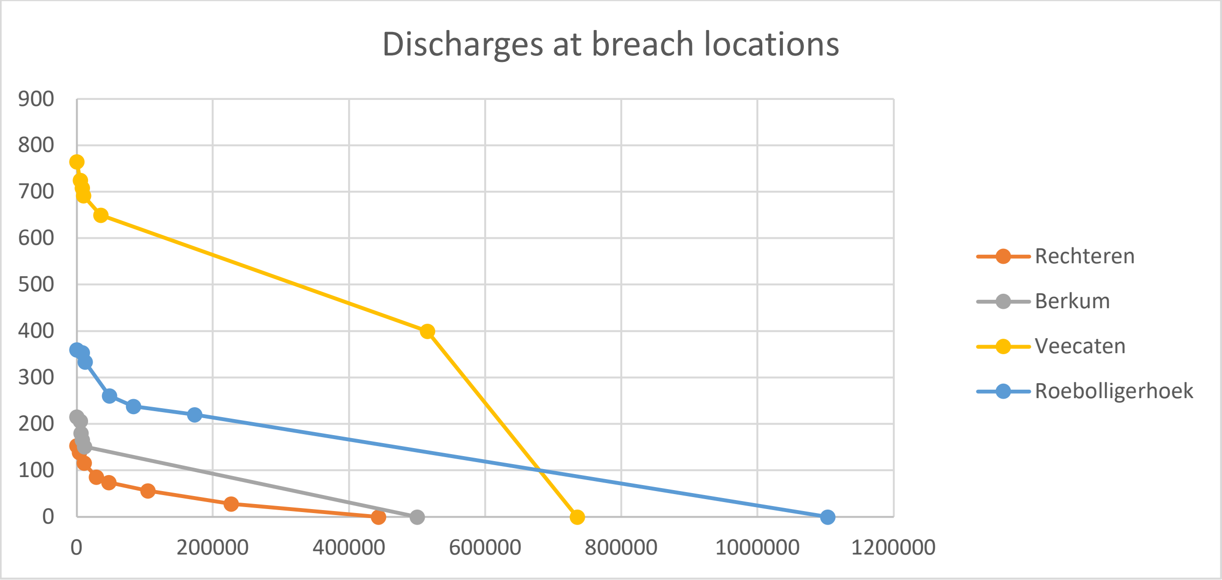
In this Appendix, the used inflow volumes for modelling floods can be found. The inflow volumes that are used have their recurrence time in common. T = 1000. The inflow volumes are, however, location dependent, due to the difference in breach size, and the water level in the river and hinterland. Because there are already flood simulations done for the used breach locations, the inflow volumes are used from these locations. For modelling purposes, the inflow is regulated by using a so called "lateral". In a lateral, a time-series can be added with discharges. In the model, three lateral locations are used, as can be seen in the figure below.



In the table below, the used time-series can be found for each lateral location. Location 2 and 3 are breach locations which the waterboard uses as well, therefore, they have a name. Location 1 is chosen because 'train track 2' has a clear influence on the flood pattern. The number before the comma indicates the time in seconds. The number behind the comma indicates the discharge. 3Di interpolates between two points in the timeseries, so between the points a linear connection is made.

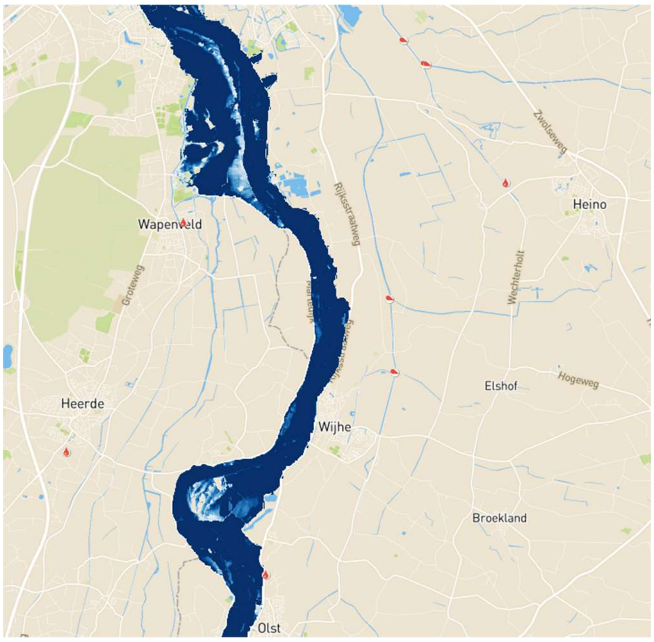
Location	**1.**	**2. Rechteren**	**3. Berkum**	**4. Veecaten**	**5.Roebolligerhoek**
Timeseries	0,153 3600,139 10800,116 28800,86 46800,74 104400,56 226800,28 442800,0	0,153 3600,139 10800,116 28800,86 46800,74 104400,56 226800,28 442800,0	0,215 5000,206 6000,180 8000,166 11000,151 500000,0	0,765 5000,725 8000,708 10000, 692 35000,650 515000,400 735000,0	0,360 8000,354 12000,334 48000,261 83000,238 173000,220 1103000,0

