Optimizing the use of Delta21 for flood prone areas not protected by flood defenses at Dordrecht

A study on the operation strategy and reliability of a new flood protection system

M. Buijs

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by

M. Buijs

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Preface

In October 2019 I came across a flyer about Delta21 on the faculty Civil Engineering and Geosciences at Delft University of Technology. The mere size and boldness of the project intrigued me and via Mark Voorendt I came into contact with Huub Lavooij and Leen Berke, the creators of the project. Together we came to the conclusion that investigating the influence of the reliability of Delta21 on the water levels in the Rhine-Meuse delta would make for a challenging and interesting MSc Thesis research. This idea has developed ever since and together with Ton Botterhuis and Bas Kolen at HKV Lijn in Water and Mark Voorendt at the TU Delft more direction to the thesis proposal has been created. Further into the process Harold van Waveren at Rijkswaterstaat agreed to lend his expertise in Dutch flood safety and Ronald van Nooyen joined the thesis committee and helped me with the operational aspect of the Delta21 project. Finally, the committee was led by Matthijs Kok, who oversaw, among other things, the overall scientific relevance of the thesis. This report is made as part of the graduation for the Master of Science in Civil Engineering at Delft University of Technology. Within this master I followed the tracks Hydraulic Engineering and Water Management with specializations in Flood Risk and Water Resources Management.

I would like to thank my thesis committee for their enthusiasm and help during these past months. Furthermore, I am very grateful to HKV Lijn in Water for the intensive effort that was put in to make my internship, and that of the other interns, as valuable as possible during this strange year. Lastly, I would like to thank my friends, family and girlfriend for the support during the graduation period and moreover my entire time at the TU Delft.

M. Buijs
Delft, December 2020

Summary

Introduction

High-water levels in the Rhine-Meuse delta are going to rise in the upcoming decades. This is due to climate change with the accompanied sea level rise and the increase of the frequency of extreme Rhine discharges. The amount of sea level rise and the increase of the frequency of extreme Rhine discharge for the year 2100 is very uncertain. These phenomena are going to lead to an rise in the delta's high-water levels and larger closure frequencies and failure probabilities of the Europoort barrier. To protect against the increase of high-water levels, the dikes in the Rhine-Meuse delta can be improved. There are however regions in the delta that are not protected by dikes and are therefore directly influenced by the increase of the high-water levels. These regions are called the flood prone areas not protected by flood defenses and one of the most well-known of these are located at the Island of Dordrecht. The flood risk of these areas is expected to rise significantly with sea level rise and higher Rhine discharges. As an alternative to dike improvements, the Delta21 project has been proposed. It is however unclear if the project, which aims to lower high-water levels in the Rhine-Meuse delta by pumping water from the Haringvliet, can also significantly reduce the flood risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht for the aforementioned sea level rise and more frequent high Rhine discharges. Using the Delta21 project for these flood prone areas not protected by flood defenses requires a specific operation scheme. The settings for such an operation scheme might differ for the set of climate scenarios for the year 2100. Also the reliability of the components of the Delta21 project and the impact of this reliability on the high-water levels at the Island of Dordrecht and the optimal operation scheme is unknown.

Objective

The main objective of this report is to determine if the inclusion of Delta21 to the flood protection system of the Rhine-Meuse delta can provide a significant reduction of the flood risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht. Furthermore, it should be determined if an optimal operational scheme is possible in which the flood protection system with Delta21 can comply with all the flood requirements of the flood prone areas not protected by flood defenses at the Island of Dordrecht and limitations to the Europoort barrier and Delta21 project while considering the reliability of the Delta21 project and the climate scenarios of the year 2100.

Methodology

To fulfill the objective, first the flood risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht for the current flood protection system and the present sea level and extreme Rhine discharges was determined using a one-dimensional flow model of the Rhine-Meuse delta. After this, the change of this risk for the future scenarios of the year 2100 was determined. In Table 1 one can find the sea level rise and maximum Rhine discharge value for the minimum, medium and maximum scenario of the year 2100.

	Minimum	**Medium**	**Maximum**
Sea level rise [m]	0.2	0.6	1.1
Maximum Rhine discharge [m^3/s]	16,000	17,600	19,200

Table 1: Minimum, medium and maximum scenario of sea level rise and Rhine discharge in 2100

Furthermore, an alternative to the current flood protection system called Plan Locks was assessed. This plan involves the construction of shipping locks in the Nieuwe and Oude Maas in combination with pumps at these locks and storage in the Oosterschelde. The plan incorporates large scale changes to the flood protection system and can therefore serve as a comparison for the Delta21 project. Next off, the Delta21 project was introduced for the future scenarios as seen in Table 1 and an optimal operation was created based on

flood requirements of the flood prone areas not protected by flood defenses and limitations of the Europoort barrier and the Delta21 project. Finally, the impact of the reliability of the Delta21 project on the high-water levels at the Island of Dordrecht was determined.

Results

It was determined that the present flood risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht is equal to €110,000 per year. For the minimum, medium and maximum scenario for the year 2100, this risk increases to €390,000, €1,300,000 and €8,100,000 per year respectively. The implementation of Plan Locks leads to a flood risk reduction of 74, 88 and 97 % for the minimum, medium and maximum scenario respectively and the optimal operation of Delta21 reduces the flood risk with 23, 15 and 64 % for the minimum, medium and maximum scenario respectively.

It was set in this report that the closure frequency of the Europoort barrier may not exceed three times per year. However, to obtain a flood risk reduction of 64 % for the maximum scenario, the closure frequency of the Europoort barrier is equal to ten times per year. Additionally, it was decided that the flood risk at any location at the flood prone areas not protected by flood defenses may be larger than 1 % of the average annual income per household at this location. From the medium scenario onward however, this value is exceeded at the historical harbor (the city center of Dordrecht).

The maximum allowable probability of failure per pump of the pumping station and per siphon of the spillway of Delta21 is about 0.5 if the correlation between the components of both these systems is smaller than 0.9. This means that the pumps and siphons may fail to discharge water about half the times they are requested to do so.

Conclusions

The inclusion of Delta21 in the current flood protection system with the present Europoort closure level can provide a significant reduction of the future flood risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht. However, it is not possible to create an optimal operational scheme for all scenarios of the year 2100 in which the flood protection system with Delta21 complies with the flood requirements of the flood prone areas not protected by flood defenses and the limitations of the Europoort barrier. Finally, the reliability of the new Delta21 components is non-decisive for the flood risk assessments that have been made as long as the components are not fully dependent.

Recommendations

Based on the conclusions, recommendations are presented for the Delta21 project to meet the flood requirements of the flood prone areas not protected by flood defenses and to deal with the Europoort barrier limitations that prevent the possibility of an optimal operational scheme.

1. Recommendations to meet flood requirements
   - (a) Investigate a closure procedure of the Europoort barrier that is moved twelve hours up relative to the present one to further lower water levels in the delta.
   - (b) Investigate either a diversion of more water to the Waal and less to the Lek at the Pannerdense Kop or to move part of the high-water discharge capacity of Delta21 from the Haringvliet to the northern branches of the Rhine-Meuse delta to limit high flows through the Dordtse Kil and Spui that act as a bottleneck of the high-water function and cause further bed erosion at these branches.
   - (c) Determine the potential flood damages at the historical harbor in more detail to find out if a large scale project such as Delta21 can provide enough flood risk reduction or if local measures such as heightening of the quays or the construction of flood walls are necessary.
2. Recommendations to deal with the Europoort barrier limitations
   - (a) Assess the combination of Delta21 with an upgraded Europoort barrier, a new storm surge barrier in the Nieuwe Waterweg or a lock complex in the Nieuwe and Oude Maas to allow for a higher closure frequency and lower the probability of failure of the barrier.

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Introduction

1.1. Motivation for this research

The new standards that have been set by the Dutch Water Law of 2017 (Ministerie van Infrastructuur en Milieu, 2017) lead to the conclusion that about 900 km of the Dutch primary flood defenses have to be reinforced by 2050. To meet the required safety standards, the High water protection program (Dutch: 'Hoogwaterbeschermingsprogramma (HWBP)') has been set up, which aims to strengthen these dikes costing an estimated 5.4 billion Euros (Ministerie van Infrastructuur en Waterstaat, 2019). After the completion of the dike reinforcements by 2050, further heightening of the dikes in the Rhine-Meuse delta depends largely on the amount of sea level rise and extreme discharges from the Rhine. In addition to the costs of dike reinforcement, there has been quite some discussion on the societal impact of these plans. The construction of the reinforcements are thought to lead to major of disturbance among residents of these areas and aesthetically the heightening and widening of the dikes might undermine the nature of the Dutch river landscape. Even more crucial are dike sections where it is physically impossible or unfeasible to reinforce the dike by heightening and widening due to spatial restrictions (INFRAM and van Paridon en de Groot, 2016).

