Evaluation of the excavation of the spillways in the dikes along the Linge and Waal in case of an inundation of dike ring 43

Stijn Janse

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Preface

Dear reader,

Before you lies my Bachelor Thesis. Finally I can present the end product of a process which has lasted a good while longer than originally anticipated. Several major events have taken place in my life over the course of the last one and a half years, having a significant impact on my last academic year of my Bachelor Civil Engineering at the University of Twente. Therefore I am incredibly happy to close the chapter and complete my Bachelor. But before doing so, I have to thank several people. Not only for their technical and academic guidance, but also for their flexibility with my more than once changing schedule.

First of all, I want to sincerely thank Marcel van de Waart from Waterboard Rivierenland. He provided my with the opportunity for a Bachelor assignment in the first place, and subsequently arranged my stay at the Waterboard even when my project got delayed by several months. Furthermore, he has provided instrumental technical guidance throughout the whole project and he provided me valuable feedback during the process.

Second, I want to thank my supervisor from the University of Twente, Vasileios Kitsikoudis. Whereas due to the nature of my Bachelor assignment the technical guidance has come more from the Waterboard, Vasileios has provided me with plenty of advice on the academic side of my Thesis assignment throughout the whole process. Additionally, I want to thank Vasileios for the very flexible attitude with regards to my planning throughout the process.

Having said that, I hope you will enjoy reading the Thesis that lies in front of you!

Stijn Janse,

Enschede, 14th of March 2025

Summary

The Netherlands famously is a low-lying country at the mouth of several Europe's largest rivers. But due to the low elevation of the country, river floods have always posed a threat. As much as 29 percent of the country is at risk from flooding of the major rivers (Planbureau voor de Leefomgeving, 2024).

The Dutch doctrine to protect the low-lying areas from floodings from both rivers and the sea revolves around dividing the low-lying areas into so-called dike rings. Each dike ring is a section of low lying area surrounded and protected by primary flood defences (such as dikes, weirs and dunes) and higher lying terrain.

As the Rhine enters the Netherlands it splits into several different branches. The two main branches are formed by the Nederrijn and its continuation the Lek in the north and the Waal in the south. In between these branches two middle-sized dike rings are located: dike ring 43 upstream and dike ring 16 downstream. The border between the two dike rings is formed by a dry dike called the Diefdijk. The Diefdijk protects the downstream dike ring 16 in case that the upstream dike ring 43 is inundated.

In between the Nederrijn and the Waal flows the Linge, a small river that lies completely within dike rings 16 and 43. The dikes along the Linge are lower than the dikes running along the Nederrijn and Waal and do not form a part of the primary flood defences protecting dike rings 16 and 43 from the large rivers. The dikes along the Linge do however provide an extra barrier if the upstream dike ring 43 is inundated.

To help to alleviate the load on the Diefdijk during an inundation of dike ring 43, the Lingewerken are constructed. The Lingewerken consist of a series of spillways in the dikes of the rivers Linge and Waal. If in the case of an inundation the water level in dike ring 43 is higher than in the Waal, the spillways of the Lingewerken can be activated to guide flood water from dike ring 43 (back) into the Waal.

While research from the 1990s has shown the positive effect of the Lingewerken on the safety of dike ring 16, little research has been conducted about the effect of the Lingewerken on dike ring 43. Also, the effect of the Lingewerken has only been quantified in terms of a water level reduction, but not in terms of damage and casualties. The research objective of the project is to evaluate for which flood scenarios of dike ring 43 it is advantageous to use the Lingewerken in order to prevent as many casualties and as much economic damage as possible.

The research is conducted by integrating the Lingewerken in the latest flood model of dike ring 43 of Waterboard Rivierenland, utilising D-HYDRO software. The subsequently found effect of the Lingewerken on the flood water level is then evaluated by using the Schade- en Slachtoffer Module (translated: Damage and Victims Module) to find the expected reduction in economic damage and amount of casualties.

The effect of the Lingewerken on preventing damage and casualties is evaluated for two different dike breach events. The first evaluation assesses the benefit of the spillways along the Waal and the Linge for a very severe inundation scenario (return period 1/10000 years) with a dike breach location south of Tiel. It is found that in case of a large scale inundation of dike ring 43, excavation of the spillways along the Waal reduces the size of the inundation considerably. The amount of damage and casualties is significantly lower by excavating the spillways along the Waal. On the other hand, excavation of the spillways along the Linge in addition to the spillways along the Waal has a limited

effect. By excavating the spillways along the Linge, the spread of the inundation is accelerated but the size of the inundation stays more or less the same.

The second evaluation is conducted to answer whether or not it is beneficial to excavate the spillways along the Linge and the Waal if there is a smaller-sized inundation from the north near Beusichem (return period 1/100 years). In a scenario without utilisation of the spillways, the dikes along the Linge form a barrier for the inundation to spread further causing significant water levels north of the Linge but low water levels south of the Linge. By excavating the spillways in the dikes along the Linge and, the water levels north of the Linge are reduced but the inundation spreads further south before leaving the dike ring through the spillways along the Waal. It is found that when the spillways are excavated, the decrease in damage and amount of victims north of the Linge does not weigh up to the extra damage and casualties south of the Linge. Excavation of the spillways along the Waal and Linge is therefore disadvantageous in case of a smaller-sized inundation from the north.

It can be concluded that for both assessed flood events, a severe flood coming from the south of Tiel and a less severe flood from the north near Beusichem, disadvantageous to excavate the Linge spillways as the excavation of the Linge spillways leads to more casualties and economic damage. On the other hand, it is certainly advantageous to excavate the Waal spillways in case of a large scale flood south of the Linge in order to reduce the damage and amount of casualties significantly.

A conclusion that the usage of the Linge spillways is disadvantageous for every flood scenario might however be premature based on only two investigated dike breach scenarios. A scenario not investigated where the Linge spillways could prove to be useful is in case of a large scale inundation north of the Linge from the Nederrijn. Excavation of the Linge spillways in addition the Waal spillways could provide a quick way for the flood water to leave dike ring 43 thereby reducing the size of the inundation. Therefore the recommendation is made to investigate the effect of the spillways along the Linge for a large scale inundation from Nederrijn before drawing definitive conclusions about the Linge spillways.

Table of Contents

1. Introduction

The Netherlands famously is a low-lying country at the mouth of several of Europe's largest rivers. That is even where the term Netherlands, or low countries, stems from. Major rivers as the Rhine, Meuse and Scheldt have given the Dutch great opportunities in terms of transport and trade. But due to the low elevation of the country, river floods have always posed a threat. As much as 29 percent of the country is at risk from flooding of the major rivers (Planbureau voor de Leefomgeving, 2024).

As the Rhine enters the Netherlands it splits into several different branches. The two main branches are the Waal and the Nederrijn. These two river branches flow parallel to each other from the German border in the east towards the North Sea in the west. In addition to the dikes running along the Nederrijn and Waal an extra dike, the Diefdijk, is constructed perpendicular to the Nederrijn and Waal, running from the Nederrijn to the Waal. Consequently, the Diefdijk divides the area between the Nederrijn and Waal into two parts. The part upstream of the Diefdijk is called dike ring 43 (further explanation about a dike ring follows in Chapter 2.1) and the part downstream of the Diefdijk is called dike ring 16. The Diefdijk protects the downstream dike ring 16 in case the upstream dike ring 43 is inundated.

To help to alleviate the load on the Diefdijk during an inundation of dike ring 43, the Lingewerken were constructed in 1809. The Lingewerken consist of a series of spillways in the dikes of the rivers Linge and Waal. If in the case of an inundation the water level in dike ring 43 is higher than in the Waal, the spillways of the Lingewerken can be activated to guide flood water from dike ring 43 (back) into the Waal.

While research from the 1990s has shown the positive effect of the Lingewerken on the safety of dike ring 16, little research has been conducted about the effect of the Lingewerken on dike ring 43. Also, the effect of the Lingewerken has only been quantified in terms of a water level reduction, but not in terms of damage and casualties.

The aim of this project is to evaluate how and when the Lingewerken should be deployed in case of an inundation of dike ring 43. This is done by integrating the Lingewerken in the latest flood model of dike ring 43 of Waterboard Rivierenland, utilising D-HYDRO software. The subsequently found effect of the Lingewerken on the flood water level is then evaluated by using the Schade- en Slachtoffer Module (translated: Damage and Victims Module) to find the expected reduction in economic damage and amount of casualties. Different inundation scenarios will be evaluated, differentiated on dike failure location, river discharge and activated parts of the Lingewerken.

The report is structured in the following way:

- In Chapter 2 the background behind the project is provided. The general Dutch flood defence strategy is explained before specifying how the Lingewerken fit into the flood defence strategy. What already is known and what still is to be investigated about the Lingewerken is also discussed in Chapter 2.
- The problem statement, research objective and research questions are discussed in Chapter 3.
- In Chapter 4 the methodology of the project is discussed. The different components that together form the current model of dike ring 43 are discussed first. Afterwards it is explained which changes are made to the current model to include the spillways along the Waal and Linge. Lastly, it is explained how the results of the altered D-HYDRO model are translated into damage and amount of casualties by the Schade- en Slachtoffer Module.

- In Chapter 5 the results of the project are shown. For each investigated scenario the impact of the spillways along the Waal and the Linge on the inundation depths is show.
- The discussion of the project follows in Chapter 6. In the discussion the limitations of the project are explained and a comparison is made between the found results of this project and the research conducted previously.
- The conclusion of the project follows in Chapter 7. In the chapter the research statement is reached by answering the research questions.
- In the last chapter, Chapter 8, recommendations for new research are made.

2. Problem context

2.1 Flood defence strategy

The Dutch doctrine to protect low-lying areas from floodings from both rivers and the sea revolves around dividing the low-lying areas into so-called dike rings. Each dike ring is a section of low lying area surrounded and protected by primary flood defences (in Dutch: primaire waterkeringen) such as dikes, weirs and dunes. In total there are 95 dike rings in the Netherlands ranging in size and importance from small villages to most of the Randstad area. Based on the consequences of an inundation, each dike ring section has an associated safety norm embedded in law, ranging from 1/100 years for small dike ring sections where an inundation only has minor consequences to 1/1 000 000 years for the dike ring section protecting the Borssele nuclear reactor (Ministerie van Infrastructuur en Milieu, 2016).

The area in between the Nederrijn and the Waal is divided into two different dike rings. The area upstream of the Diefdijk forms dike ring 43 and the area downstream of the Diefdijk forms dike ring 16. Figure 2.1 provides a map of the Netherlands where dike rings 16 and 43 and the Diefdijk (which is part of both dike rings) are highlighted.

Figure 2.1:Location of the dike rings 16, dike ring 43 and the Diefdijk

In addition to the primary flood defences, which form the backbone of the flood defence system, there may be regional flood defences (in Dutch: regionale waterkeringen) within a dike ring . Regional flood defences are generally smaller in size than the primary flood defences and are meant to protect the surrounding against small rivers and canals. The regional flood defences are therefore built to a lower standard than the primary flood defences, but they do provide additional barriers for the flood water when the primary flood defences fail (Informatiepunt Leefomgeving, 2025). Additionally there may be further elements within a dike ring such as railways and highways that are not built or maintained as flood defence but act as an extra barrier for the flood water if the primary flood defences fail.

The regional flood defences and additional barriers as railways and highways divide the dike ring area into several different compartments. When the primary flood defences of the dike ring fail, the flood water is expected to flow towards the nearest regional flood defence. Once the first compartment is filled up such that the regional flood defence is overtopped (or when the regional flood defence fails), the flood water will flow into the next compartment. The severity of the inundation determines how many compartments are inundated. The strategy of dividing the dike ring area into different compartments called compartmentalisation.

2.2 The Lingewerken

Dike rings 16 and 43 are located between the river Waal in the south and the rivers Nederrijn and its continuation the Lek in the north, as shown in Figure 2.2. The Waal and Nederrijn/Lek are branches of the Rhine river flowing from east to west. Within dike ring 43 is the small river Linge, crossing dike ring 43 in the east by a pumping station and in the west by a small set of locks (Waterschap Rivierenland, 2017). Separating the two dike rings is the Diefdijk. This dry dike has no river flowing next to it and is there to protect the downstream dike ring 16 in case of an inundation of the upstream dike ring 43.

Figure 2.2: Overview of dike rings 16 and 43 and the surrounding river system

Whereas the Diefdijk and the dikes along the Nederrijn/Lek and Waal are primary flood defences, the dikes alongside the Linge are regional flood defences. Therefore, the dikes along the Linge are subject to less stringent safety regulations (Ministerie van Infrastructuur en Milieu, 2016). The dikes along the Linge do however form a compartmentalising factor if dike ring 43 is inundated.

If dike ring 43 is inundated from either the Nederrijn or the Waal, the flood water will flow from east to west towards the lower-lying dike ring 16. As such, the pressure on the Diefdijk protecting dike ring 16 is dramatically increased. A significant portion of the flood water is expected to follow the river Linge, too much for the set of locks in the west to handle (Waterschap Rivierenland, 2017). In order to create another path for the flood water to leave dike ring 43 and consequently reduce the pressure on the Diefdijk, the Lingewerken have been constructed.

The Lingewerken consist of a series of spillways in the dikes along the Linge and Waal with the aim of guiding flood water from the inundated dike ring 43 into the Waal. The spillways themselves are dike sections constructed in such a way they can be quickly excavated to a lower height. It is important to make the distinction between the spillways north of the Waal (from here onwards called the 'Waal spillways') on one hand and the spillways along the Linge on the other hand (from here onwards called the 'Linge spillways').

The Waal spillways, with a combined length of 694 metres, are provide a way for the flood water to leave the dike ring. On the other hand, the spillways north (in total 5150 metres) and south (in total 2763 metres) of the Linge can accelerate the movement of water towards the Waal by reducing the compartmentalising factor of the dikes along the Linge, but they do not allow the flood water to leave the dike ring themselves (Waterschap Rivierenland, 2017). In Figure 2.3, an overview of the spillways making up the Lingewerken is given.

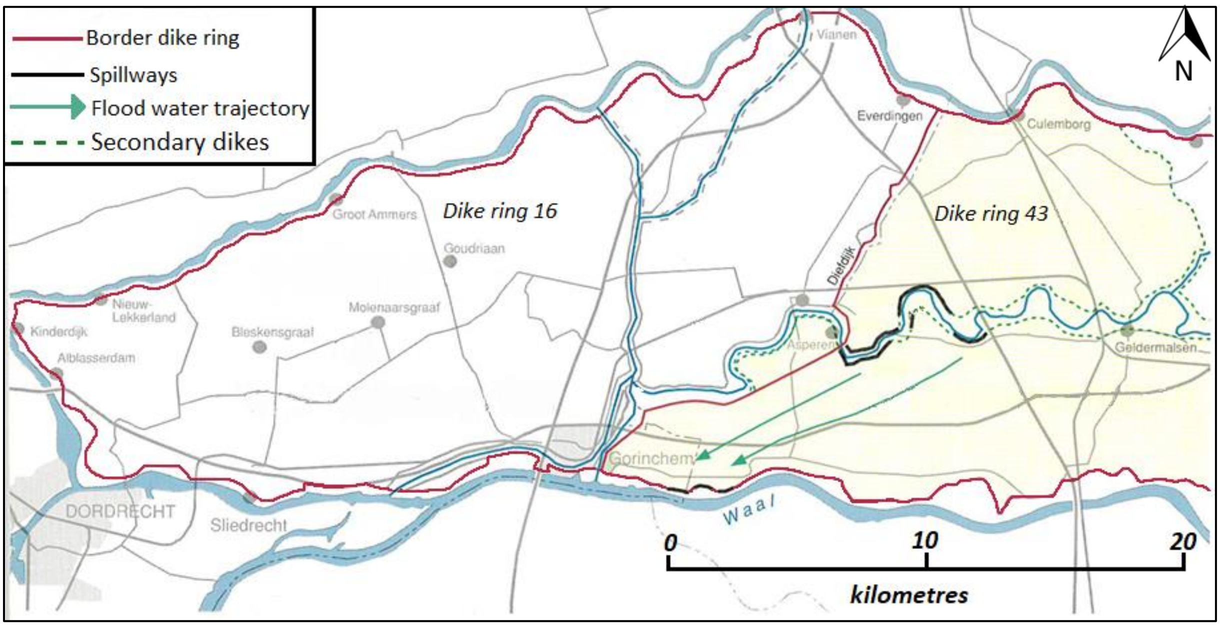


Figure 2.3: Overview of dike ring 16, the western part of dike ring 43 and the Waal and Linge Spillways (Provincie Zuid-Holland, 1990)

2.3 Prior research

In 1990, Province South-Holland published a report about Lingewerken. The main goal was to investigate the influence of the Lingewerken on the protection of dike ring 16. The necessary height of the Diefdijk to protect dike ring 16 was determined for scenarios with and without the Lingewerken present. Furthermore, the contribution of the individual parts of the Lingewerken (the spillways along the Linge and the spillways along the Waal) towards the overall effect of the Lingewerken was evaluated (Provincie Zuid-Holland, 1990).