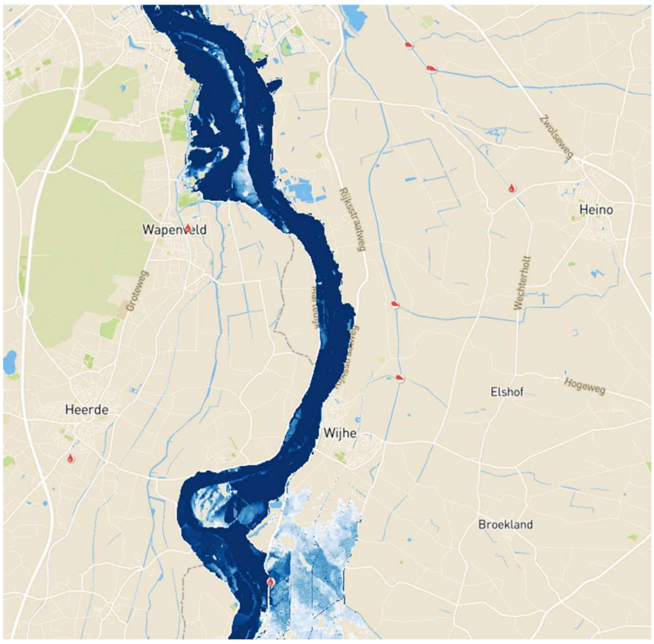
In the graph on the next page, the discharges can be compared. The duration of the breach at Veecaten is shorter than the other ones, because the water level in the hinterland caused counter-pressure.

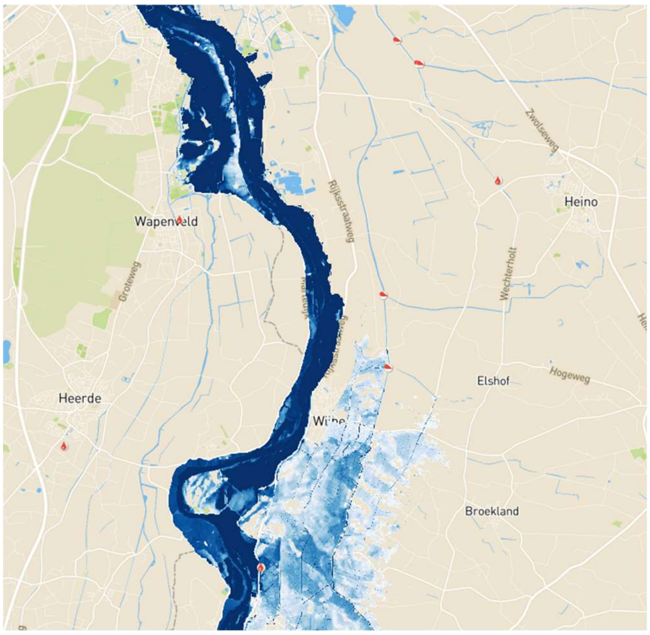

Discharges at breach locations
900
800
700
600
500
400
300
200
100
0
0
200000
400000
600000
800000
1000000
1200000
Rechteren
Berkum
Veecaten
Roebolligerhoek