As an alternative to this traditional approach to Dutch flood protection, the plan Delta21 has been created. Using the, also traditionally Dutch, method of pumping away water, the need for dike heightening can be diminished by doing so during extreme water levels. By stationing a large pumping station at the mouth of the Haringvliet, the water levels in the Rhine-Meuse delta can be lowered during extreme conditions and the current stress on the Maeslant barrier can be alleviated. During high river discharges and high water levels at sea, Delta21 can make sure that the water levels in the rivers do not exceed critical values. Even though the costs of this project are estimated to be in the order of billions of euros, a large portion of these investment costs might be earned back by reducing the need for heightening of the dikes in the Rhine-Meuse delta (Berke and Lavooij, 2019).

The Delta21 plan is centered around a lake that is connected to the south of the Maasvlakte and connects to Goeree-Overflakkee with a new storm surge barrier, as is schematized in Figure 1.1. The Haringvliet sluices can be permanently opened and during a combination of storm surge (closed off storm surge barriers) and high river discharges (>5000 m^3/s), a spillway on the Haringvliet-side of the lake is opened to let river water flow into the lake. The pumping station positioned on the sea-side can pump out the water entering the lake via the spillway (Berke and Lavooij, 2019).

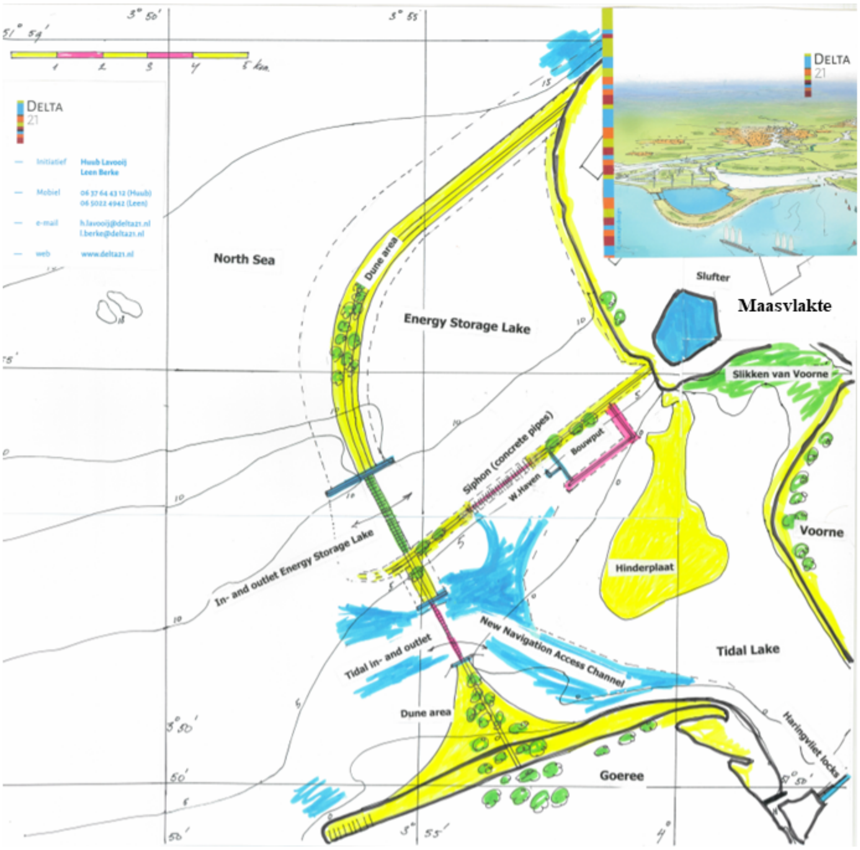


Figure 1.1: Layout Delta21 Energy Lake (Berke and Lavooij, 2019).

Not all areas in the Rhine-Meuse delta are protected by flood defenses. These flood prone areas not protected by flood defenses are located at larger elevations than the areas within the flood defenses, which provides them with some protection against high water levels in the river. An example of such flood prone areas are the flood prone areas not protected by flood defenses at the Island of Dordrecht. The Island of Dordrecht has been a subject for flood protection research for a long time because of its location in the Delta-Meuse delta. It is surrounded by river segments originating from both the Rhine and the Meuse and the water levels can be influenced by both high river discharges and storm surge at the North Sea. The Europoort barrier limits the influence of storm surge at the North Sea, but in case of a (partial) failure of the barrier or extreme Rhine discharges, water levels can exceed the allowed values.

To make sure that the hinterland of the Rhine-Meuse delta does not get flooded, the Delta21 system needs to function adequately and the dikes need to be able to withstand the generated water levels due to the high river discharges and the storm surge at sea. It is however not a given that the Delta21 system always operates correctly. There is the possibility that one or more pumps stop working, one or more gates of a storm surge barrier do not close or part of the spillway does not open. Such occurrences might lead to a situation where the new flood protection system with Delta21 does not fulfill its function. All these situations have a certain probability of occurrence and have different impacts on the hydraulic situation in the delta. Hence, to determine whether Delta21 gives a reduction in the flooding probabilities that is large enough to comply with the Water Law (Ministerie van Infrastructuur en Milieu, 2017), the whole system needs to be analyzed. The influence of the reliability on the extreme water levels in the Rhine-Meuse delta needs to be known.

Because the flood prone areas not protected by flood defenses are not protected by dikes, flooding events in these areas occur more frequently compared to areas within the flood defenses. The rise of the sea level along with an increase in high Rhine discharges means that the value at risk due to flooding is going to increase over the course of the 21st century. As residents of such areas are responsible for any damages themselves, an increase in flooding frequencies and flood risk might decrease the economical, cultural and historical value of theses areas and discourage new development investments (Klostermann et al., 2013). This means that the full potential of these areas might be lost. This MSc-project investigates if and how the Delta21 plan can help these areas in staying at their full potential by assessing the flood risk and frequencies and the possible reduction of the risk and frequencies due to the implementation of the Delta21 project.

1.2. Problem Analysis

1.2.1. Flood protection in the Rhine-Meuse delta

The Rhine-Meuse Delta composes all the branches and canals that originate from the Rhine entering the Netherlands at Lobith and the Meuse coming in through Maastricht. Currently the probability of flooding at many places along the delta is too high. By 2050, 924 km of main flood defenses that do not meet the current Delta program requirements need to be improved (Ministerie van Infrastructuur en Waterstaat, 2020). Due to sea level rise (Sterl et al., 2009) and a larger variation in river discharges (Kwadijk and Middelkoop, 1994), this probability is bound to increase over the next century meaning that the flood defenses need to be reinforced or the hydraulic loads need to be reduced.

Another problem that arises with the aforementioned sea level rise is that the Maeslant barrier's performance is expected to become inadequate. Currently the barrier has to be closed every ten years on average and the probability that it does not close is once every 100 closures. Hence, during a random year the barrier has a probability of non-closure equal to $\frac{1}{1000}$. If the sea level were to rise significantly, the barrier needs to be closed more often than every ten years, which means that the probability of non-closure of the barrier increases (Vrancken et al., 2008). According to Botterhuis et al. (2012), the Europoort barrier, of which the Maeslant barrier is a part, needs to be closed once every three years by 2050 and every more than once a year by 2100 for the current closure level (Dutch: 'sluitpeil') according to the medium KNMI climate scenario of 2006 (Hurk et al., 2006). This means that the probability of non-closure could rise up to, or even exceed, $\frac{1}{100}$ per year. Also the frequency of closure might become a problem by the year 2100. Currently, it is estimated that the maximum allowable frequency of closure is three times per year. This is based on structural limitations by the barrier itself. This frequency will be exceeded at a sea level rise equal to about 0.85 m (Botterhuis et al., 2012). To make sure that this closure frequency is not exceeded, the closure level of the Europoort barrier might need to be increased in the future. Partly for these reasons, the water levels for certain return periods are bound to rise if the current closure rate of once every ten years and thus a higher closure level were to be maintained. This is important for dike reliability along the delta for large return periods, but for flood prone areas not protected by flood defenses this poses even larger problems.

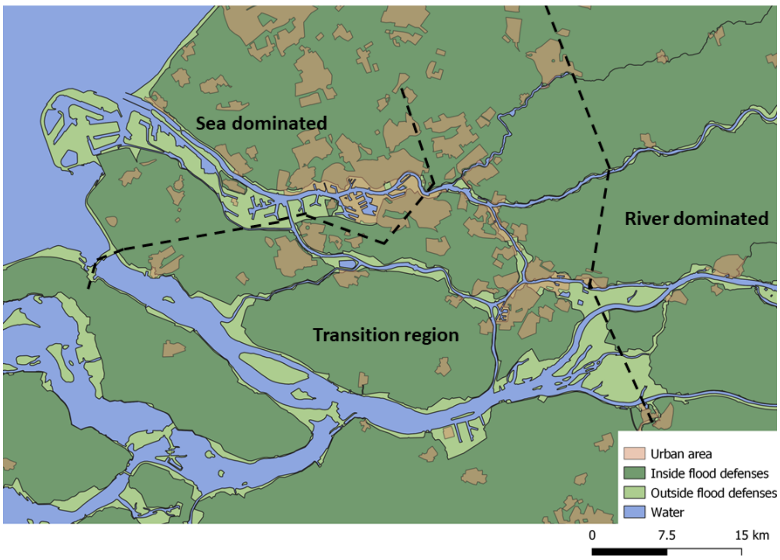


Figure 1.2: Map of the Rhine-Meuse delta with the different regions

In Figure 1.2 the flood prone areas not protected by flood defenses in the Rhine-Meuse delta are colored light green. Several of these areas are located high above NAP + 0 m, such as the Maasvlakte, which is located at about NAP + 5 m (Segers et al., 2001). Other areas that are situated closer to NAP + 0 m, such as those on the Island of Dordrecht, are subjected to water levels with larger frequencies. These water levels are greatly influenced by a rise of the Europoort barrier closure level and a small rise in water levels can greatly increase the flooding probability (Botterhuis et al., 2012).