The used discharge values and dike breach locations directly influence the severity of the expected inundations and subsequently influence the conclusions about the Lingewerken. Therefore the assumed discharge values and dike breach locations and the reasoning behind them is explained.

To determine the necessary height of the Diefdijk, a discharge of 18000 m^3/s at Lobith (the entry point of the Rhine to the Netherlands) was assumed. This corresponded to a high water event expected once per 2000 years, at the time the safety standard of dike ring 16 (and therefore of the Diefdijk) (Provincie Zuid-Holland, 1990).

For the evaluation of the individual parts of the Lingewerken a lower discharge of 16500 m^3/s at Lobith was assumed, corresponding to a high water event expected once per 1250 years, at the time the safety standard of dike ring 43. The discharge connected to the lower safety standard of 1/1250 years was used as dike breaches and subsequently the usage of the Lingewerken is expected with that discharge (Provincie Zuid-Holland, 1990).

The dike breach locations chosen where expected to create as much pressure on the Diefdijk as possible (important to determine the necessary height of the Diefdijk, one of the main goals of the investigation). Within dike ring 43 there are several barriers and regional flood defences present, which divide the dike ring into five different compartments. These barriers are no primary flood defences and have a lower height than the dikes forming the outside of the dike ring. The barriers are expected to withstand the inflowing water until they are overtopped. For each compartment at least one breach location is chosen to model an inundation scenario. The breach locations are located as upstream possible within each compartment. This is done as the larger the elevation of the breach location, the larger the expected water levels at the Diefdijk, the larger the pressure on the Diefdijk. An overview of the dike breach locations is shown in Figure 2.4.

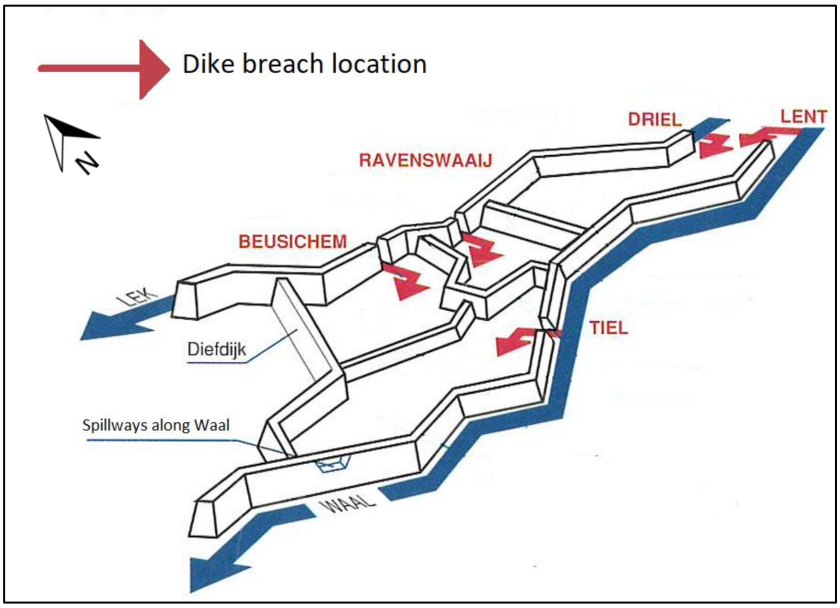


Figure 2.4: Schematisation of the compartments and breach locations evaluated previously of dike ring 43 (Provincie Zuid-Holland, 1990)

In Table 2.1 the found inundation depth and volume for each of the five breach locations evaluated by province South-Holland in 1990 are shown (Provincie Zuid-Holland, 1990). Noteworthy is that the largest inundation both in terms of depth and volume are formed by breaches of the dike along the Waal as opposed to a dike breach along the Nederrijn.

Table 2.1: Inundation depth and inflow volume for inundations with an 1/1250 year frequency (Provincie Zuid-Holland, 1990)

Riverbranch	Nederrijn		Lek	Waal	
Breach location	Driel	Ravenswaay	Beusichem	Lent	Tiel
Inundation depth at the Diefdijk (m+NAP)	4.85	4.77	4.85	5.50	5.50
Net inflow volume (10^6 m^3)	799	755	732	1047	995

Based on the high inundation depth and the close proximity to the Diefdijk (and therefore fast rise of water at the Diefdijk), the dike breach location at Tiel was chosen as the guiding inundation scenario to determine the necessary height of the Diefdijk. The report concluded that it is necessary to raise the height of the Diefdijk from NAP +6.40m to NAP +8.30m if the Lingewerken were to be removed in order to provide the necessary protection of dike ring 16. (Provincie Zuid-Holland, 1990). This signifies the importance of the Lingewerken system as a whole. A secondary conclusion however was that while the spillways along the Waal are instrumental towards the overall effect of the Lingewerken, the spillways located in the dikes along the Linge are not nearly as effective in reducing the stress on the Diefdijk (Provincie Zuid-Holland, 1990).

2.4 Knowledge gap

It is known that the Lingewerken have a positive impact on reducing the water levels at the Diefdijk in case of a flooding of dike ring 43. Furthermore it is known that the spillways located in the dike along the Waal are more influential on the inundated water levels than the spillways along the Linge. There are however still some knowledge gaps that this project aims to address.

Notably, the report from 1990 did not create a link between inundation levels on one hand and the amount of economic damage and casualties on the other hand. The report was mainly focussed if the protection of the downstream dike ring 16 was insured if the upstream dike ring 43 was to inundate. Therefore the report only outlined the benefits of the Lingewerken for dike ring 16 and not for dike ring 43 were the actual Lingewerken are located.

Furthermore, since 1990 the safety standard of dike ring 43 has increased significantly. In 1990 the maximum exceedance probability of the design water level the dike must sustain was 1/1250 years (Provincie Zuid-Holland, 1990). Nowadays the safety standard has increased to 1/10 000 years for most of the dike ring with a stretch in the north having a lower standard of 1/3000 years (Ministerie van Infrastructuur en Milieu, 2016). While the increased safety levels mean that an inundation will be less likely, the inundation itself is expected to be more severe when it occurs (as a higher river discharge is required for the dikes to fail). The influence of the Lingewerken on the flood water level is yet unknown for the more severe inundations expected with the current higher safety standards.

3. Problem Statement

3.1 Research objective

In this section, the problem statement and the research objective are given. In the problem statement a description of the problem is given. The research objective describes the goal to be achieved in order to solve the stated problem.

Problem statement

The Lingewerken are designed to guide flood water from dike ring 43 into the Waal, thereby reducing water levels inside the dike ring. It is yet unknown how many casualties are prevented and how much economic damage is reduced by the Lingewerken.

Research objective

The objective of the research is to evaluate for which flood scenarios of dike ring 43 it is advantageous to use the Lingewerken in order to prevent as many casualties and as much economic damage as possible.

3.2 Research questions

The following research questions are asked, which when answered help to achieve the research objective.

- How are the water levels and flow patterns affected when the Lingewerken are utilised in case of a flooding in dike ring 43?
- How are the casualties and economic damage affected by utilisation of the Lingewerken in case of flooding in dike ring 43?
- For which flood scenarios of dike ring 43 should the Lingewerken be utilised in order to have as few casualties and as little economic damage as possible?

4. Methodology

4.1 Investigated inundation scenarios

The effect of the Lingewerken on preventing damage and casualties is evaluated for two different dike breach events. The first evaluation assesses the benefit of the Lingewerken for a very severe inundation scenario in terms of location and return period in order to place a value on the Lingewerken. The second evaluation is conducted to answer whether or not it is beneficial to excavate the Linge and Waal spillways if there is a smaller-sized inundation from the north.

Currently, the safety standard of most of dike ring 43 is 1/10 000 years, meaning that the dikes are built in such a way that they may fail only once per 10 000 years (Ministerie van Infrastructuur en Milieu, 2016). To investigate the added benefit of the Lingewerken on the inundation depths at the Diefijk, simulations are run for a T10000 event (an event with a return period of 10 000 years) with a dike breach location south of Tiel. Earlier simulations (without any spillways) conducted by the waterboard showed that the dike breach location south of Tiel causes the largest inundation depths of all dike breach locations of dike ring 43. Therefore it is expected that the added benefit of the Lingewerken can most clearly be seen for the dike breach location south of Tiel. Furthermore, it is evaluated whether or not it is beneficial to excavate the Linge spillways in addition to the Waal spillways in case of an inundation south of the Linge spillways. Excavation of the Linge spillways is likely to spread the water over a larger area whilst creating lower inundation depths.

Another question to be answered is whether or not it is beneficial to excavate the dikes along the Linge in case of smaller-sized inundation from the Lek in the north. The specific scenario chosen to investigate this question is a T100 event with a dike breach near Beusichem. In case of a dike breach near Beusichem for a T100 event the flood water is not expected to spread much further south than the Linge due to the compartmentalising function of the dikes along the Linge based on earlier simulations by the waterboard. If the dikes along the Linge are excavated to form spillways the inundation water is expected to spread over a larger area whilst reaching lower water depths. It is interesting to investigate which option is expected to cause the least damage and casualties.

The five different simulations conducted for this project are listed in Table 4.1.

Table 4.1: List of investigated inundation scenarios

Simulation	Breach location	Flood event	Lingewerken variant
1	Tiel	T10000	All spillways excavated
2	Tiel	T10000	Waal spillways excavated only
3	Tiel	T10000	No spillways excavated
4	Beusichem	T100	All spillways excavated
5	Beusichem	T100	No spillways excavated

Figure 4.1 provides an overview of the two different dike breach locations (south of Tiel and Beusichem) along with the location of the Waal and Linge spillways.

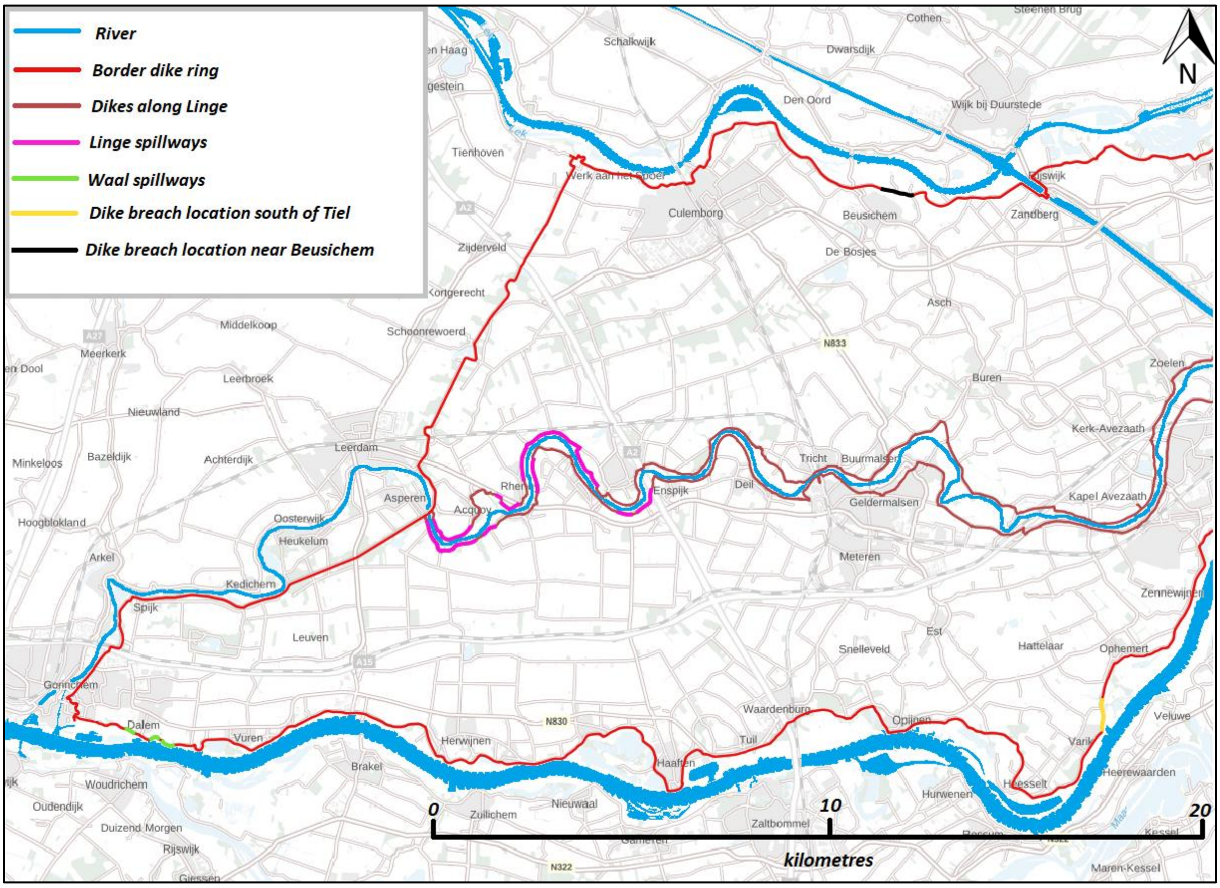


Figure 4.1: Overview of the investigated dike breach locations and the investigated spillways of dike ring 43.

4.2 Integration of the Lingewerken into D-HYDRO

4.2.1 Model structure

The D-HYDRO Suite has been designed with the aim of replacing a number of different software packages at Rijkswaterstaat and the different Water Boards (Minns et al., 2022). To cater for the variety of different applications, different modules focussed on waves, morphology, water quality have been introduced alongside the core D-Flow Flexible Mesh module. More modules focussed on real-time control and particle tracking are still to come (Deltares, 2024a). The D-HYDRO Suite has only been introduced recently with a first release only dating back to 2015 (Minns et al., 2022).

At the core of the D-HYDRO Suite is the D-Flow Flexible Mesh module, or D-Flow FM (Deltares, 2024a). With the D-Flow FM module, 1-, 2- and 3-dimensional hydrodynamic simulations can be made with a flexible mesh. The flexible mesh means that the size and shape of the grid can be changed for different areas at the users discretion. One might define a more detailed grid for a hill (where there is a lot of elevation change in a small area), than for a flat pasture. This way, more accurate results can be achieved with a shorter computation time.