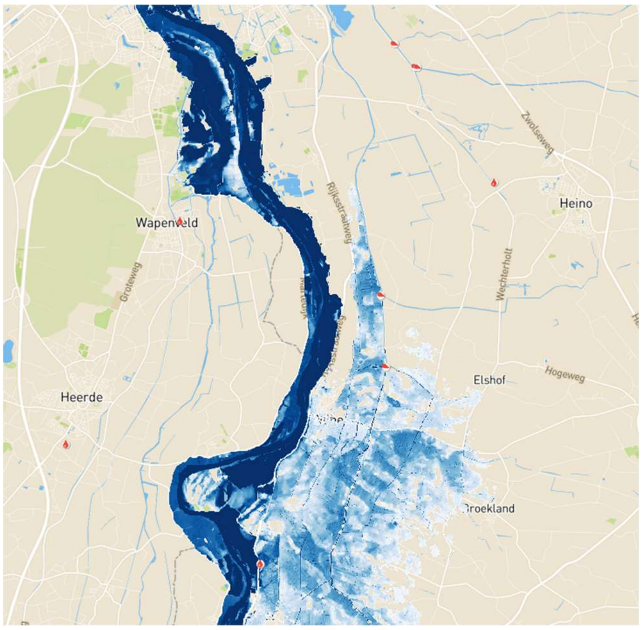
Appendix V Flood pattern analysis

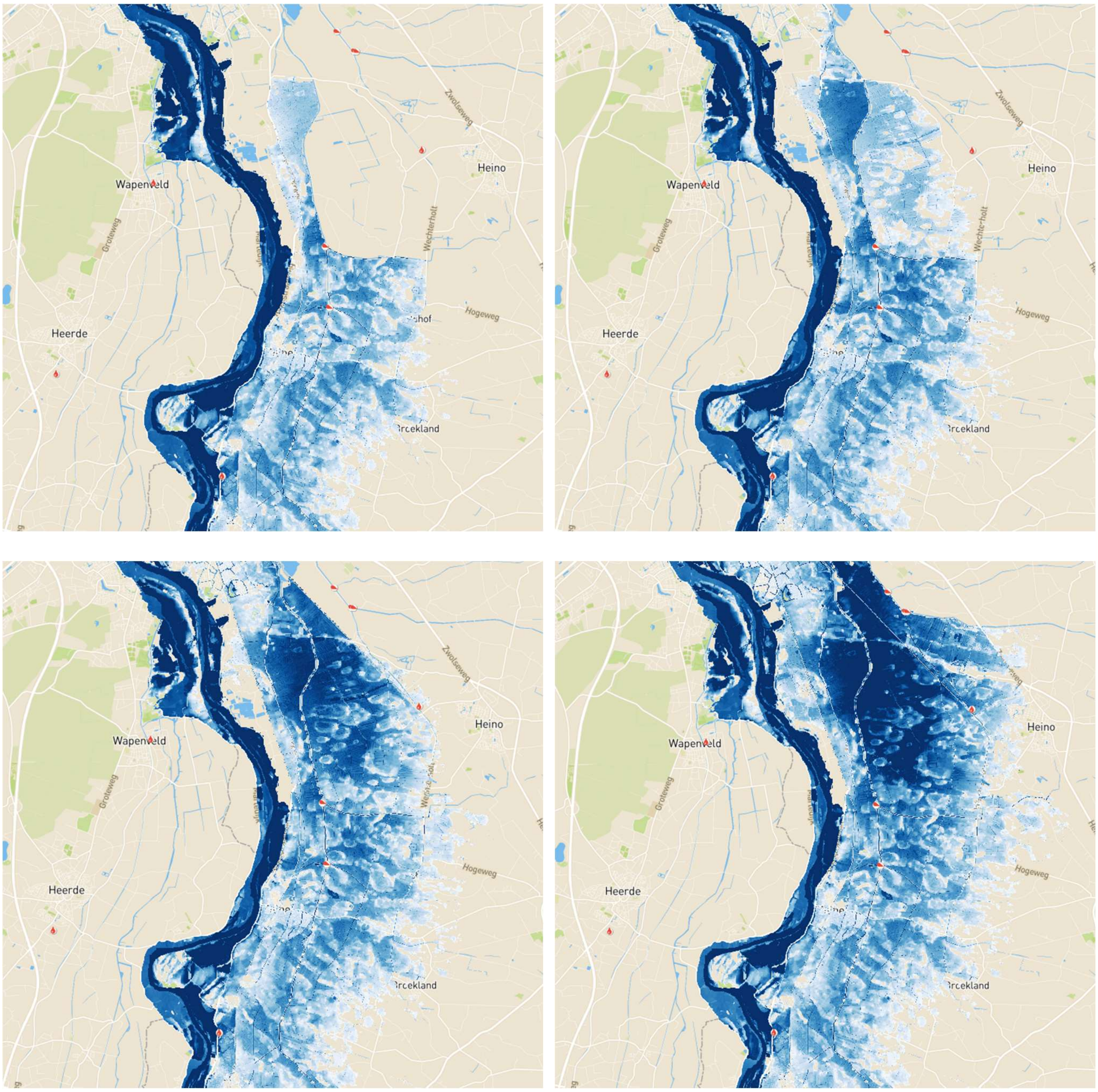
In this Appendix, a example of a flood pattern analysis is given. Each screenshot shows new developments the water has made after a breach at Olst. By looking closely to simulation results, line-elements, and other landscape elements which (temporarily) influence the flood pattern can be identified.










Wapenveld
Heino
Heerde
Groteweg
Zwolseweg
Wechterholt
Hogeweg
rcekland