Currently, one of the options to deal with the large unreliability of the Europoort barrier for large sea level rise scenarios is by permanently closing it and letting ships coming to and from the harbor of Rotterdam pass through locks. This plan is called Plan Locks (Dutch: 'Plan Sluizen') (Dorrepaal, 2016). One of the disadvantages of this plan is however, that the implementation of this plan will have large consequences for the capacity of the harbor of Rotterdam.

To tackle these problems, the Delta21 plan has been set up. Regarding flood protection it aims to alleviate future stress on the Europoort barrier, lower water levels due to high river discharges and storm surge at sea and reduce the need for intensive dike heightening along the banks of the Rhine-Meuse delta branches. Furthermore, in theory the plan makes sure that permanent closure of the Nieuwe Waterweg can be prevented.

Regarding the occurrence of high water at sea or in the rivers, the functions of each of the river branches, barriers and storage areas are clear and can be simplified in a simple 1D scheme. In Figure 1.3 this schematization can be found. This schematization shows the main river branches discharging river water from the Rhine and the Meuse to the North Sea. Additionally, some of these branches experience an influence by the tide at the North Sea. Also the barriers and locks that are most important regarding high water situations are marked. The Maeslant barrier and the Hartel barrier make up the Europoort barrier. These barriers are only used in case of high water. The Haringvliet barrier and the Volkerak locks also have different functions. During a storm event however, the Haringvliet barrier is used to discharge river water during low tide and the Volkerak locks can be used to let water flow towards the Volkerak to create a storage area.

Figure 1.3: 1D schematization current flood protection system Rhine-Meuse delta (Google Maps, 2020).

1.2.2. Flood risk Island of Dordrecht

General flood risk Dordrecht
Dordrecht is a city in the province of Zuid-Holland. The city is situated on the Island of Dordrecht, which is a piece of land that is surrounded by the Nieuwe Merwede, the Dordtse Kil, the Oude Maas and the Beneden

Merwede; all originating from the Waal. The daily tidal range at the west side of the island is about 80 cm and on the east side, at the north-eastern Biesbosch, this tidal range is only 30 cm (Kelder et al., 2013). The main flood defense called dike ring 22 surrounds part of the island that is located beneath NAP + 0 m. However, part of the island is situated outside this dike ring and is called the flood prone areas not protected by flood defenses at the Island of Dordrecht (Dutch: 'Dordrecht buitendijks') (Van Herk et al., 2011). These areas are located higher than those within the dike ring, but are not protected from flooding by any flood defenses. In Figure 1.4 one can see that the island is comprised of four areas, where the dark green part is situated inside the dike ring and the other three outside.

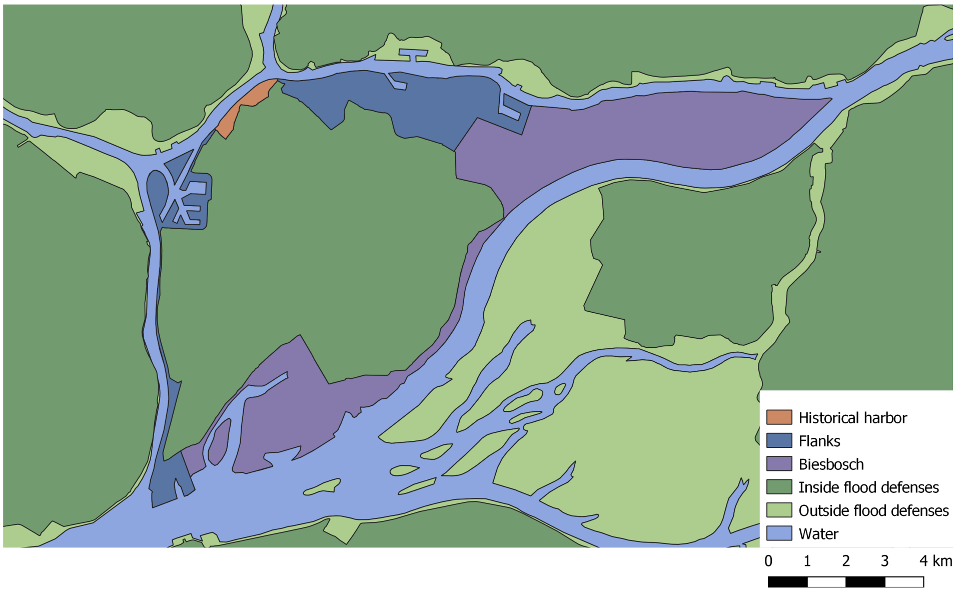


Figure 1.4: Flood prone areas not protected by flood defenses at the Island of Dordrecht

In Figure 1.5 the elevations of the ground level of the Island of Dordrecht can be found. The flood prone areas not protected by flood defenses that have been defined in Figure 1.4 can be identified rather easily and it is obvious where the dikes are located.

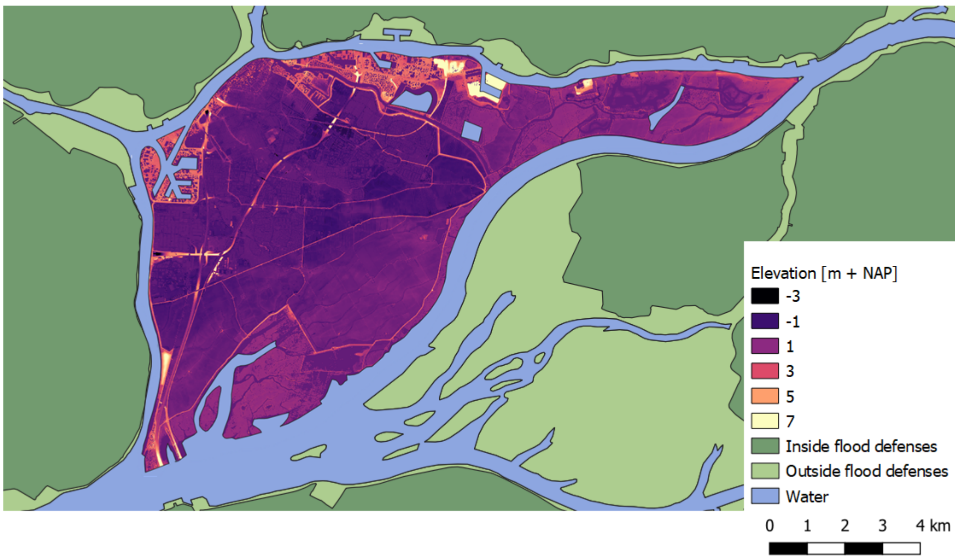


Figure 1.5: Elevation map of the Island of Dordrecht with respect to NAP + 0 m (AHN, 2019)

Flood risk of flood prone areas not protected by flood defenses

The flood prone areas of Dordrecht that are not protected by flood defenses are usually higher lying areas. They are not protected by dikes, but instead rely on the fact that they are located higher than areas within the flood defenses that they are not flooded too frequently. According to Kolen and Huizinga (2017), the flood prone areas at Dordrecht not protected by flood defenses experience a much different situation when it comes to flooding compared to the areas inside the dike ring. On average once every two years some parts of the areas at lower elevations experience water on the quays.

As can be seen in Figure 1.4, the flood prone areas not protected by flood defenses are divided into three different regions: the historical harbor, the flanks and the Biesbosch. Around 3,000, 28,000 and 500 people live in these regions respectively (CBS, 2020). In total that is about 31,500 people on a total population of around 120,000 people living in the municipality of Dordrecht and therefore the Island of Dordrecht. Hence, about 25% of the inhabitant of the Island of Dordrecht are resided in the flood prone areas not protected by flood defenses. The historical harbor area, as can be seen in Figure 1.6, experiences flooding on a relatively regular basis. The so called flanks (Dutch: 'buitendijkse flanken'), as can be seen in Figure 1.4 and Figure 1.6 are located at about NAP + 2.7 to + 3.5 m, which is on average up to a almost a meter higher than the historic harbor area. This also means that these areas are only vulnerable to water levels with return periods of about 2,000 years. The current advise for new residential buildings is to keep NAP + 3.3 m as a minimum level for the lower floors (Van Herk et al., 2014).