The modelling part of the project is conducted by integrating the spillways of the Lingewerken into the existing D-HYDRO model of dike ring 43 created by the waterboard. The theoretical heart of the existing model is formed by D-flow FM module provided by Deltares, with a Graphical User Interface (or GUI) created by the waterboard itself.

At the core of the D-flow FM module is the Master Definition Unstructured file, abbreviated as mdu-file. The mdu-file defines the general settings of the model (such as the location of the output files, the time steps to be taken or the used physical parameters) and ties together the different other files, together forming the model. Whilst edited in a text editor, the mdu-file is loaded to the GUI of the waterboard to start the D-flow FM module to run the simulation.

To understand the changes made to the base model it is important to first understand the main elements which together form the model. An overview of the main elements of the base model provided by the waterboard, tied together by the mdu-file, can be seen below:

- **(Computational) grid:** The modelled area is defined by the 2d-computational grid. In Figure 4.2 the entire area is shown in the GUI of the waterboard.
  The entire grid can be divided into two sections. The largest section covers the entire area *inside* the dike ring (so without rivers). In addition, a small piece of river is added near the dike breach location to regulate the inflow of water.

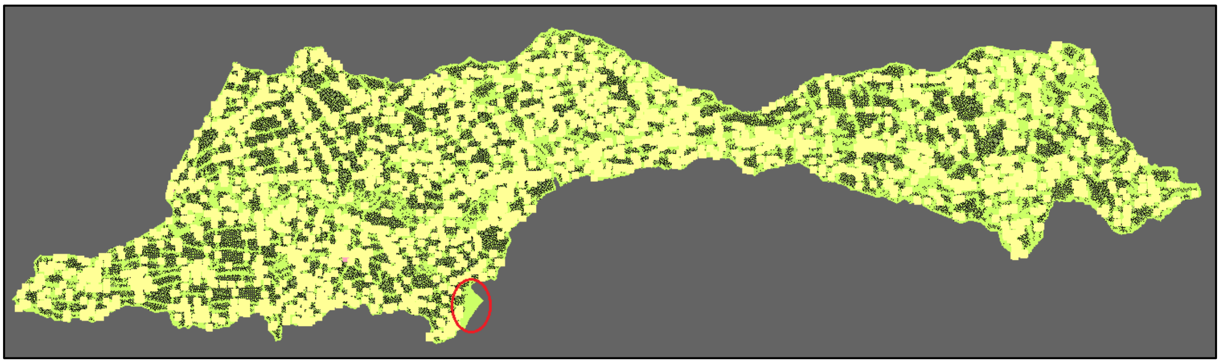


Figure 4.2: The grid of the model as seen in the GUI, with the added river piece circled in red

The grid consists of cells of varying sizes and shapes depending on the underlying terrain. When the grid is added as an overlay to satellite imagery as in Figure 4.3. one can see that the grid follows elements as waterways or highways. In doing so, there is a high uniformity of characteristics (height, roughness) within each cell. This provides a more accurate model whilst keeping the number of cells low and computational time relatively low (as opposed to a rectangular grid). In case of a culvert, underpass or bridge extra 1D elements are added in addition to the 2D grid. The location, width, height and shape (rectangle or pipe shape) are defined for the 1D elements in external files tied to the mdu-file.

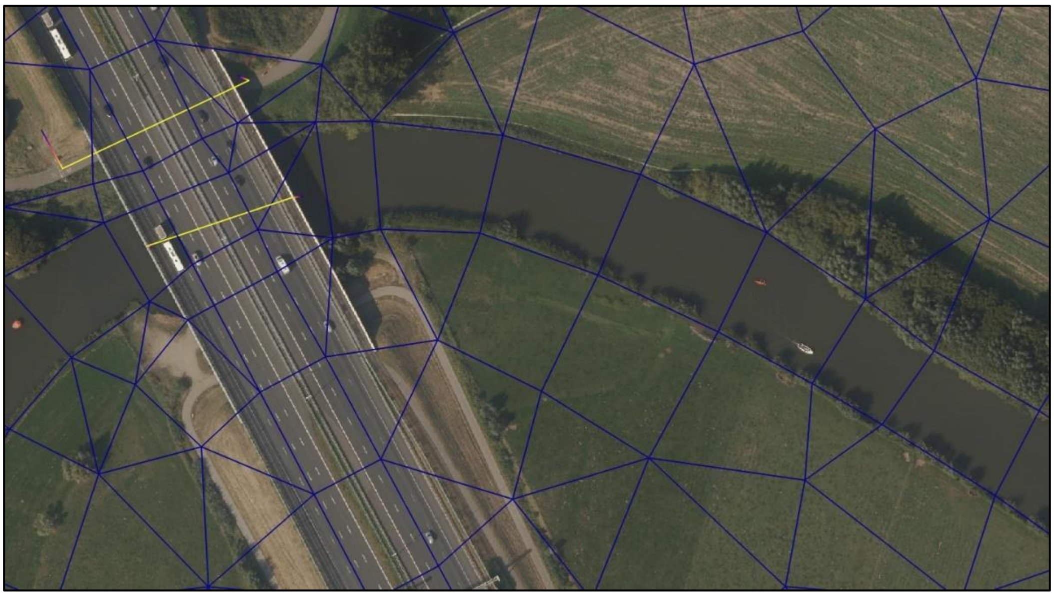


Figure 4.3: Zoomed in grid with a satellite view background, with 1D elements in yellow

- **Fixed weirs:** The bed level of the network defines the average height of each cell. But for elements that are higher than the surrounding area such as dikes, roads or railway lines a so-called fixed weir is added. The fixed weirs are line elements with an added height. The addition of the fixed weirs ensures that the water must overcome the highest line in the immediate area instead of a height line based on the average values of the cells. An example of the fixed weirs can be seen in Figure 4.4.

Figure 4.4: Fixed weirs for a section of the modelled area

- **Roughness coefficient & bed level**
  The roughness coefficient and bed level of the model are defined in the same way. Two files, one for the roughness coefficient and one for the bed level, contain the coordinates of each cell along with the value of the roughness coefficient and bed level respectively. In Figure 4.5 this can be seen for the roughness coefficient.

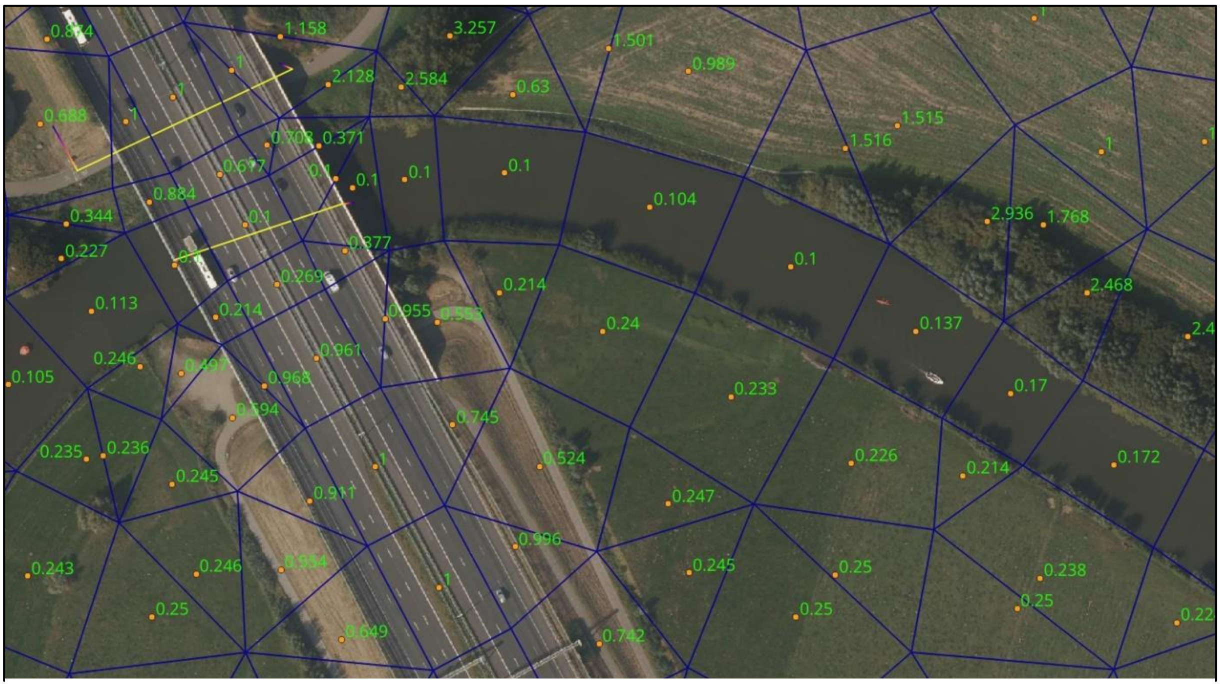


Figure 4.5: Roughness coefficient for a section of the modelled area

- **Initial water level**
  The different streams, ponds and wadis are filled up before the start of the simulation by adding an initial water level. Furthermore, the initial water levels are provided to the grid extensions near the dike breach and near the Waal spillways as well. The water level is taken for a situation where the different wadis are already filled up to create a conservative simulation where little extra storage is provided by the streams, ponds and wadis. The initial water level is provided in a similar manner as the roughness coefficient and the bed level, with the difference being that only the cells containing water have a value assigned to it (as opposed to every cell in the grid).

- **Dike breach**
  The dike breach causing the inundation takes place two hours into the simulation. The initial dike breach width is 10 metres with further breach growth modelled with the Verheij-Van der Knaap formula. A small piece of the river (Nederrijn or Waal depending on the breach location) is added to the grid near the breach location to allow water to flow from the river into the dike ring. The inflow of water is regulated by a boundary condition at the edge of the grid. The boundary condition itself is given as a time series of the water level of the discharge wave of the high water event. In Figure 4.6 the dike breach location south of Tiel can be seen.

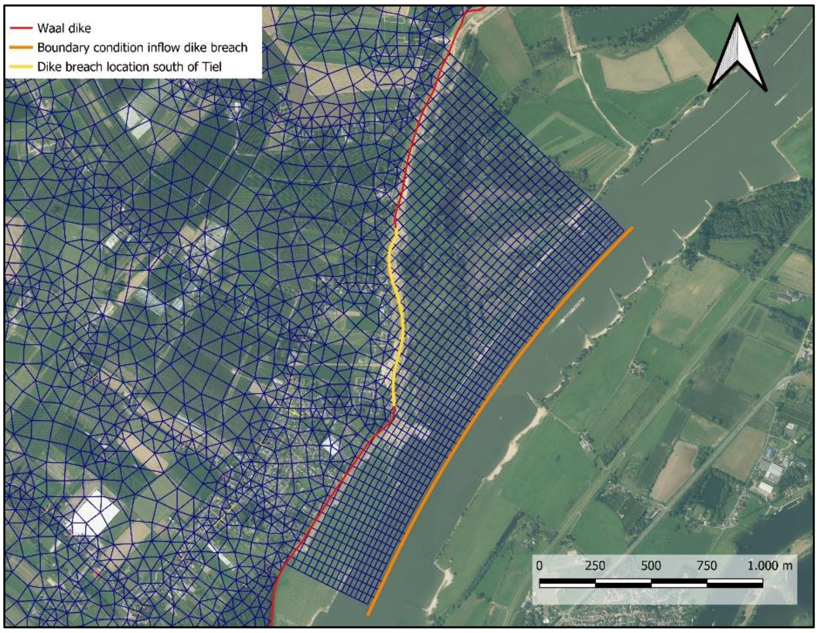


Figure 4.6: The grid extension of the dike breach location south of Tiel

4.2.2 Theoretical heart D-HYDRO

With the grid established, the in- and outflow between for each grid cell can be determined. To model floods, a 2D approach is used. A 2D approach provides more detail than an 1D approach while requiring less computational time than a 3D approach.

D-HYDRO models by solving the continuity equation and two momentum equations. The momentum equations for the x- and y-direction are given by Equations 1 and 2 respectively (Deltares, 2024b):

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial V}{\partial y} - fV = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + F_x + \frac{\partial}{\partial z}\left(\nu_v\frac{\partial U}{\partial z}\right) + M_x \tag{1}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial V}{\partial y} + fU = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + F_y + \frac{\partial}{\partial z}\left(\nu_v\frac{\partial V}{\partial z}\right) + M_y \tag{2}$$

Where U and V are the flow velocities [m/s] in the x- and y-directions respectively, f is the Coriolis parameter [1/s], ρ is the density of the water [kg/m^3], p is the pressure [N/m^2], F_x and F_y represent

Figure 4.6:

the unbalance in horizontal Reynold stresses [N], z is the vertical water depth [m], ν_v is the vertical eddy viscosity coefficient [m^2/s] and M_x and M_y represent the contributions due to external sources or sinks of momentum [Nm].

The continuity equation is given by Equation 3 (Deltares, 2024b):

$$\frac{\partial h}{\partial t} + \frac{\partial Uh}{\partial x} + \frac{\partial Vh}{\partial y} = Q \tag{3}$$

Where h is the water depth [m], U and V are the flow velocities [m/s] in the x- and y-directions respectively and Q is the contribution of discharge or withdrawal of water, precipitation or evaporation per unit area [m/s] (Deltares, 2024b):

$$Q = \int_0^h (q_{in} - q_{out})dz + P - E \tag{4}$$

Where q_{in} and q_{out} are the local sources and sinks of water per unit of volume [1/s], P is the precipitation [m/s] and E is the evaporation [m/s].

4.2.3 Adding river extension for the water to leave the dike ring

The current grid of dike ring 43 only covers the area inside the dike ring plus one small section near the dike breach location upstream. Consequently, the current grid provides no way for the flood water to leave the modelled area downstream. This clearly creates a conflict with the function of the Waal spillways, which is to allow a way for the flood water to leave the dike ring. To solve this problem, an extra piece of river is added near the Waal spillways. Two boundary conditions are added to the river extension: one boundary condition of the river extension regulates the inflow of the water into the river extension while the other boundary condition regulates the outflow of water out of the modelled area.

Besides allowing the water to leave the grid, the added piece of the Waal allows for a more accurate representation of reality as the water level outside of the Waal spillways influences when the spillways can be excavated and how fast the inundation water can be drained. An overview of the river extension, along with the location of the imposed boundary conditions can be seen in Figure 4.7. It is noteworthy to repeat that the water flows from east to west.