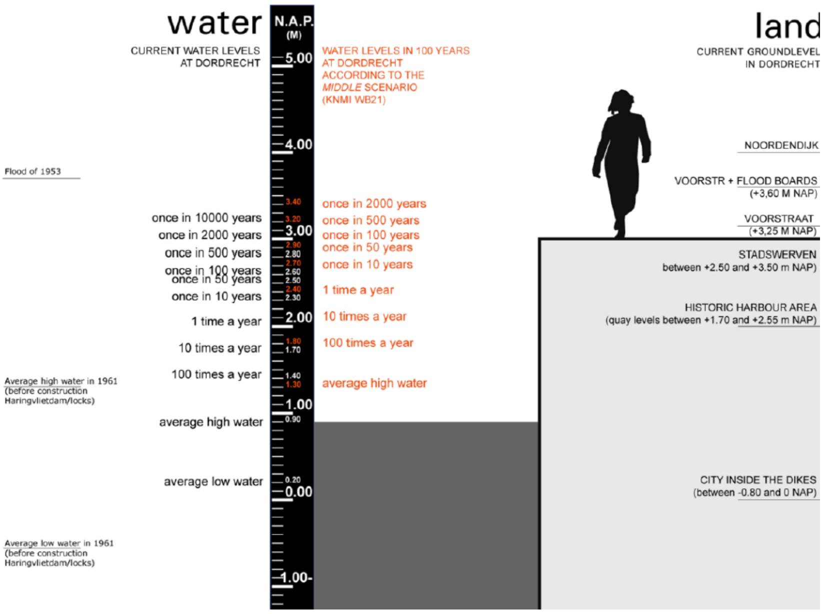


Figure 1.6: Heights different areas of the island (Van Herk et al., 2014).

One can observe from Figure 1.6 that the frequency of high water levels is going to increase due to climate change. An increase in rainfall in winter months leads to higher extreme river discharges (Bessembinder et al., 2008) and due to sea-level rise the Europoort barrier needs to be closed more frequently (Botterhuis et al., 2012). The scenario on which Figure 1.6 is equal to the medium scenario from SSROC of the IPCC (Hinkel et al., 2019). The water level that currently occurs approximately every 10 years, will occur annually around the year 2050 for this scenario (Bessembinder et al., 2008). Hence, it can be concluded that the historic harbor area of Dordrecht is becoming more and more vulnerable to the rising water levels in the rivers and also the main flood defenses and the other higher-lying areas not protected by flood defenses are becoming more prone to flooding.

1.2.3. Flood protection system with the Delta21 project

Functions and components

The goal of the Delta21 project is to be a solution for the aforementioned issues regarding flood protection, in addition to energy storage and nature conservation in the south-western delta of the Netherlands (Berke and Lavooij, 2019). Each of these goals or functions are fulfilled by one or more of the components of the plan, where some components serve multiple functions. The flood protection goal is made up from multiple sub-functions, where each of these sub-functions is fulfilled by one or more of its components.

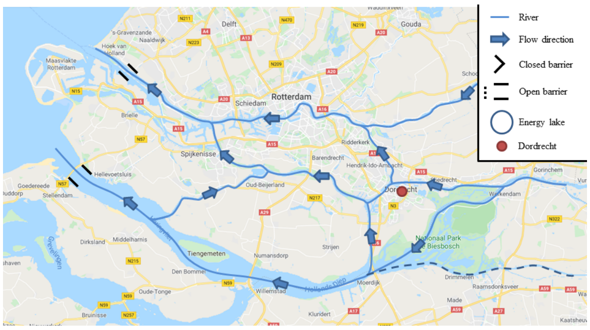
Components of Delta21:

- Energy lake
- Spillway (in the form of siphons)
- Pumping station
- Storm surge barrier

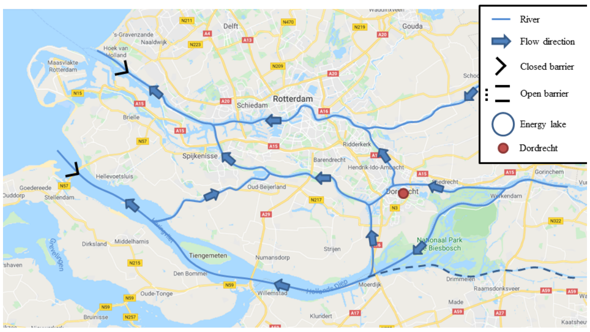
The core of the plan is to create a lake in between the Maasvlakte and Goeree-Overflakkee. The function of this lake is to act as an energy storage lake (pumped storage) where water from the lake is pumped onto sea when a surplus of wind energy is present. In case the energy demand is higher than the supply of energy from wind turbines and solar panels, water from sea is allowed to flow into the lake through a set of turbines. By doing so, the discrepancies between energy supply and demand from these renewable energy sources can be smoothed out. This is important if a larger portion of the Dutch electrical supply network is made up from renewable energy sources (Trainer, 2017). The other function of the lake is to let water flow into it during closure of the new storm surge barrier and in case of high water discharges in the delta. This discharge can subsequently be pumped out of the lake and into sea. The lake is connected to the mainland of Goeree-Overflakkee through a storm surge barrier. This barrier closes off the area west of the Haringvliet sluices from the sea. The barrier's purpose is to create a closed off area at which the water level can be artificially lowered. A schematization of the plan can be seen in Figure 1.1.

Flood protection function

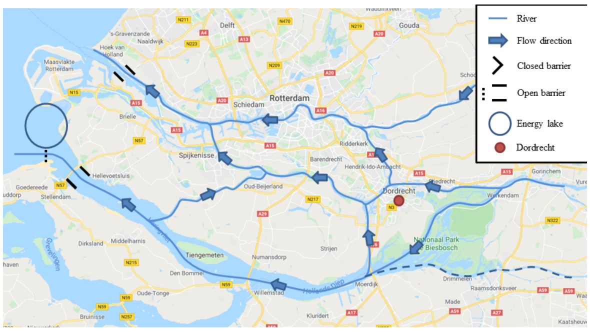
Basically, water coming into The Netherlands through the Rhine and Meuse flows into the North Sea via the Nieuwe Waterweg or the Haringvliet. The Nieuwe Waterweg is ordinarily open to let river water flow freely into the sea, whereas the Haringvliet sluices can be both open and closed (partly) during normal conditions. This depends mostly on the tides and the operation as set in the Kierbesluit (Rijkswaterstaat, 2018). During high water levels at sea, these barriers can be closed off completely to protect the hinterland from flooding from sea. During this period, water that flows through the Rhine and the Meuse is trapped behind these barriers and hence the water levels in the rivers rise during the storm that caused the higher water level at sea. This is not necessarily a problem as long as water that is trapped does not cause flooding of the hinterland. Therefore, there are combinations of high sea levels and high river discharges that can lead to flooding of these areas. In such a situation the new storm surge barrier is closed as well as the Maeslant barrier. Additionally, the spillway of the energy storage lake is opened, letting river water flow into the lake. This water is subsequently pumped out of the lake into sea. The idea of Delta21 is that the capacity of the spillway, lake and the pumps is large enough so that the water levels in the rivers do not lead to failure of the river dikes. This function of the plan should reduce the need for heightening of these dikes, as in the (current) situation without Delta21 the river water is piled up behind the Maeslant barrier and the Haringvliet sluices. A schematization of the current situation and the situation with Delta21 can be found in Figure 1.7.



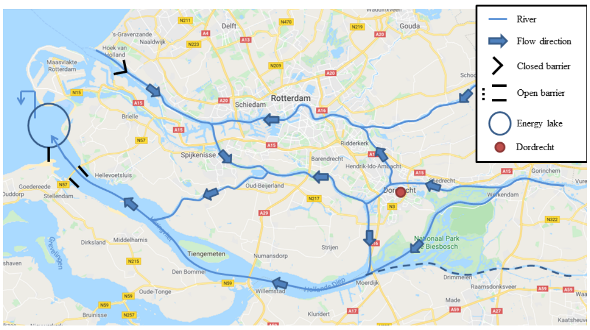
Normal conditions without Delta21



Storm conditions without Delta21



Normal conditions with Delta21



Storm conditions with Delta21

Figure 1.7: Schematization of the Rhine-Meuse delta during normal and storm conditions without and with Delta21 (Google Maps, 2020).

Figure 1.7 shows the flow directions changing for the situation with Delta 21 during storm conditions. The arrows in this schematization are all equally large, but in reality it is surely not the case that these flows are equal. It depends per case which flow directions some waterways are going to have. This is fully dependent on the total river discharges, pump and spillway capacity, closure and initiation levels and duration of the closure of the storm surges among other things.
The large discharge capacity of the Delta21 project should not only reduce the need for dike heightening, but it also means that it might be possible to discard the floating function of the Maeslant barrier during low tide for high river discharges (Dutch: 'kentering'). Removing the need for such movements might decrease the probability of a failure of closure and/or opening, though this has not been scientifically proven yet (Berke and Lavooij, 2019).

Operation optimization of the flood defense system

The operation guidelines for the current flood protection system and more specifically the Europoort barrier might not be optimal anymore for the new flood protection system with Delta21. As there is a clear interaction between the use of the pumping station, the spillway and the use of the Europoort barrier, the operation settings should be redefined. Specifically for the flood prone areas not protected by flood defenses, it is unclear how the new system can best reduce the flooding frequencies of these areas.