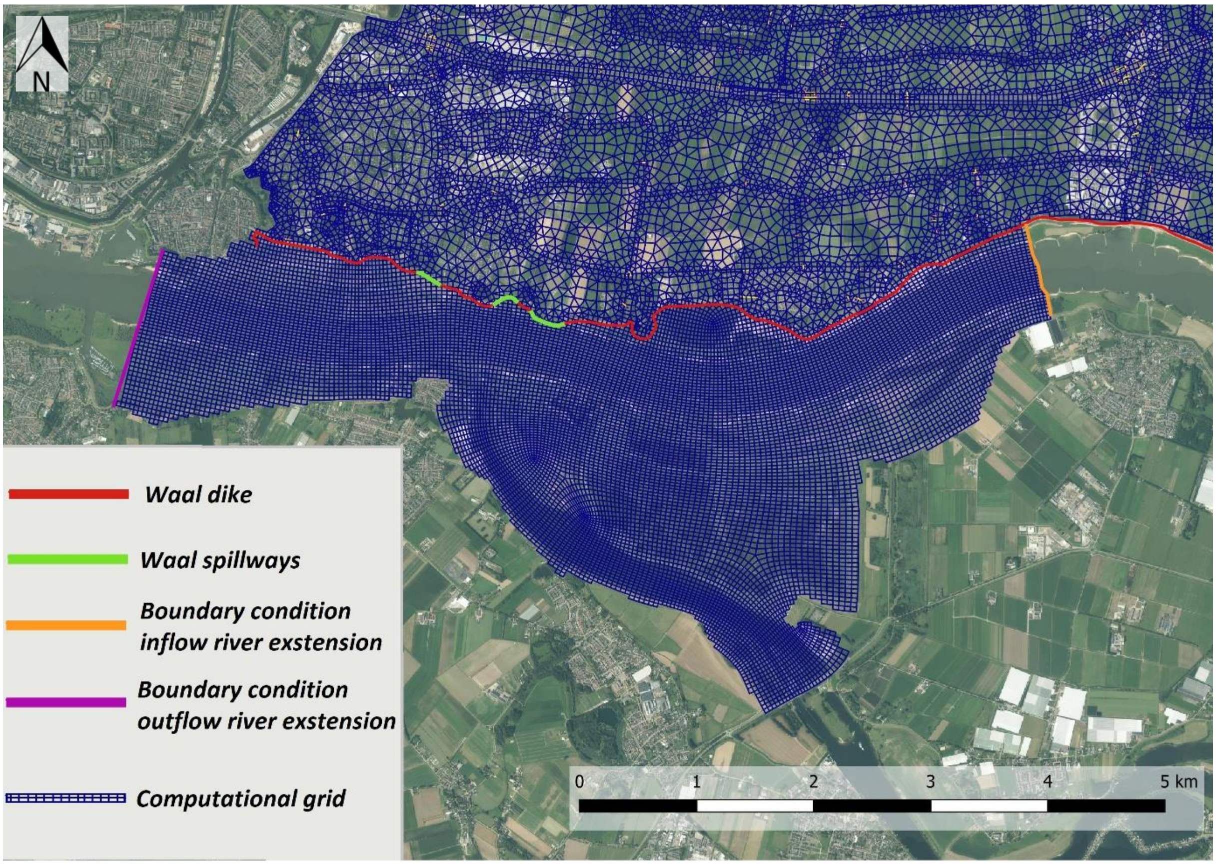


Figure 4.7: Added river extension near the Waal spillways

The grid itself is expanded in the GUI of the waterboard by copy-pasting a piece of the Waal from an existing model of the river of the waterboard to the original grid of dike ring 43. The fixed weirs and bed level values of the extension are provided by the waterboard as well. The roughness coefficient of the river extension is added in a separate file where the coordinates of the cells are taken from bed level file and the roughness is added separately. For the entire river extension the roughness is set to 0.1, the same roughness value used for water elsewhere in the model.

The boundary condition for the flow into the river extension of the grid is defined as a time series of the discharge wave of the high water event, whereas the boundary condition for the flow out of the river extension is defined as a Q-H relationship. The amount of discharge flowing into the river extension is dependent on the used return period and on the breach location. For the T10000 event the discharge will naturally be higher than for the T100 event.

As for the influence of the breach location: if dike ring 43 is inundated from a dike breach further upstream along the Waal further (as is the case for the dike breach south of Tiel), the discharge of the Waal near the spillways is lower as a portion of the discharge of the river (the flood water) is flowing through the dike breach into the dike ring. To take this effect into account, the portion of discharge flowing into the dike ring is subtracted from the total discharge near the breach location upstream to find the discharge value used for the boundary condition of the river extension downstream. Both the discharge flowing into the dike ring and the total discharge near the breach location are provided by the waterboard. If dike ring 43 is inundated from the Lek or Nederrijn instead of the Waal, the discharge into the river extension will not be affected by the amount of flood water flowing into the dike ring. As for the dike breach near Beusichem (from the Lek), the time series of the discharge is provided by the waterboard directly. More detail about determining the flow into the network expansion can be seen in appendix A.

The boundary condition for the flow out of the river extension is defined as a Q-H relationship. The Q-H relationship is defined separately for the T100 and T10000 event. A 1D river model provided by the waterboard contains simulations of the T100 and T10000 flood waves with a data point near the outflow boundary of the added river extension. To find the Q-H relationship, the discharge and water level of the data point are used to define the Q-H relationship.

4.2.4 Adding the Waal spillways

The excavated spillways along the Waal are modelled as dike breaches in the D-HYDRO software. By modelling the spillways as dike breaches, it is possible to activate the spillways at a predetermined point in the simulation. It is necessary to not excavate the Waal spillways from the start of the simulation as in the beginning of the simulation the water level of the Waal is still higher than the water level inside the dike ring. A large part of the discharge wave of the Waal namely still needs to pass the spillways in the first days of the simulation whereas the flood wave inside the dike ring still has to reach the Waal spillways.

The size of the dike breaches resembling the excavated spillways is defined by the time series of the geometry of the dike breach instead of the Verheij-vdKnaap formula, which is used for the dike breach further upstream causing the inundation. With the time series method, the excavated spillways can have a fixed width and height from a predefined time point. The used dimensions of the three Waal spillways can be seen in Table 4.2.

Table 4.2: Dimensions of the three spillways along the Waal (Provincie Zuid-Holland, 1990)l

	Crest level spillway (m+NAP)	Width of spillway (m)
Spillway Waal 1 (east)	2.11	282
Spillway Waal 2 (centre)	2.01	194
Spillway Waal 3 (west)	2.01	155

The moment of excavating of the Waal spillways is based on earlier research which showed that in case of an inundation from Tiel 66 hours are needed for the water level in the Waal to be lower than the water level inside the dike ring (Provincie Zuid-Holland, 1990).

For the T10000 situation with only the Waal spillways the 66 hours proved to be fairly accurate, with the water level inside the dike ring higher than in the Waal for only a few hours. But for the scenario where the Waal and Linge spillways are excavated the 66 hours are to too optimistic as the flood water initially spread faster towards the north instead of the east in the dike ring due to the added spillways in the dikes along the Linge. Therefore a the moment of excavation of the Waal spillways for the T10000 event with all Lingewerken excavated is extended to 75 hours into the simulation.

4.2.5 Adding the Linge spillways

Unlike the Waal spillways, if the Linge spillways are excavated from the start of the simulation, no extra water flows into the dike ring. This allows the Linge spillways to be added into the model by simply lowering the height of the dikes from the start of the simulation. Also, some height values of the underlying bed level file are altered as the bed level values of some cells are directly taken near the top of the dike (and thus higher than the spillways when excavated).

The Linge spillways are added to the relevant models by lowering the height of the dikes in the fixedweir file to 2.98 metres for the spillways north of the Linge and to 2.68 metres for the spillways south of the Linge (Provincie Zuid-Holland, 1990).

4.2.6 Postprocessing of the T10000 event with no excavated spillways

The dikes along the Waal have an infinite height in the base model provided by the waterboard. Only for the scenarios where the Waal spillways are excavated, the height of the Waal dike near the Waal spillways is changed to the real-world values.

For the reference scenarios where no spillways are excavated the height of the Waal dike was however not lowered from infinite due to the false assumption that the flood water would not leave dike ring 43. But for the reference scenario (so with no excavated spillways) of a T10000 event with a dike breach south of Tiel, the flood water would however leave dike ring 43 in reality. The flood water does not leave the dike ring through the Waal spillways, but by overtopping the dike along the Waal.

In the D-HYDRO simulation of the T10000 event with no excavated spillways, the found water level was around 7.05 metres above NAP where the Waal dike is the lowest. The lowest point of the Waal dike is in reality 6.25 metres above NAP. To correct this, 0.80 metres was subtracted from the found water height for the T10000 before translating the water depth into damage. The correction is only conducted for the scenario with a dike breach near Tiel with no excavated spillways. In all the other simulations the water level stays below the 6.25 metre high dike.

4.3 Estimating the economic damage and number of casualties

The D-HYDRO software is limited to modelling an inundation itself (inundation depths over time) as there are no damage functions integrated. While it is an option to evaluate the effect of the Lingewerken purely based on inundation depths, meaning can be added to the evaluation by modelling the effect of the Lingewerken on the damage caused by an inundation instead of just modelling the water height. To translate the characteristics of an inundation into an estimation of number of casualties and economic damage, Deltares on behalf of Rijkswaterstaat developed the so-called Schade en Slachtoffer Module (damage and casualties module in English), or SSM for short.

Both SSM and D-HYDRO are both cell-based, although SSM uses square cells with a resolution of 5x5 metres instead of the flexible mesh used by D-HYDRO. Furthermore, the output files of D-HYDRO are formatted differently to the input files of SSM. A Python script provided by the waterboard is used to convert the .net output files of D-HYDRO to the required .tif input files of SSM. Amidst the conversion the flexible mesh grid of the D-HYDRO output is changed to the 5x5m grid of SSM as well.

SSM has an integrated land use file spanning the whole of the Netherlands, assigning one of the in total 75 land use categories to each cell. For each land use categories there are imbedded functions to calculate the economic damage and amount of casualties, based on the water depth and flow velocity as the input variables (STOWA, 2024). To gain the final economic damage the found damage of all the cells are added up by using Equation 5.

$$D = \sum_{i=1}^{N} \alpha_i n_i S_i \tag{5}$$

With D representing the total economic damage [€], N the number of categories [-], α_i the damage factor of each category i [-], n_i the number of units of category i [-] and S_i the maximum damage of category i [€].

The damage factor α differs for each land use category and is dependent on the water depth, ascent rate and flow velocity of the inundation at the cell in question. An example of a damage function, in this case of infrastructure, can be seen in Figure 4.8.

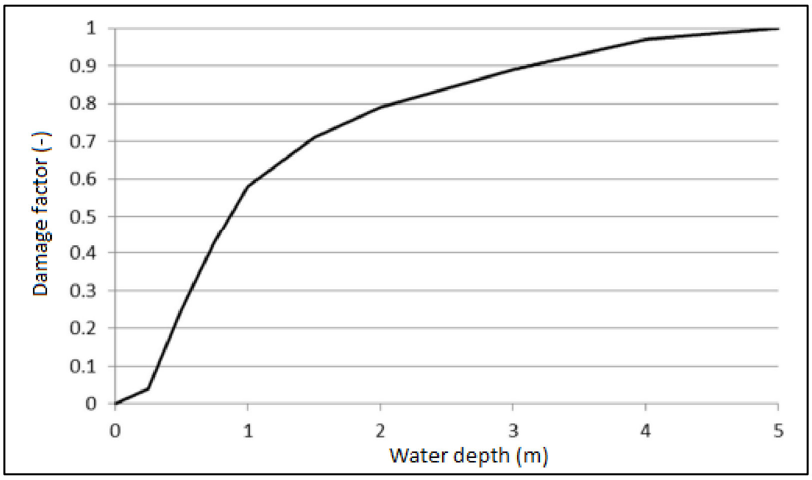


Figure 4.8: Damage function of infrastructure land use classes (Deltares, 2017)

While there is just one damage function for all the infrastructure land use classes, the maximum damage S_i differs per class. The maximum damage S_i for the different infrastructure land use classes can be seen in Table 4.3.

Table 1.3: maximum damage per metre for the infrastructure land use classes (Deltares, 2017)

Category	**Maximum damage per metre (€)**
Highways ('Rijkswegen in Dutch')	1770
Express ways ('Autowegen in Dutch')	1200
Other roads	327
Non-electrified railways	1350
Electrified railways	5400

This means that if in the inundated area for example 200 metres of electrified railway would be flooded by 2 metres the added damage to the total equals $\alpha \cdot n \cdot S = 0.8 \cdot 200 \cdot 5400 = 864{,}000$ euros.

The calculation of the number of casualties is based on mortality functions describing the probability of death for everybody in the inundated area when the dike breach occurs. The probability of death is subsequently coupled to the number of people in the inundated area.

The inundated area is split up into four zones based on the accent rate up to 1.5 metres and the flow velocity. Each zone has its own mortality function.

- Zone 1. The area directly at the dike breach. Here a mortality rate of 1 is assumed by SSM regardless of the water depth.
- Zone 2. The second zone describes the area where the ascent rate of the water is very high.
- Zone 3. The third zone is a transition zone where the ascent of the water is not very high nor low.
- Zone 4. The fourth zone covers the area where the ascent rate of the water is very low.

The mortality functions of the four zones can be seen in Figure 4.8.

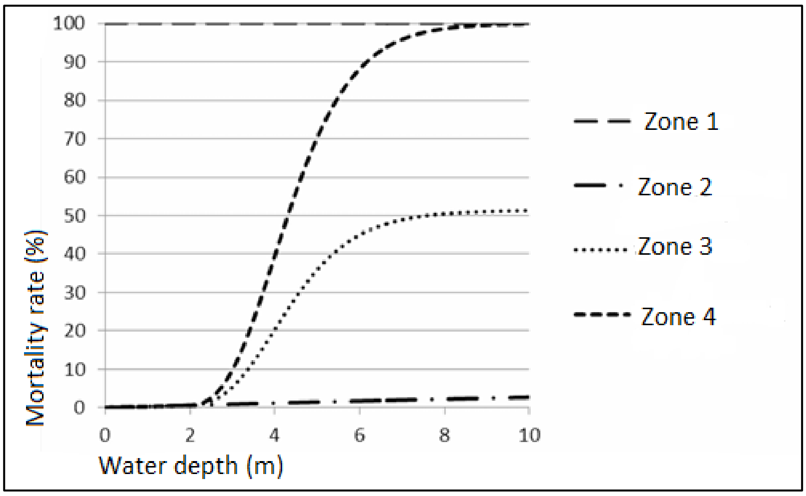


Figure 4.8: Mortality functions used by SSM (Deltares, 2017)

5. Results

5.1 Analysis of the simulations

The objective of the research is to evaluate for which scenarios it is beneficial to utilise the Lingewerken. The objective is reached by first analysing how the water levels and flow patterns of the two flood events are affected by excavating the Waal and Linge spillways. The second step is to translate the found water levels into the expected amount of casualties and economic damage for each simulation before lastly drawing the conclusion whether or not the spillways of the Lingewerken should be utilised for each of the two investigated flood events.

The analysis of the water levels and flow patterns is carried out by evaluating the maps of the maximum inundation depth for all five D-HYDRO simulations. To gain more insight in how the inundation develops over time, the water level over time is shown for locations in Acquoy and Gorinchem. Acquoy and Gorinchem are chosen as the highest water levels north and south of the Linge are found in Acquoy and Gorinchem respectively. The locations of the two data points in Acquoy and Gorinchem are shown in Figure 5.1.

After the analysis of the water levels and flow patterns, the output of the SSM software is evaluated by comparing the amount of casualties, the number of people living in the flooded area and the damage for the scenarios with and without excavated spillways.

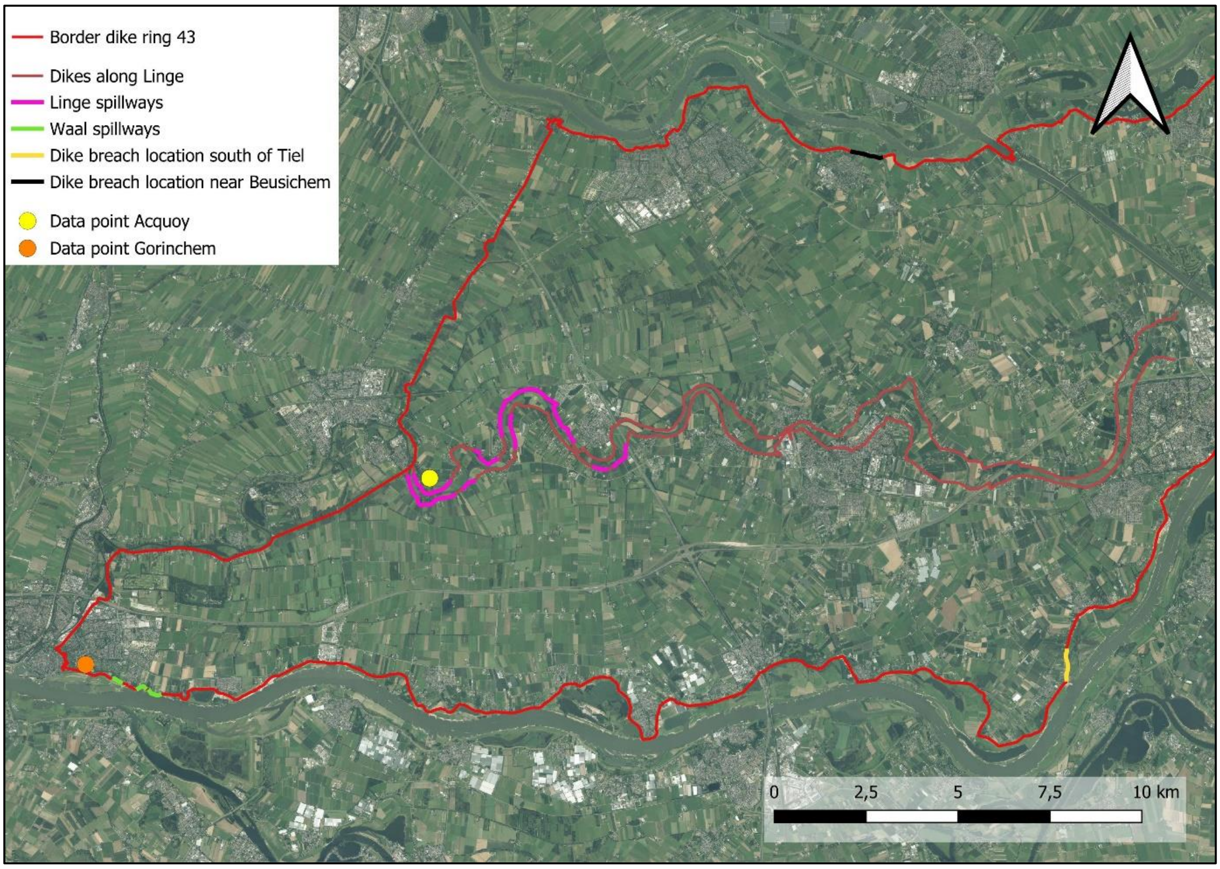


Figure 5.1: Overview of the investigated dike breach locations, investigated spillways and used data points of dike ring 43.

5.2 T10000 event south of Tiel

The maximum water depth of the flood waves can be seen below in Figures 5.2, 5.3 and 5.4. The area is clipped so that it does not include either the Waal or Nederrijn rivers, as the water heights there naturally do not cause any damage. The Amsterdam-Rhine Canal and Linge are included however, and can be differentiated as their lower bed levels are translated into high water depths.

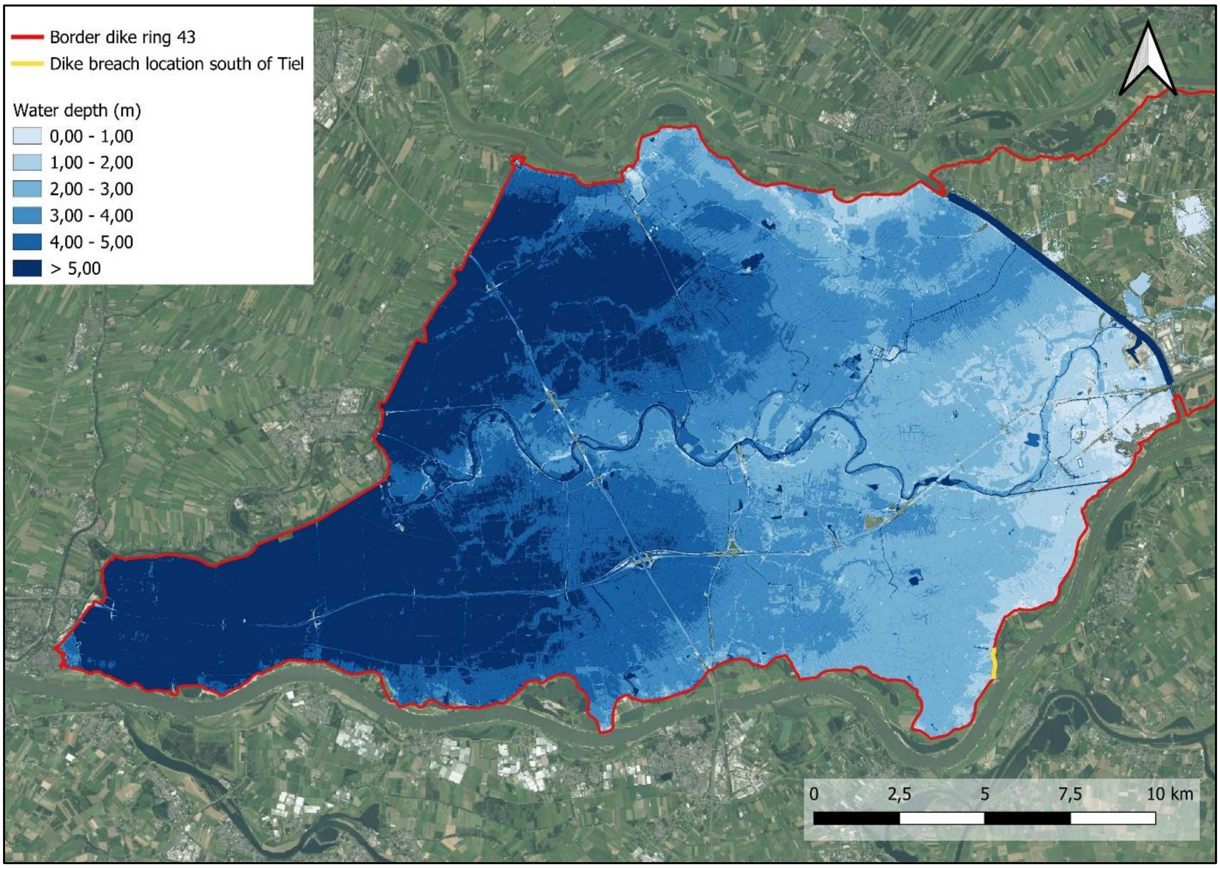


Figure 5.2: Maximum water depth T10000 event with a dike breach south of Tiel with no excavated spillways

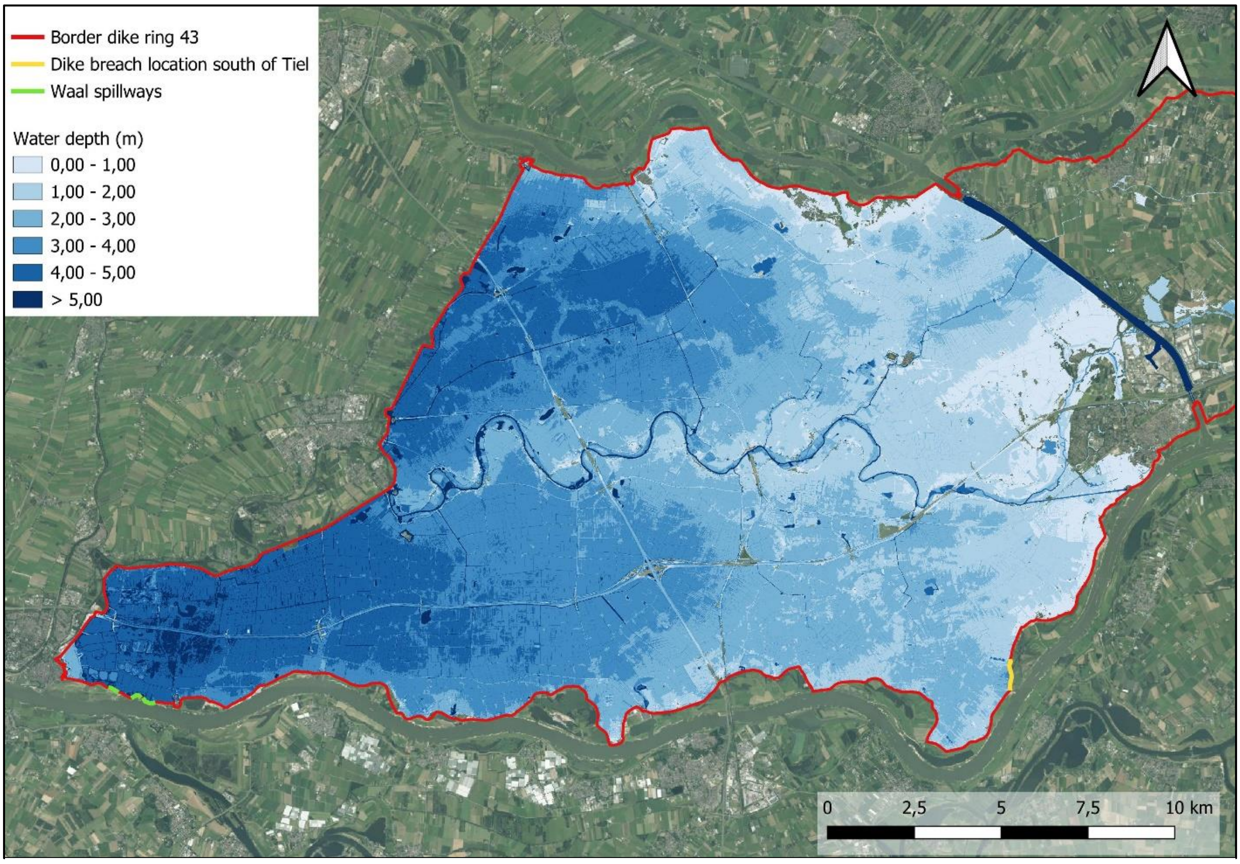


Figure 5.3: Maximum water depth T10000 event with a dike breach south of Tiel with the Waal spillways excavated

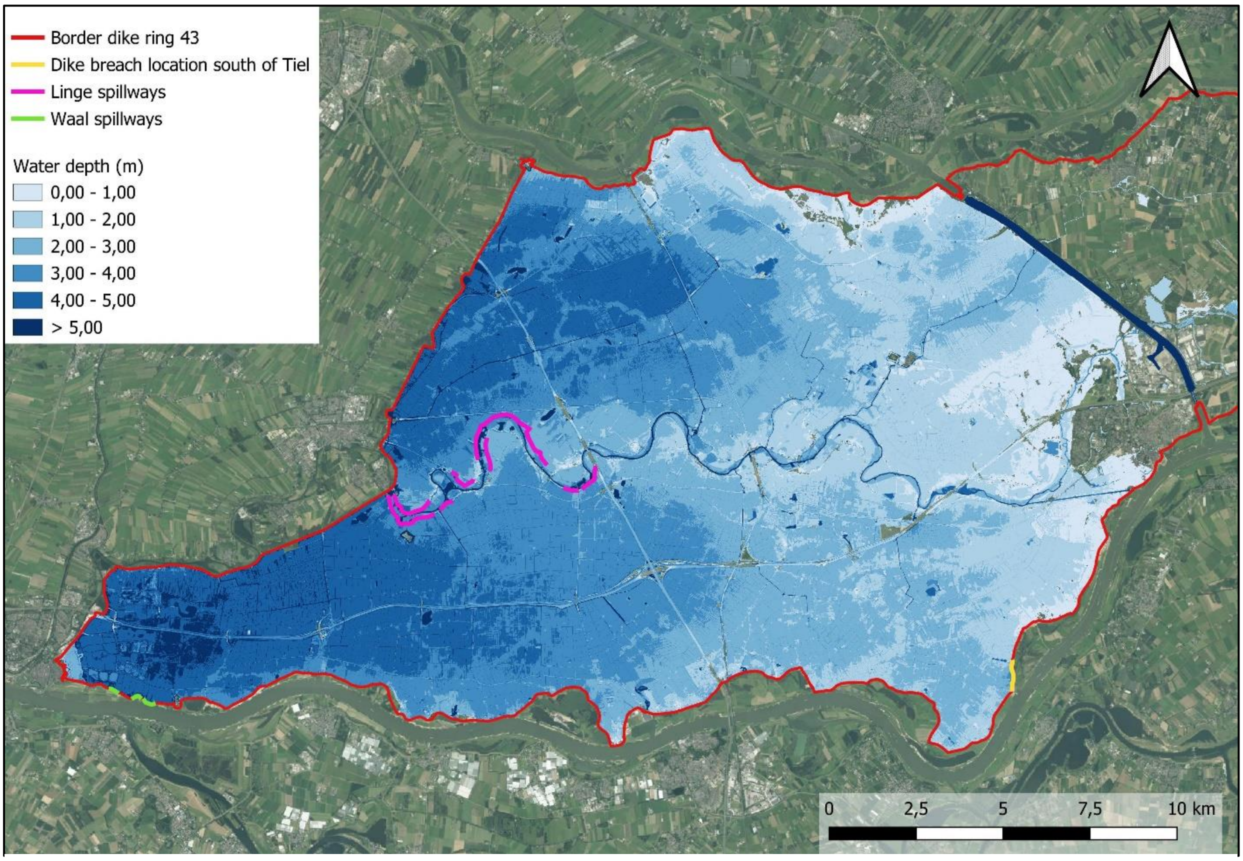


Figure 5.4: Maximum water depth T10000 event with a dike breach south of Tiel with the Waal and Linge spillways excavated

The effect of the Waal spillways is shown by the difference in water depths between Figure 5.2 on one hand and Figures 5.3 and 5.4 on the other hand. The inundated area is however similar in size in all three scenarios due to the compartmentalising factor of the Amsterdam-Rhine Canal.

The effect of the Linge spillways however is almost unnoticeable when comparing Figures 5.3 and 5.4. After further analysis, it becomes clear that the Linge spillways are just accelerating the general movement of water. This goes for the initial spread of the inundation as well as for when the inundated area is cleared through the Waal spillways. This can be seen in Figures 5.5 and 5.6, which show the spread of the flood 56 hours after the inundation, before the inundation reaches its maximum extend.