The Europoort barrier, which the Maeslant barrier is part of, closes based on an expected water level at Rotterdam or Dordrecht during extreme conditions. Such extreme conditions can be storm surge at sea or extreme Rhine discharges and a combination of both. Based on an accepted closure frequency, the closure water levels of the Europoort barrier can be raised or lowered. The same principle goes for the new components of the system with Delta21. The water levels at which the pumping station is turned on and at which the spillway is opened can be adjusted to create lower water levels at Dordrecht and therefore reduce the flooding probabilities of the flood prone areas not protected by flood defenses.

The closure frequency of the Europoort barrier cannot be too high to minimize the impact on the cargo ships navigating through the Nieuwe Waterweg and also it is currently expected that the closure frequency of the Europoort barrier can not exceed three times per year, because of mechanical limitations to the barrier.

Also, there are financial aspects regarding the use of the new Delta21 components that have an influence on the most optimal operation. An example for this can be the costs associated with the use of Delta21, mainly its pumping station.

Finally, there is also the impact of climate change, with an emphasis on sea-level rise, that might impact the optimal operation strategy. Since it there are many sea-level rise projections, there is a need for some flexibility in the operation of the new flood defense system.

Reliability of the flood defense system

Having discussed the reliability of the Europoort barrier, it is also essential to include the reliability of the Delta21 project when implementing it into the current flood protection system. The reliability of this new system is defined as the ability of the system to perform their required function. Here the function could be the discharge of river water towards the energy storage lake by the spillway or the pumping away of water from the energy storage lake to sea by the pumping station. There are different gradations in which one of these sub-systems can fail to fulfill a certain function. Additionally, since the different components of each system work together and are dependent on certain conditions, there is a correlation of the possible failure to fulfill their function. This correlation may be caused largely by the hydraulic conditions that act upon the components, but failure of one component might actually have an influence of the functionality of another component depending on the configuration of the system. Every type of failure of the system to fulfill one or more of its functions results in different consequences. To assess the gradation of a failure of fulfilling a function, it needs to be linked to the consequences that accompany this failure. These consequences are mainly the rise of high-water levels at the Island of Dordrecht. Hence, it is critical to assess if a (partial) failure of the Delta21 project may be of significance to the high-water levels and therefore flood risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht.

1.2.4. Problem statement

High-water levels in the Rhine-Meuse delta are going to rise in the upcoming decades. This is due to climate change with the accompanied sea level rise and the increase of the frequency of extreme Rhine discharges. The amount of sea level rise and the increase of the frequency of extreme Rhine discharge for the year 2100 is very uncertain. These phenomena are going to lead to an rise in the delta's high-water levels and larger closure frequencies and failure probabilities of the Europoort barrier. To protect against the increase of high-water levels, the dikes in the Rhine-Meuse delta can be improved. There are however regions in the delta that are not protected by dikes and are therefore directly influenced by the increase of the high-water levels. These regions are called the flood prone areas not protected by flood defenses and one of the most well-known of these are located at the Island of Dordrecht. The flood risk of these areas is expected to rise significantly with sea level rise and higher Rhine discharges. As an alternative to dike improvements, the Delta21 project has been proposed. It is however unclear if the project, which aims to lower high-water levels in the Rhine-Meuse delta by pumping water from the Haringvliet, can also significantly reduce the flood risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht for the aforementioned sea level rise and more frequent high Rhine discharges. Using the Delta21 project for these flood prone areas not protected by flood defenses requires a specific operation scheme. The settings for such an operation scheme might differ for the set of climate scenarios for the year 2100. Also the reliability of the components of the Delta21 project and the impact of this reliability on the high-water levels at the Island of Dordrecht and the optimal operation scheme is unknown.

1.3. Objective

The main objective of this report is to determine if the inclusion of Delta21 to the flood protection system of the Rhine-Meuse delta can provide a significant reduction of the flood risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht. Furthermore it should be determined if an optimal operational scheme is possible in which the flood protection system with Delta21 can comply with all the flood requirements of the flood prone areas not protected by flood defenses at the Island of Dordrecht and limitations to the Europoort barrier and Delta21 project while considering the reliability of the system and the climate scenarios of the year 2100.

This objective is achieved by the following steps:

1. Determining the reference (current) situation of the flood protection system and hydraulic boundary conditions and set-up of possible future scenarios of sea level rise and operational decisions for the Europoort barrier.
2. Determining the flood risk of the flood prone areas not protected by flood defenses for the reference situation and the possible future scenarios for the current flood protection system without Delta21 and Plan Locks.
3. Determining the future boundary conditions and configuration variants for the flood protection system with Delta21 given the climate change scenarios.
4. Determining an optimum use of the new flood protection system with Delta21 based on the future flood risk reduction, flood frequencies, the closure frequency of the Europoort barrier and the initiation frequency of the Delta21 project.
5. Determining the impact of the reliability of the new flood protection system with Delta21 on high-water levels at the Island of Dordrecht.

By following these steps, the Delta21 project can be properly compared to the current flood protection system and Plan Locks. Next to flood risk reduction only, also the closure and initiation levels associated with the Delta21 project are included in the analysis to properly assess whether the flood prone areas not protected by flood defenses can become less prone to flooding through the implementation of Delta21.

1.4. Methodology

This research was made up from five main steps. Each step acts as a foundation for the next one.

1. **Determining the present and future situation and boundary conditions**
   The reference (current) situation and possible future scenarios of the flood protection system and the hydraulic boundary conditions of the Rhine-Meuse delta were determined by creating sets of varying hydraulic boundary conditions based on projections that are derived from literature. The reference situation was set as the current sea water level, operation of the Europoort barrier and river discharge occurrences. The possible future scenarios were mainly differentiated by their respective sea-level rises and increase of maximum Rhine discharge. Additionally, alternatives for the current flood protection system such as Plan Locks were examined. The reference situation and scenarios resulting from this step were used in step 2.

2. **Determining the present and future flood risk of the flood prone areas not protected by flood defenses**
   An inventory was made of the potential damages for certain flood depths at the flood prone areas not protected by flood defenses. This was done using the program SSM-2017. This program contains maps with land-uses and their respective damage functions. The economic damages were divided into four categories: companies, infrastructure, residences and other. Relating the damages to current occurrence probabilities of water levels gave the present flood risk of these areas.

   Next off, the flooding probability of the flood prone areas not protected by flood defenses was determined for the reference situation and the possible future scenarios. This was done by using Normative High Water processor (Dutch: 'Maatgevend Hoogwaterprocessor') or MHWp5 and Hydra. MHWp5 is a program that runs a one-dimensional SOBEK model of the Rhine-Meuse delta for a multitude of storm surges, river discharges and operational settings of the Europoort barrier. The water level at a number of locations for the duration of the run was given as output. By varying the input parameters such as sea water level, river discharge and the closure and initiation levels of the Europoort barrier, frequency curves of the water level at flood prone flood prone areas not protected by flood defenses of Dordrecht are found using Hydra. This program makes use of known correlations between these input parameters and their marginal distributions to create these frequency curves. The water level frequency curves of Plan Locks were retrieved from Stijnen and Botterhuis (2015a) and were not calculated for the same scenarios.

The flooding probabilities were combined with the associated damages to calculate the flood risk for the flood prone areas not protected by flood defenses at the Island of Dordrecht for the reference situation and the future scenarios.

3. **Determining the boundary conditions and configuration variants for system with Delta21**
The flood protection system with Delta21 was introduced along with the set-up of the control systems. These control systems were linked to each of the components of the Delta21 project. Furthermore, a set of configuration variants was proposed. The basis of these variants was their dependency on the Europoort barrier. Half of the variants had the characteristic that Delta21 can only be used if the Europoort barrier is closed, whereas the other half did not use the Europoort barrier operation as input. This meant that along the variants the initiation level of the new Delta21 components and the closure level of the Europoort barrier were varied.

4. **Optimizing the operation of the flood protection system with Delta21 for the flood prone areas not protected by flood defenses at the Island of Dordrecht**
The flood risk and flood frequency reduction results for each of the configuration variants of the flood protection system with Delta21 were presented for the future scenarios. The variants were assessed based on flood requirements of the flood prone areas not protected by flood defenses and the limitations of the closure and initiation frequency of the Europoort barrier and the Delta21 project. From this assessment an optimal operation of the flood protection system with Delta21 for each scenario of the year 2100 was proposed.

5. **Determining the impact of the reliability of the new flood protection system with Delta21**
The impact of the reliability of the new flood protection system with Delta21 on the high-water levels at the Island of Dordrecht was determined using a top-down approach. This means that a maximum allowable impact was set and from this it was calculated if the resulting maximum allowable failure probabilities of the individual components was normative. This was done for the configuration of Delta21 with the lowest initiation level of Delta21 and for the maximum scenario, hence the most intensive use of Delta21.

1.5. Outline final report

The final report is made up from five main chapters that meet the objective given in Section 1.3 and follow the methodological steps given in Section 1.4. Hence, each methodological step is addressed by a separate chapter, which leads to five steps. In the sixth step the outcomes of the first five steps are discussed and conclusions are drawn regarding the results.

Step 1
Chapter 2 gives the reference situation and possible future scenarios of the flood protection system and hydraulic boundary conditions of the Rhine-Meuse delta that are to be used as a basis for the following chapters.

Step 2
Chapter 3 determines the flood risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht for the current flood protection system and Plan Locks for the reference situation and possible future scenarios obtained in step 1.

Step 3
In Chapter 4 the Delta21 flood protection system is introduced along with the to be assessed configuration variants.

Step 4
Chapter 5 optimizes the operation of the new flood protection system with Delta21 for the flood prone areas not protected by flood defenses at the Island of Dordrecht for the the minimum, medium and maximum scenarios.

Step 5
In Chapter 6 the impact of the reliability of the new flood protection system with Delta21 on the high-water levels at the Island of Dordrecht is determined.

Step 6
Finally, the results of the report are discussed and a conclusion is drawn as to whether the main objective stated in the start of the report is reached and what the most important outcomes are. Recommendations regarding the main objective are given based on the conclusions of the report. If necessary further research can be proposed.

2

Present and future boundary conditions in the Rhine-Meuse delta without the Delta21 project

In this chapter research step 1 is elaborated. The chapter's goal is to set up a reference situation and several scenarios on which the current flood protection system without Delta21 can be assessed. This means that several climate projections of the hydraulic boundary conditions such as the sea level and maximum Rhine flow are described and the operation and reliability of the Europoort barrier are examined. Additionally, the boundary conditions for Plan Locks are given.

2.1. Present hydraulic boundary conditions in the Rhine-Meuse delta

In addition to the information provided in Chapter 1, here a more quantitative description of the hydraulic boundary conditions and the flood protection system are given. Specifically the current mean sea level, tidal characteristics, storm surge characteristics, river discharge frequencies and the operation and reliability of the Europoort barrier are discussed.

2.1.1. Present sea level at Dutch coast

Present mean sea level along Dutch coast

The mean sea level along the Dutch coast averaged over six coastal stations is NAP + 6.3 cm in 2020 (Centraal Bureau voor de Statistiek, 2018). This mean sea level varies year by year depending on the number of storm events, annual average temperature and measurement inaccuracies.

Modeled tidal signal at Dutch coast

To model the tide at the Dutch coast during extreme events, two distinct tidal signals were used. The signal at the Haringvliet and the Nieuwe Waterweg were used to model the system's response to extreme hydraulic boundary conditions. According to Bosboom and Stive (2012), the tidal signal at these locations is dominated by the M_2 (semi-diurnal lunar) tide and the S_2 (semi-diurnal solar) tide. Furthermore, several other components such as the M_4, MS_4, N_2, 0_1, and SA tidal components make up the tide at each location. In Figure 2.1 the astronomical tide at Stellendam (Haringvliet) in 2019 can be observed. Here it is obvious there are several annual, monthly and other components in the tidal cycle as mentioned.

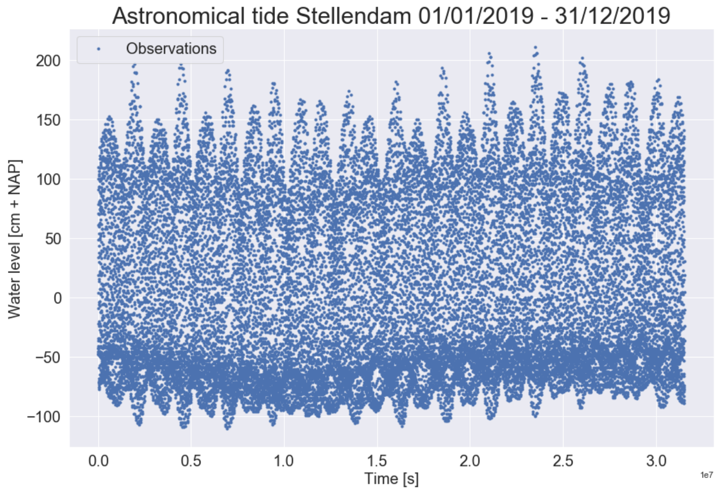


Figure 2.1: Astronomical tide Stellendam 2019 (Waterinfo, 2020).

An overestimation of the flood risk in the Rhine-Meuse delta may be created when the evaluated extreme situations are modeled for a tide that is at a monthly or yearly maximum. Hence, a mean high-water and mean low-water were used for the modeled tide.

In Figure 2.2 the modeled tidal signals at the Haringvliet and the Nieuwe Waterweg can be seen.

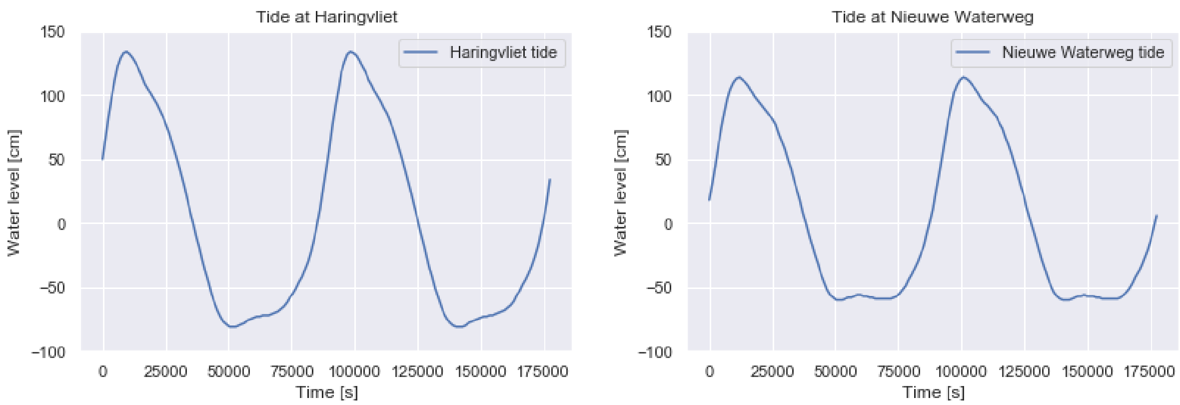


Figure 2.2: Modeled tidal signal at Haringvliet and Nieuwe Waterweg

It is clear that the tidal signal at the Nieuwe Waterweg has a small lag to that compared at the Haringvliet. Additionally, the tidal range at the Haringvliet is larger with lower low waters and higher high waters.

Current storm surge at the North Sea

Storm surge at the Dutch coast is a result of high, long-lasting winds from the North Sea and the resulting wind set-up. Together with the astronomical tide, storm surge accounts for the largest portion of extreme water levels at the Dutch coast. In Figure 2.3 the frequency curve of storm surge intensities for the current climate can be found. Here the 108-year ESSENCE subsets in red are created to account for a bias from the historical observations in blue (Sterl et al., 2009). On the right side of the figure the range in red indicates the uncertainty band of possible storm surges with a return period of 10,000 years. For storm surges with smaller return periods, this uncertainty band is smaller.

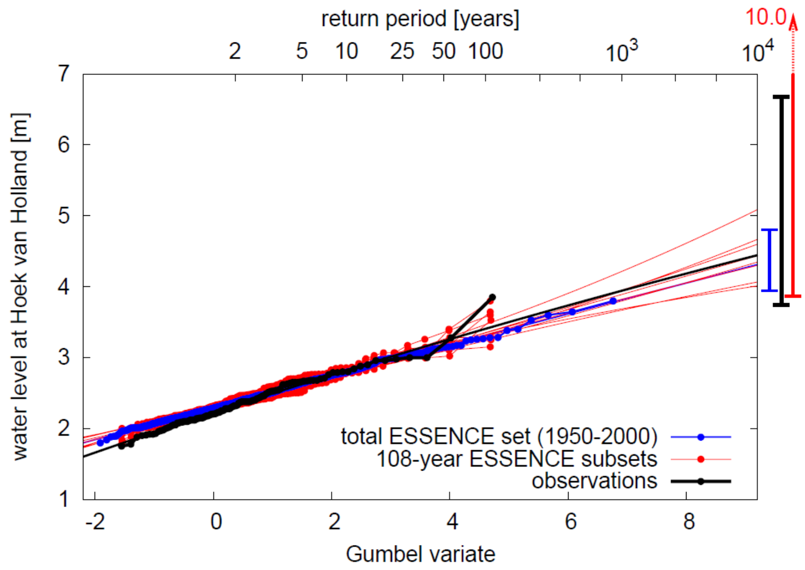


Figure 2.3: Storm surge frequency curve for current climate (Sterl et al., 2009).

2.1.2. Present river discharges in Rhine-Meuse delta

The river discharges from the Rhine and the Meuse are distributed over three main river segments as can be seen in Figure 2.4. For every river discharge of the Rhine at Lobith an estimation for the river discharge in the Meuse could be obtained. By combining the values of the river discharges of the Rhine and the Meuse, given the known distribution of river water in the eastern part of the Dutch rivers, the discharges in the Rhine-Meuse delta at Tiel, Hagestein and Lith, which correspond to the Waal, Lek and Meuse respectively, could be obtained.