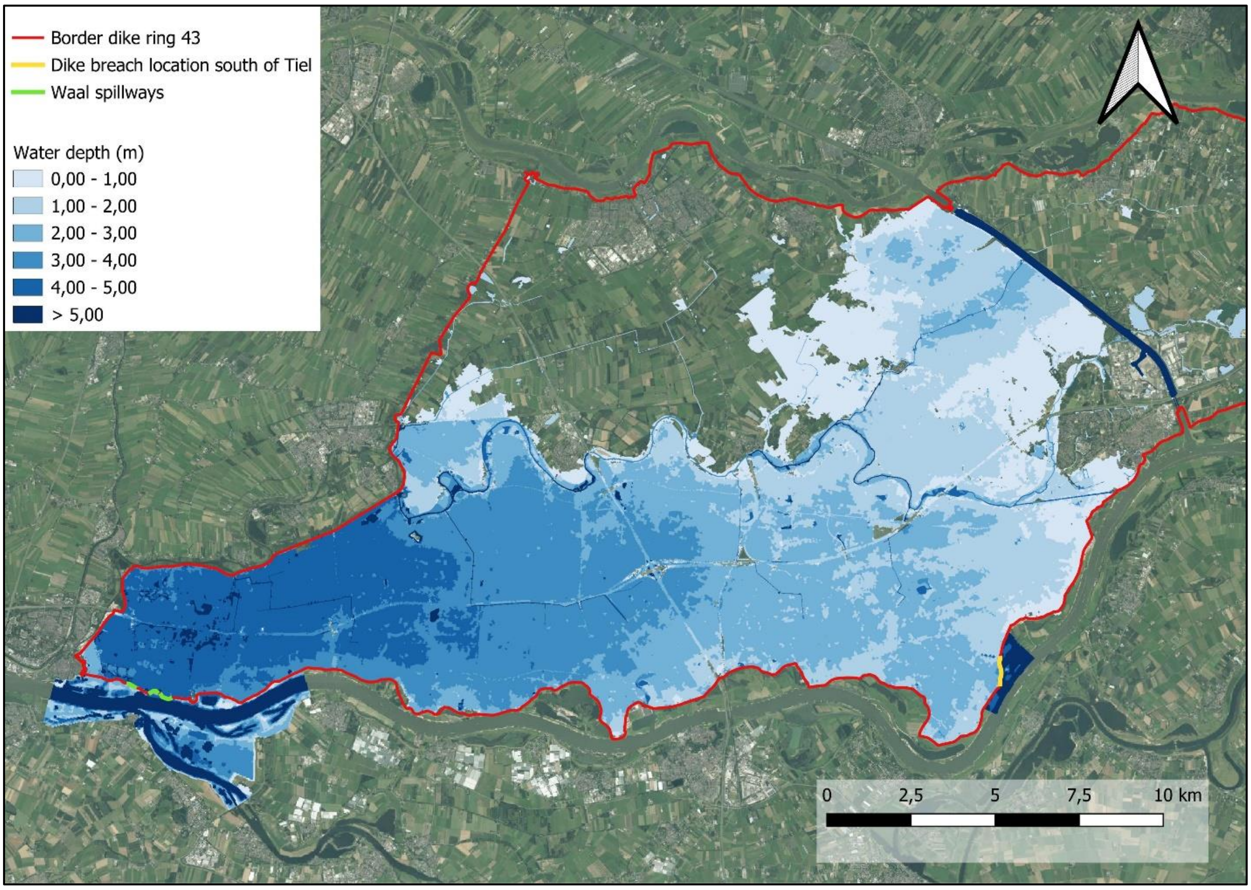


Figure 5.5: Water depth after 56 hours T10000 event with excavated spillways along the Waal

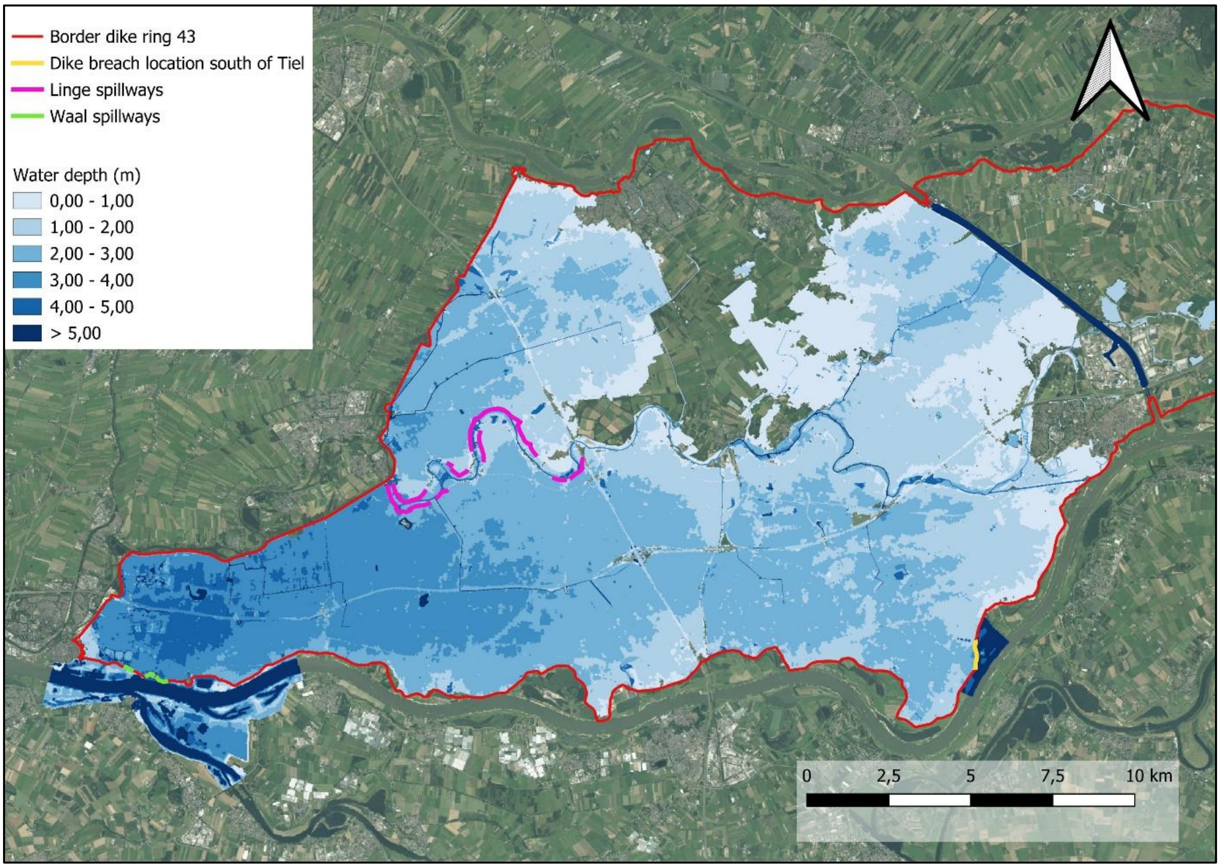


Figure 5.64: Water depth after 56 hours T10000 event with excavated spillways along the Linge and Waal

To illustrate the story further, the water depth in Gorinchem (at the southwestern end of the dike ring) can be seen in Figure 5.7.

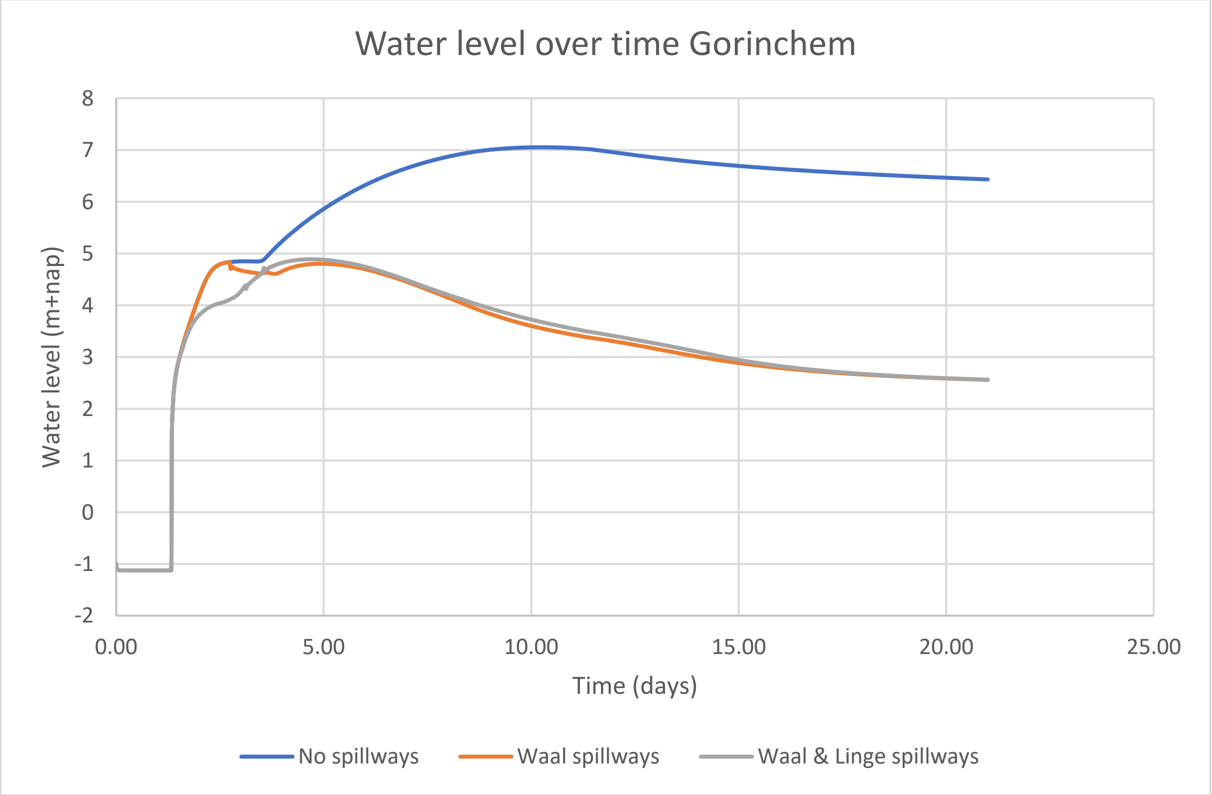


Figure 5.7: Water level in Gorinchem for a T10000 event with a dike breach south of Tiel

In Figure 5.7, the maximum value of the scenario without any spillways is far and away the highest, showing that the Waal spillways definitely do cause lower inundation depths. The maximum values of the scenarios with the Waal spillways only and with the Waal and Linge spillways almost show the same value, meaning that the maximum inundation depth does not differ much at all. There is a significant delay however between the scenario with and without the Linge spillways for the location in Gorinchem, owing to the faster spread towards the north when the Linge spillways are excavated which causes the water to reach its highest point in the west a bit later. Naturally, one expects that As expected is the for location north of the Linge spillways this effect would be reversed, which can be seen in Figure 5.8.

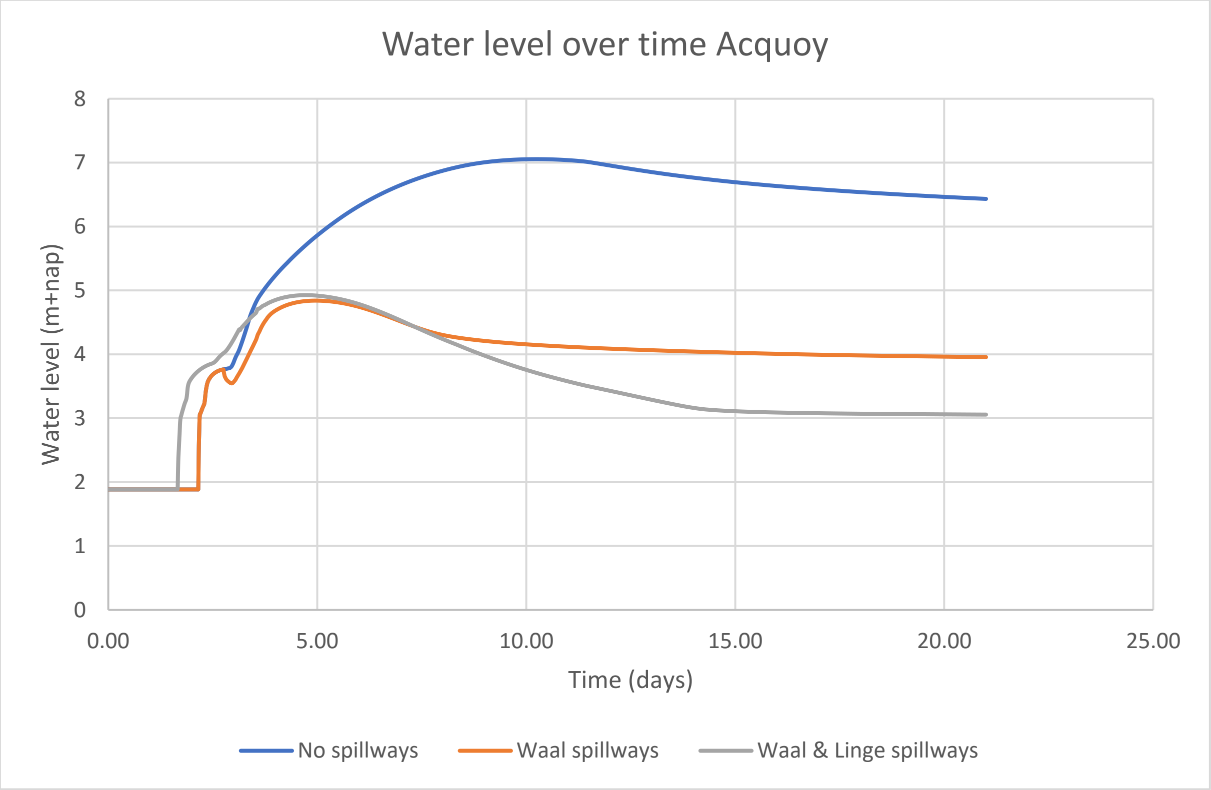


Figure 5.8: Water level in Acquoy for a T10000 event with a dike breach south of Tiel

As expected reaches the flood wave of the scenario with the Linge spillways excavated Acquoy first. Interestingly enough causes excavating the Linge spillways a slightly higher maximum inundation depth with respect to the scenario with only the Waal spillways excavated. Besides providing an earlier arrival of the flood wave, the excavation of the Linge spillways does cause the water to leave the area quicker as well. More importantly though, excavation of the Waal spillways causes a significantly lower inundation depths, with or without the Linge spillways present.

Translating the figures and graph into numbers results in the numbers as seen in Table 5.1.

Table 2.1: Flood characteristics for a T10000 event south of Tiel

	No spillways	Waal spillways	Waal & Linge spillways
Maximum water level Gorinchem (m+NAP)	6.25	4.83	4.89
Maximum water level Acquoy (m+NAP)	6.25	4.84	4.93
Inundated Area at the highest extend (km^2)	336.38	307.72	308.31

The numbers seen in Table 5 confirm the image created by the figures and graphs. Excavation of the Waal spillways cause a significantly lower maximum water depth while the inundated area also shrinks. Excavation of the Linge spillways on the other hand adds, albeit slightly, towards the maximum water depth and inundated area.

When using the SSM software to translate the inundation depths into casualties, inhabitants of the inundated area and damage numbers, one gets the values seen in Table 5.2.

Table 5.2: Damage and casualties for a T10000 event south of Tiel

	No spillways	Waal spillways	Waal & Linge spillways
Casualties (-)	4590	2709	2771
Inhabitants affected area (-)	137,300	114,400	115,200
Damage (€)	21 billion	15 billion	15 billion

The effect of the Lingewerken on the damage and casualties done by the flood follows the same line as the effect of the Lingewerken on the severity of the flood. Excavation of the Waal spillways lowers the damage and amount of casualties significantly, while excavation of the Linge spillways in addition to the Waal adds very slightly to the amount of casualties.

5.3 T100 event near Beusichem

The maximum water depths of the T100 event near Beusichem can be seen below in Figures 5.9 and 5.10. The Waal and Nederrijn/Lek once again are not included in the figures, but the Amsterdam-Rhine Canal and to a lesser extent the Linge can be differentiated in the picture.

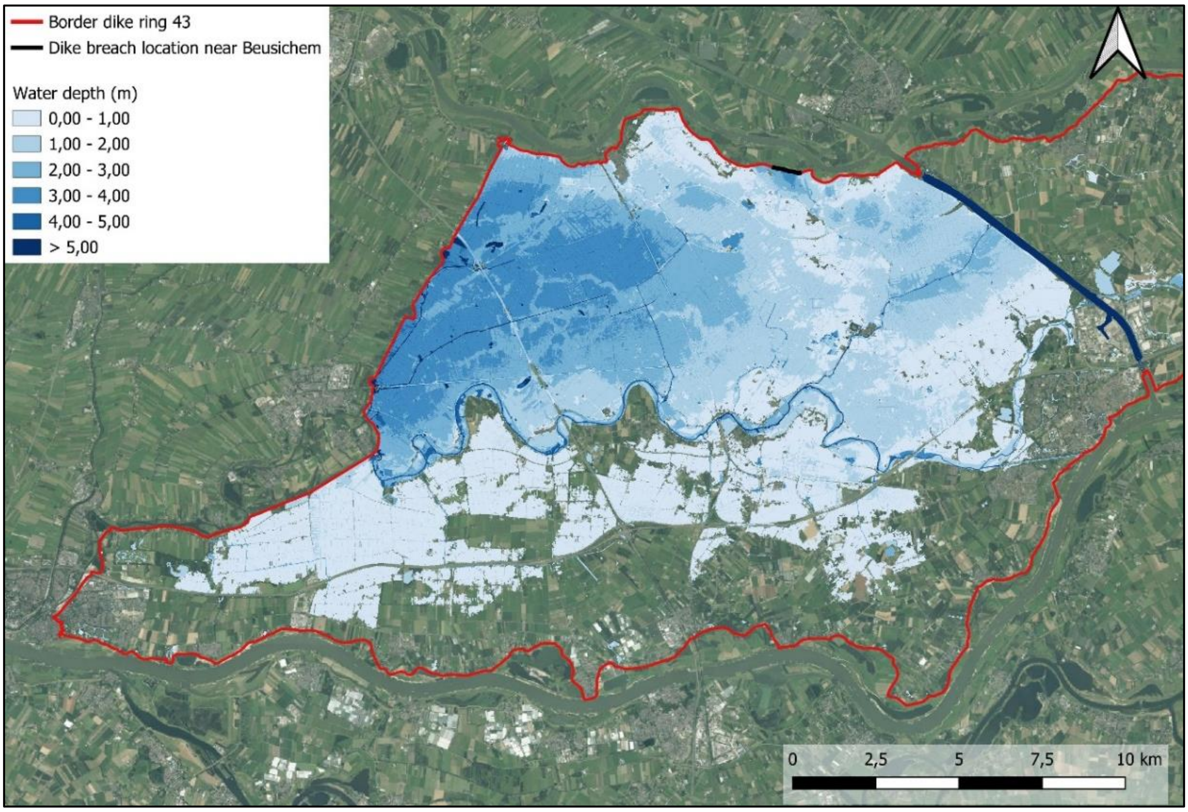


Figure 5.9: Maximum water depth T100 event with a dike breach near Beusichem with no excavated spillways

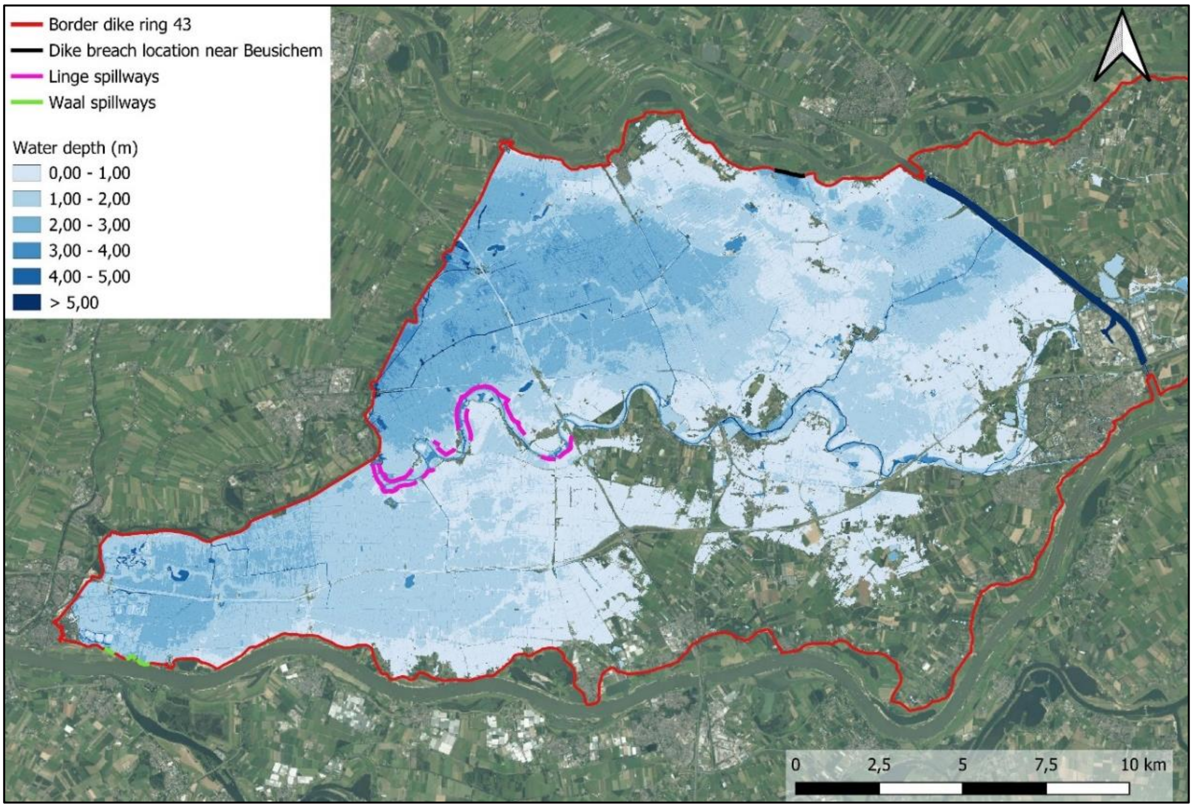


Figure 5.10: Maximum water depth T100 event with a dike breach near Beusichem with excavated spillways along the Linge and Waal

The effect of excavating the Waal and Linge spillways can be seen clearly in the difference between Figures 5.9. and 5.10. Excavation of the Linge spillways causes a larger area to be inundated south of the Linge as expected. The inundation depth north of the Linge is on average however lower. This is further supported by graphs of the water depth over time in Gorinchem (south of the Linge) and Acquoy (north of the Linge) in Figures 5.11 and 5.12.

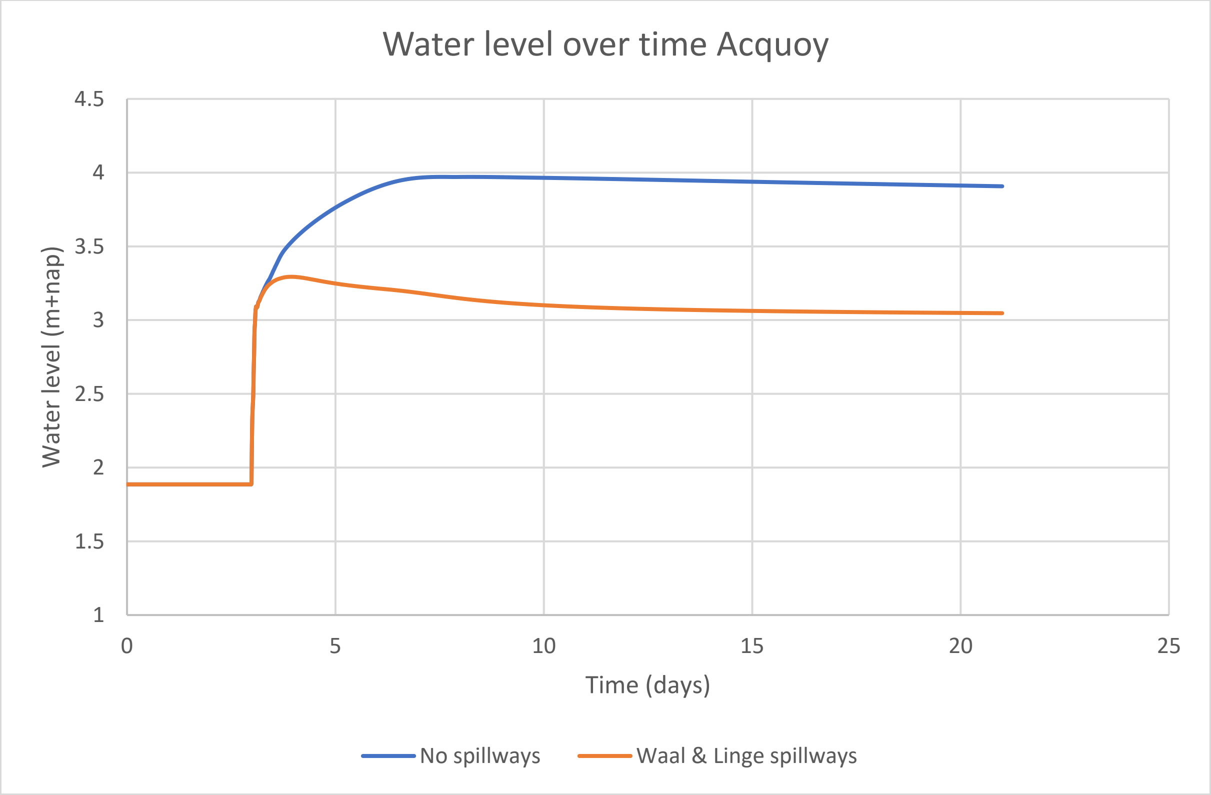


Figure 5.11: Water level in Acquoy for a T100 event with a dike breach near Beusichem

In Acquoy, just north of the Linge, the water level stabilises at a considerably lower level when the Linge spillways are excavated as a part of the inundation water is allowed to flow south instead of being stopped at the dikes along the Linge.

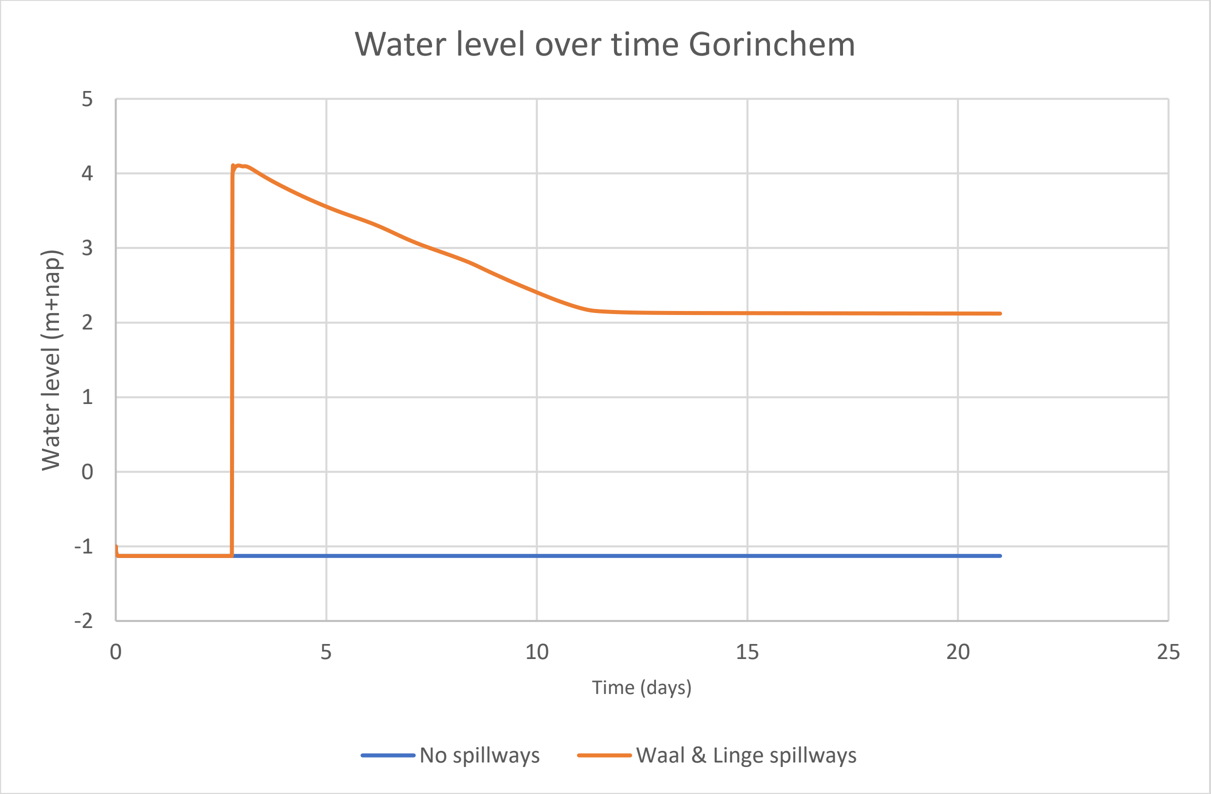


Figure 5.6: Water level in Gorinchem for a T100 event with a dike breach near Beusichem

When the Linge spillways are excavated the flood area becomes larger, the effect of which can be seen in Gorinchem. Whereas the water level remains zero when the spillways are not utilised, the water level jumps up several metres for when the spillways are used. The influence of the Waal spillways can also be seen: the peak water level is reached relatively early after which the water level decreases as flood water leaves the area through the Waal spillways. After a while the water level becomes stagnated as the crest level of the Waal spillways becomes too high for the water to leave the area.

Translating the figures and graph into numbers results in the numbers as seen in Table 7.

Table 5.3: Flood characteristics for a T100 event near Beusichem

	No spillways	Waal & Linge spillways
Maximum water level Gorinchem (m+NAP)	n/a, bed level is -1.13 NAP	4.11
Maximum level Acquoy (m+NAP)	3.97	3.29
Inundated Area at the highest extend (km^2)	204.06	242.30

Besides confirming the general story, it is noteworthy to mention that the when the spillways are excavated the water depth in Gorinchem is higher than in Acquoy, while Gorinchem is located quite a bit further from the dike breach location.

When using the SSM software to translate the inundation depths into casualties, inhabitants of the inundated area and damage numbers, one gets the values seen in Table 8.

Table 5.3: Damage and casualties for a T100 event near Beusichem

	No spillways	Waal & Linge spillways
Casualties (-)	180	200
Inhabitants affected area (-)	54,040	69,490
Damage (€)	5.9 billion	6.9 billion

The amount of inhabitants of the affected area is larger if the spillways are excavated, which is logical consequence given the larger inundated area. Noteworthy is the outcome that despite causing lower water depths north of the Linge, excavation of the Linge spillways leads to more casualties and damage when taking the whole area into account.

6. Discussion

Some caveats do have to be placed regarding the found results of this research. Firstly, although D-HYDRO provides of the latest and most sophisticated flood model packages used in the Netherlands, it does remain a model. And models do remain dependent on the validity and accuracy of the input parameters. Several assumptions and simplifications have been made throughout the modelling process which could have great impact on the subsequent results. These include the assumption about the share of river discharge which enters the dike breach and the simplification that the Waal spillways can be excavated instantly. Due to time constraints no sensitivity analysis has been conducted to investigate the influence of these assumptions and simplifications.

Another simplification made is that besides the dike breach modelled no other dikes fail in the simulations (apart from overtopping). This includes the Diefdijk, which while part of dike ring 43 does not actually protect dike ring 43 itself but the lower lying dike ring 16. So if the Diefdijk fails severe damage is done to the previously not inundated dike ring 16. The Diefdijk is only in use in case of a flooding of the upstream dike ring 43 and therefore has the odd designated safety standard of 1/10 events, meaning that the Diefdijk may fail once per every ten floodings of dike ring 43 (Ministerie van Infrastructuur en Milieu, 2016). This 1/10 chance of significant extra damage is not considered in this project for the sake of simplicity.