It is clear that the distribution among the river sections changes as total discharges become larger. For small total discharges, the flow along Tiel comprises almost the total flow, hence almost all water flows through the Waal. On the right chart in Figure 2.4 the percentages of flow in each section compared to the total flow can be observed.

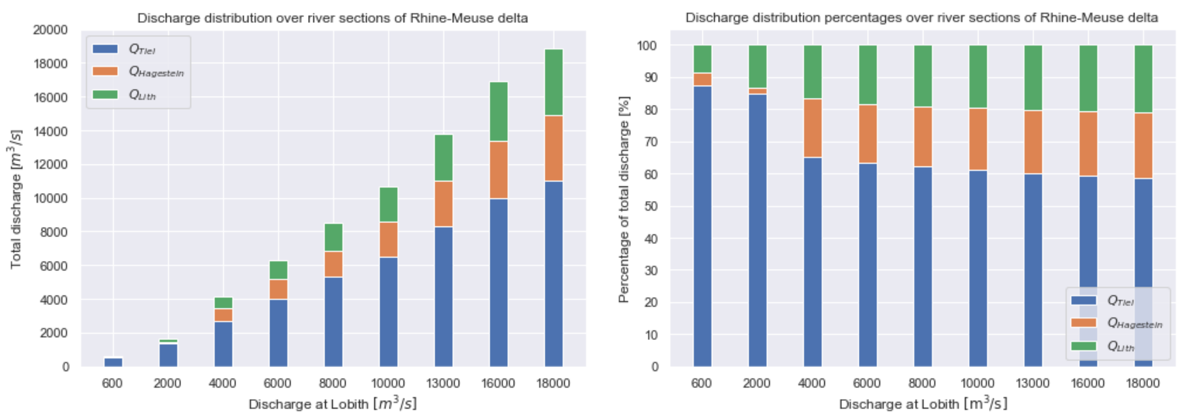


Figure 2.4: Discharge distribution in the Rhine-Meuse delta.

The mean discharge in the river Rhine at Lobith during a random year is about 2,200 m^3/s with lower flows during summer and higher flows in winter. During extreme circumstances such as intense rainfall and immense snow melt in the catchment area of the Rhine, the discharge can increase up to 16,000 m^3/s or more. These are however extreme circumstances that only occur once every so many years on average. In Figure 2.5 the current frequency curve of the discharge in the Rhine can be seen.

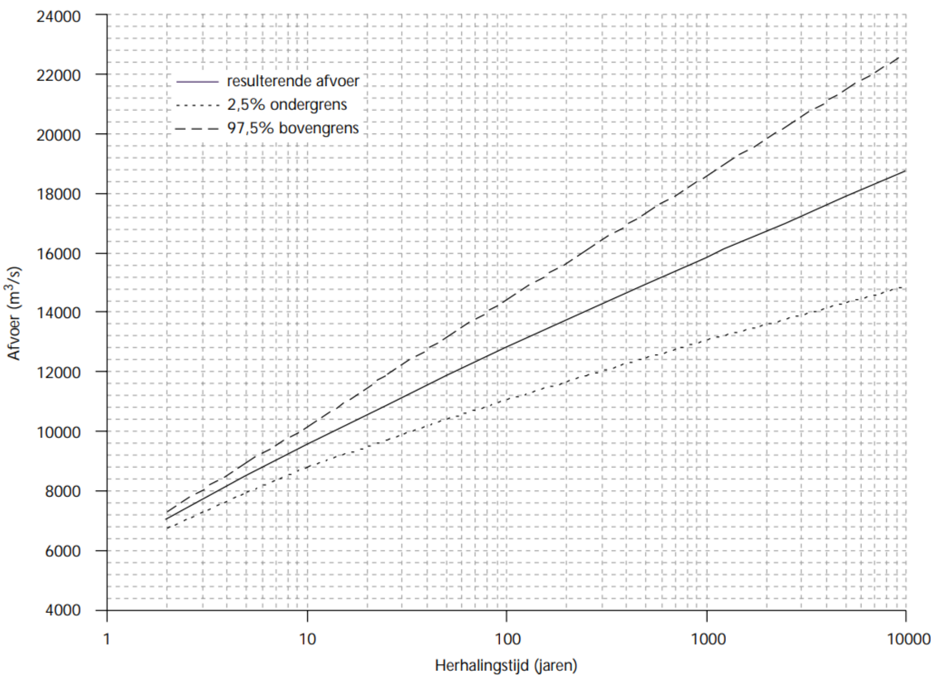


Figure 2.5: Present Rhine discharge frequency curve (Parmet et al., 2002)

2.2. Present operation, reliability and closure frequency limit Europoort barrier

2.2.1. Present operation Europoort barrier

The Europoort barrier's operation is based on both water levels at sea and river discharges in the Rhine. Currently, once a combination of these variables is expected to lead to water levels of NAP +2.9 m at Dordrecht or NAP +3.0 m at Rotterdam, a closure decision is made based on computations made by a one-dimensional flow model of the Rhine-Meuse delta. These critical water levels are called the closure decision level H_s. For the duration that this expectation holds, the barrier is in operation. The decision to whether the barrier is closed or opened depends on two other parameters: the closure level H_c and the critical Rhine flow Q_c. If the present flow in the Rhine is larger than Q_c and the water level at the barrier H_c, the barrier is closed. In case Q_c is not surpassed, but the water level at Hook of Holland is larger than the water level at Rotterdam, the barrier is also closed (Zhong et al., 2012). There are more operational steps in between and mechanisms such as partial opening to discharge water during low tide but these are the main mechanism by which the Europoort barrier is operated. In Figure 2.6 a schematic of the operational control of the Europoort barrier can be seen.

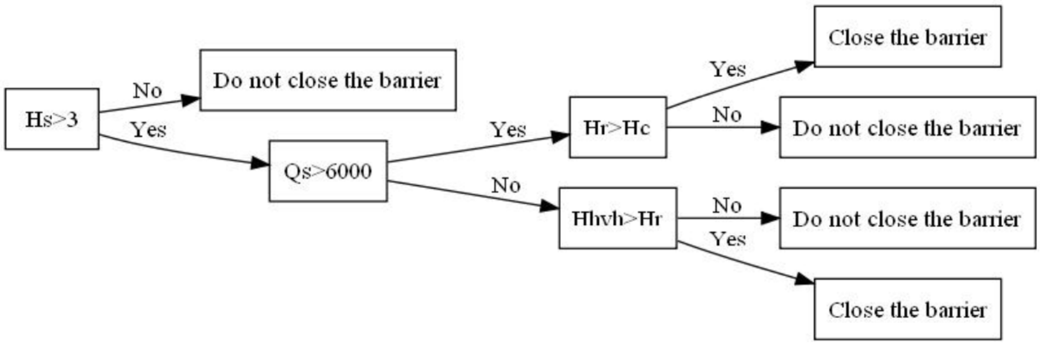


Figure 2.6: Operational control Europoort barrier (Zhong et al., 2012).

As one can observe, the Europoort barrier has two main closure types; regular closure and shifting closure (Dutch: 'kenteringsluiting'). Regular closure occurs for Rhine discharges smaller than the critical Rhine flow Q_c and shifting closure for Rhine discharges that are larger than that. The difference in these closure types is that for normal closure the Maeslant gates close horizontally, then are placed on the sill until the moment that water levels at sea are not large enough anymore that the water level at Dordrecht and Rotterdam exceed a certain limit. During shifting closure the barrier is lifted up during closure whenever water levels at sea are smaller than just upstream of the barrier. This is done to discharge as much river water as possible so that water level in the Nieuwe Waterweg does not rise too much. Additionally, the rising and lowering of the gate can only be done for very small flow velocities, because of the limitation to the horizontal forcing, hence the 'kentering' at the turn of the tide (Zhong et al., 2012).

The Europoort barrier control system receives forecasts for discharges in the Rhine and water levels at in the North Sea every 10 minutes for the next 24 hours. In order to assess whether the closure decision needs to be made, these two variables are combined to determine the resulting water level at Rotterdam and Dordrecht. The Decision and Supporting System (Dutch: 'Beslissings- en Ondersteuningssysteem (BOS)') of the barrier runs a one dimensional SOBEK Flow model of the Rhine-Meuse delta (Bol, 2005). Whenever the combination of the sea level at Hook of Holland and the Rhine discharge at Lobith exceeds the closure decision level H_s, the closure decision is taken and the operational control in Figure 2.6 is followed. As soon as the closure decision has been taken, it needs to be determined at what moment in time or at what hydraulic conditions the closure is started. As mentioned in Section 2.2.1, this decision is based on the closure level H_c and the critical Rhine discharge Q_{Rhine}. Q_{Rhine} is set as a flow that might not be able to be stored in the delta in case of a closure. The barrier can in this case not simply be closed in case the water level at Hook of Holland is higher than that in Rotterdam. Hence, there is a consideration between the obstruction of shipping due to a closure and the available storage in the delta for river discharge during closure. Currently, the critical Rhine flow at Lobith is set at 6,000 m^3/s and the closure level at NAP + 2.0 m.