Additionally, there are some subjects related to finding the damage prevented by using the Lingewerken that fall outside the scope of the project and thus have not been considered. Damage to for example nature or cultural heritage (extending beyond just the economic damage) has not been considered for the sake of simplicity.

Besides the severity of the flood itself, there are quite some other factors playing a role in determining the damage and amount of casualties during a flood. The accuracy of high water event predictions, decisiveness of the relevant ministries, mayors and Water Boards, evacuation readiness, availability of evacuation routes all play a role in preventing damage and casualties. These factors have not been a focus of this project and are only touched upon lightly in the ‘Schade en Slachtoffer Module’ software used to model the damage of the inundation (Rijkswaterstaat , 2024).

Furthermore, the effect of the Lingewerken has only been assessed based on only five simulations spread over two different dike locations and return periods. For the conducted simulations, usage of the Linge spillways turned out to be disadvantageous. A conclusion that the usage of the Linge spillways is disadvantageous for every flood scenario might be premature as further analysis of the Lingewerken with more dike breach locations and return periods could provide a different conclusion.

7. Conclusion

The objective of the research is to evaluate for which flood scenarios of dike ring 43 it is advantageous to use the Lingewerken in order to prevent as many casualties and as much economic damage as possible. The objective is reached by answering the following research questions:

How are the water levels and flow patterns affected when the Lingewerken are utilised in case of a flooding in dike ring 43?

When there is a severe inundation of dike ring 43 from the south Tiel, the Lingewerken have a limited influence on the amount of land that is inundated. Excavation of the Waal spillways does however lead to significantly lower water levels. Excavation of the Linge spillways in addition to the Waal spillways has a limited influence on the water levels, but does allow the area north of the Linge to be inundated more quickly.

In case of a smaller sized inundation coming from Beusichem, excavation of the Lingewerken causes much more flood water and consequently higher water levels in the area south of the Linge. The water levels in the area north of the Linge are however significantly lowered in return.

How are the amount of casualties and economic damage affected by utilisation of the Lingewerken in case of flooding in dike ring 43?

If there is a large scale inundation of dike ring 43 from the Waal south of Tiel, excavation of the Waal spillways leads to significantly less casualties and economic damage. Excavation of the Linge spillways in addition to the Waal spillways has a very little influence on the damage while the number of casualties increases slightly.

When dike ring 43 is flooded from the north near Beusichem, utilisation of the Lingewerken causes both the amount of casualties and economic damage to increase. The number of casualties increases slightly, while the increase of the amount of economic damage is relatively large compared to the increase in number of casualties.

For which flood scenarios of dike ring 43 should the Lingewerken be utilised in order to create as few casualties and as little economic damage as possible?

It is for both assessed flood events, a severe flood coming from the south of Tiel and a less severe flood from the north near Beusichem, disadvantageous to excavate the Linge spillways as the excavation of the Linge spillways leads to more casualties and economic damage. On the other hand, it is certainly advantageous to excavate the Waal spillways in case of a large scale flood south of the Linge in order to reduce the damage and amount of casualties significantly.

8. Recommendations

For the two investigated flood events it is clear that excavation of the Waal spillways is beneficial, certainly in the case of a large scale inundation. But for the scenarios that were investigated, the Linge spillways did more harm than good. There are however some flood events where the Linge spillways could be preventing damage instead of adding damage. A conclusion that the usage of the Linge spillways is disadvantageous for every flood scenario might be premature based on only two investigated dike breach scenarios.

A scenario not investigated where the Linge spillways could prove to be useful is in case of a large scale inundation north of the Linge from the Nederrijn or Lek. Excavation of the Linge spillways in addition the Waal spillways could provide a quick way for the flood water to leave dike ring 43 thereby reducing the size of the inundation. Therefore the recommendation is made to investigate the effect of the spillways along the Linge for a large scale inundation from Nederrijn before drawing definitive conclusions about the Linge spillways.

References

Deltares. (2017). *Standaardmethode 2017 Schade en slachtoffers als gevolg van overstromingen.*

Deltares. (2024a, October 6). *D-HYDRO Suite 2D3D*. Opgehaald van deltares.nl: https://www.deltares.nl/software-en-data/producten/d-hydro-suite-2d3d

Deltares. (2024b). *D-Flow Flexible Mesh Computational Cores and User Interface User Manual.*

Informatiepunt Leefomgeving. (2025, March 14). *Regionale waterkeringen algemene beschrijving*. Opgehaald van iplo.nl: https://iplo.nl/thema/water/waterveiligheid/regionale-waterkeringen/regionale-waterkeringen-algemene-beschrijving/

Ministerie van Infrastructuur en Milieu. (2016). *Achtergronden bij de normering van de primaire waterkeringen in Nederland.* Ministerie van Infrastructuur en Milieu.

Minns, T., Spruyt, A., & Kerkhoven, D. (2022). *Specificaties zesde-generatie modellen met D-HYDRO.* Deltares.

Planbureau voor de Leefomgeving. (2024, October 6). *Kleine kansen, grote gevolgen*. Opgehaald van themasites.pbl.nl: https://themasites.pbl.nl/o/risico-overstromingen/

Provincie Zuid-Holland. (1990). *De Lingewerken een waterstaatkundige 'noodzaak'.*

Rijkswaterstaat . (2024). *Gebruikershandleiding Schade Slachtoffer Module SSM2023 v4.x.* Rijkswaterstaat.

STOWA. (2024). *Vergelijking waardeschatter en de schade en slachtoffer module* . Amersfoort: STOWA.

Waterschap Rivierenland. (2017). *Lingesysteem* .

Appendix

Appendix A: calculation of water flow into the river extension

To allow the flood water to leave dike ring 43 via the Waal spillways, the grid of the D-HYDRO model is expanded with a piece of the Waal right outside of the spillways. To model the flow of the water in the river extension accurately, two boundary conditions are applied. To regulate the inflow of water into the river extension a time series of the incoming discharge is added, and to regulate the outflow of water a Q-H boundary is added.

Calculation of the water flow into the river extension

The discharge into the river extension is depended on two different factors. The first factor is the used return period and consequently the amount of discharge expected upstream. The second factor is how much water flows into the dike breach upstream from the same river branch.

Furthermore, it must be taken into account that the simulation starts two hours before the water level at the dike breach location reaches its maximum height. The discharge wave at the river extension needs to be shifted accordingly so that it corresponds time-wise with the discharge wave at the dike breach location.

The discharge waves corresponding to the T100 and T10000 peaks are provided by the waterboard for every kilometre in the Rhine delta with a 1D SOBEK model. SOBEK allows to model the expected discharge and water height along Rhine delta given a specific discharge wave at Lobith. Figure A.1 gives an overview of the provided SOBEK model, where alongside the Waal, Nederrijn and Lek also the Amsterdam-Rhine Canal and a portion of the IJssel are included.

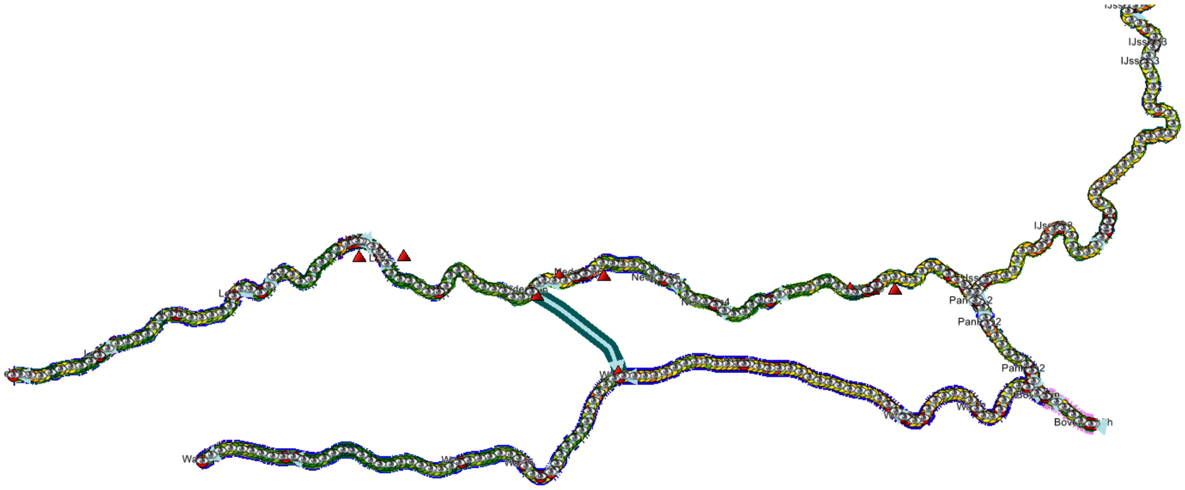


Figure A.1: Overview of the SOBEK model of the Rhine delta

The nearest data points of the SOBEK model for each location are listed below in Table A.1. These points are used to for the following calculations.

Table A.1: SOBEK data points

	SOBEK data point
Dike breach location Tiel	WA 922.00
Dike breach location Beusichem	LE 932.00
Inflow point river extension	WA 947.00

Discharge time series T10000 event south of Tiel

The first step in finding the discharge inflow into the river extension for the T10000 event south of Tiel is to subtract the inflow of flood water into dike ring 43 from the total discharge at the dike breach location. To find the time series of the discharge into the dike ring an earlier D-HYDRO model of the waterboard (without the Lingewerken present) is used. A simplification is made here by assuming that the values of the discharge wave at the dike breach location are still representative at the inflow point into the river extension.

After determining the discharge values of the flow into the river extension, the point from which the discharge wave should start in the D-HYDRO model starts was determined. The simulation starts two hours before the water level reaches its maximum at the dike breach location. A simplification is made by assuming that at the start of the simulation the discharge wave also begins two hours before the maximum is reached at the dike breach location. By comparing the tops of the discharge waves for the dike breach location and for the inflow point of the river extension it is found that there is a roughly five hour delay. The first rows of the calculation can be seen in Table A.2.

Table A.2: Calculation of the discharge at the inflow point of the river extension for the T10000 event south of Tiel

date and time	Discharge through dike breach [m³/s]	Total Discharge Tiel [m³/s]	Total discharge Tiel minus Discharge through dike breach [m³/s]	Discharge at the inflow point of the river extension [m³/s]
8-6-2020 00:00		10458	10458	10440
8-6-2020 01:00		10458	10458	10446
8-6-2020 02:00		10458	10458	10451
8-6-2020 03:00	1428.02	10457	9029	10454
8-6-2020 04:00	1806.38	10456	8649.6	10457
8-6-2020 05:00	2044.87	10454	8409.1	10458
8-6-2020 06:00	2213.84	10452	8238.2	10458
8-6-2020 07:00	2333.31	10449	8115.7	10458
8-6-2020 08:00	2423.44	10446	8022.6	9028.98

8-6-2020 09:00	2494.46	10443	7948.5	8649.62
8-6-2020 10:00	2552.23	10440	7887.8	8409.13
8-6-2020 11:00	2600.37	10436	7835.6	8238.16

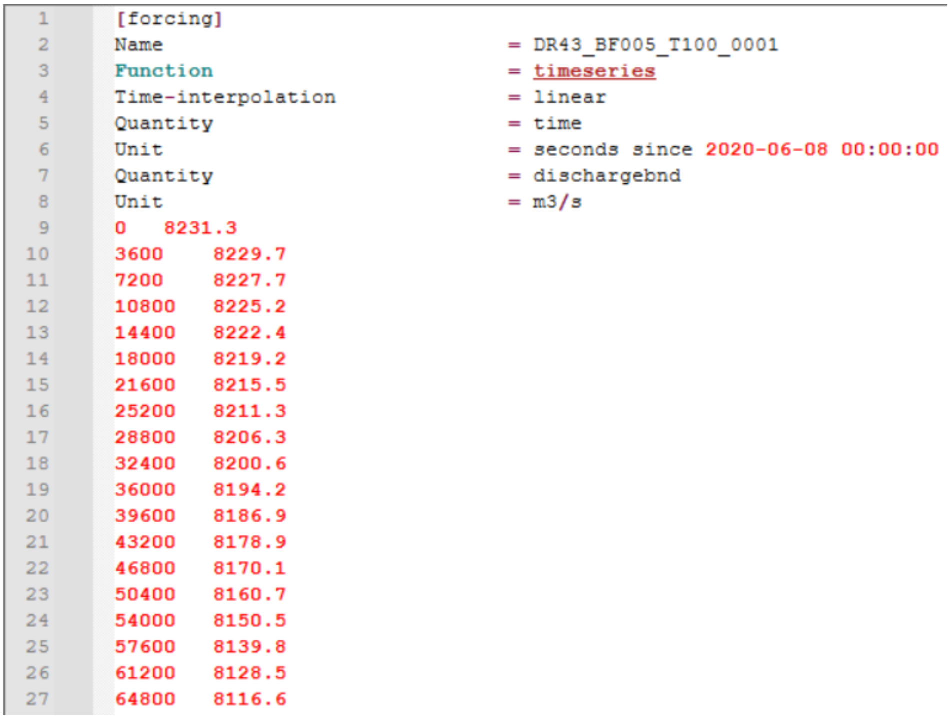
Discharge time series T100 event near Beusichem

To find the discharge wave for the T100 event with a dike breach near Beusichem is relatively straightforward as the inundation takes place from the Lek instead of the Waal, which means that inflow of water into the dike ring does not need to be subtracted from the discharge wave of the river extension. The only thing that needs to be considered is from which point of the discharge wave the simulation in the D-HYDRO model starts. To this end, the values around the peak of the water wave for the T100 event can be seen in Table A.3.

Table A.3: Peak discharge values T100 event for Beusichem and for the inflow point of the river extension

Simulation time SOBEK	Discharge inflow point river extension (m^3/s)	Discharge breach location Beusichem (m^3/s)	Water level breach location Beusichem (m^3/s)
2010-01-16 20:00:00	8233.4	2712.4	7.5775
2010-01-16 21:00:00	8232.5	2712.0	7.5778
2010-01-16 22:00:00	*8231.3*	*2711.5*	*7.5780*
2010-01-16 23:00:00	8229.7	2710.8	7.5781
2010-01-17 00:00:00	8227.7	2710.1	**7.5782**
2010-01-17 01:00:00	8225.2	2709.2	**7.5782**
2010-01-17 02:00:00	8222.4	2708.2	7.5781

From Table A.3 follows that the peak water level for Beusichem occurred at time ’01-17 00:00:00’ of the SOBEK simulation. As the simulation starts two hours before the highest water level is reached at the breach location, the discharge wave at the inflow point of the river extension starts from the value of 82321.3 (m^3/s) found at ‘2010-01-16 22:00:00’. In the corresponding file of the D-HYDRO model this results as in Figure A.2.



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Function                            = timeseries
Time-interpolation                  = linear
Quantity                            = time
Unit                                = seconds since 2020-06-08 00:00:00
Quantity                            = dischargebnd
Unit                                = m3/s
0   8231.3
3600    8229.7
7200    8227.7
10800   8225.2
14400   8222.4
18000   8219.2
21600   8215.5
25200   8211.3
28800   8206.3
32400   8200.6
36000   8194.2
39600   8186.9
43200   8178.9
46800   8170.1
50400   8160.7
54000   8150.5
57600   8139.8
61200   8128.5
64800   8116.6
```

Figure A.2: First rows of the discharge time series of the T10000 event with a dike breach south of Tiel