2.2.2. Present reliability Europoort barrier

As mentioned in Section 1.2.1 the Europoort barrier is expected to not close once every 100 closures. For the present sea level and maximum Rhine discharge the barrier needs to be closed every 10 years on average and therefore during a random year the barrier has a probability of non-closure equal to $\frac{1}{1000}$ (Vrancken et al., 2008). The same goes for the opening of the barrier, as also this probability is equal to $\frac{1}{1000}$. As concluded in Botterhuis et al. (2012), the inclusion of partial failure into the fault tree of the Europoort barrier does not give significant difference in water levels at Dordrecht, so these are not assessed in this report.

As the sea level is going to rise in the remainder of the 21st century, the closure rate of the Europoort barrier is going to rise, leading to a larger probability of non-closure and non-opening. The exact value however, depends largely on the specific operation for the corresponding climate projection.

2.2.3. Present closure frequency limit Europoort barrier

Additionally to the probabilities of failure, there is also a limit to the closure frequency of the barrier. Presently the closure frequency of the Europoort barrier is equal to $\frac{1}{10}$ year^{-1}, but in the future this may rise because of sea level rise. Due to mechanical issues, it is currently accepted that the closure frequency of the Europoort barrier may not exceed the limit of 3 $year^{-1}$ (Van Waveren, H., personal communication, October 26 2020). If the closure frequency exceeds this value, mechanical issues start to arise and failure rates might go up significantly. This frequency is based on the current operation with ordinary and shifting closure (Dutch: 'kenteringsluiting').

Each year the barrier needs to be out of service for about 5 to 6 months for maintenance work. This is done in summers, because during this period the probability of storm surge and extreme Rhine discharge is much smaller than in winter (Rijkswaterstaat, 2020). For the present closure frequency of the barrier, this required maintenance period is not an issue, However, if the closure frequency were to rise, the probability that the barrier needs to be closed during this maintenance period is going to increase. This adds to the importance of a closure frequency limit, which is set at three times per year.

2.3. Setup of reference situation from present boundary conditions

This section analyzes the properties of the reference or current situation to compare any influences of climate change or a change to the flood protection system.

The reference situation is defined as a Rhine-Meuse delta with the present mean water level at sea, maximum discharge of the Rhine and operation of the Europoort barrier. Specifically this means that these three variables need to be defined.

2.3.1. Reference situation: Hydraulic boundary conditions

The sea level along the Dutch coast averaged over six coastal stations is situated at NAP + 6.3 cm in 2020 (Centraal Bureau voor de Statistiek, 2018). Furthermore, the maximum discharge of the Rhine at Lobith is set at 16,000 m^3/s. This neglects the fact that the discharge with a return period of 1,000 years is expected to be about 5 to 10% larger by 2050 compared to 2000 (see Section 2.4.3). This might mean that this discharge might already be larger by 2020, but this is not taken into account.

2.3.2. Reference situation: Europoort barrier

For the reference situation the current values for Q_{Rhine} and H_c as explained in Section 2.2.1 are used. This means that the critical Rhine flow is set at 6,000 m^3/s and the closure level at NAP +2.0 m.

The failure mechanisms mentioned in Section 2.2.2 are included in the reference situation so that the most important factors impacting the reliability of the Europoort barrier are assessed.

2.4. Future boundary conditions in the Rhine-Meuse delta

The Representative Concentration Pathway or RCP projections set by the Intergovernmental Panel on Climate Change (IPCC) are the most commonly used climate projections. Here the most frequently assessed pathways are RCP 2.6, 4.5, 6 and 8.5. These values relate to the possible radiative forcing values for the year 2100, which means that an increase in greenhouse gasses will lead to more radiative forcing and therefore an intenser change of global temperatures (IPCC, 2019). In Figure 2.7 one can observe the associated global surface warming for each of the RCP's.

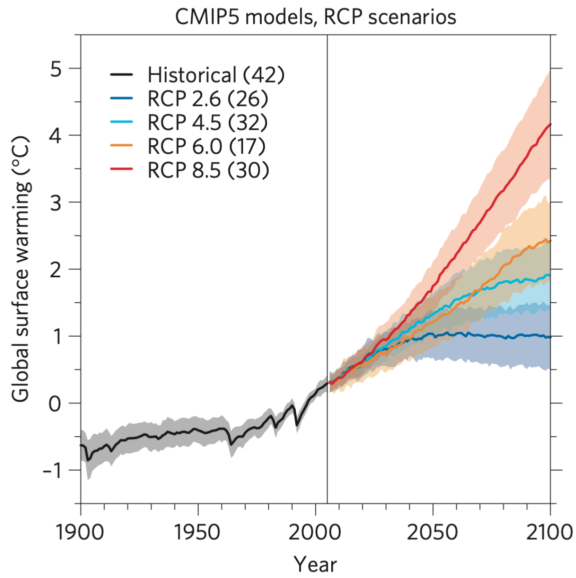


Figure 2.7: Global surface warming projections set by IPCC (Knutti and Sedláček, 2013)

In the Netherlands sometimes a different set of climate projections is used to assess climate change impact on flood protections. At the start of the new millennium a set of climate projections was created by the committee 'Water Management' or WB21 (Stumpe and Tielrooij, 2000). These projections were made to analyze whether the current flood protection program of The Netherlands was properly prepared for the coming century. For these climate projections a minimum, medium and maximum influence of climate change on the sea level and maximum discharge in the Rhine was defined. In this report also a minimum, medium and maximum scenario is created, but now based on the climate projections from Hinkel et al. (2019) and IPCC (2019).

2.4.1. Sea level rise

The climate projections as set by IPCC (2019) lead to varying values of global mean sea level rise. In Figure 2.8 below the likely ranges of sea level rise for each of the RCP's from Church et al. (2013) and Hinkel et al. (2019) can be found. These likely ranges represent the 17-83 percentile and therefore values outside this range are certainly possible, but unlikely.

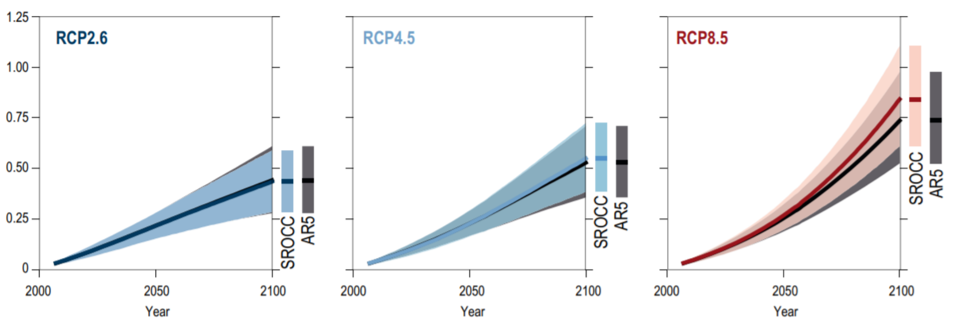


Figure 2.8: Time series of Global Mean Sea Level for RCP's 2.6, 4.5 and 8.5 (Hinkel et al., 2019)

According to Church et al. (2013), the possible rises in temperatures given in the RCP's will lead to a sea level at IJmuiden in 2100 that is between 0.20 and 1.05 meters higher than in the year 1990. This can be observed in Figure 2.9. However, from Figure 2.8 it can be concluded that the global sea level rise values found in Church et al. (2013) for RCP8.5 are slightly lower than the current models used for Hinkel et al. (2019) show. Hence, it is chosen to take the range of likely sea level rise values at IJmuiden for the year 2100 to be between

0.20 and 1.10 meters.

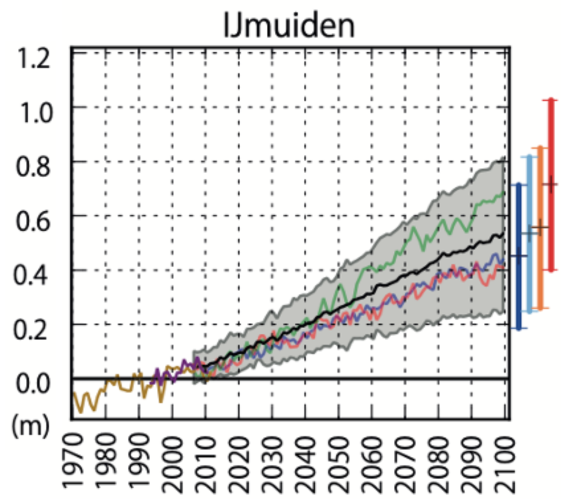


Figure 2.9: Sea level rise projections at IJmuiden relative to sea level in 2000 (Church et al., 2013).

It should be noted that a sea level rise of 0.20 meters at the Dutch coast means that no acceleration occurs up until 2100. Though this is the trend that has been observed for the past century as found by Baart et al. (2019), the probability that no acceleration of the sea level rise will occur in the next 80 years is deemed unlikely (Hinkel et al., 2019). The WB21 projections show similar sea level rises. The minimum and maximum sea level rise in 2100 is actually similar to that given by the RCP's. In Table 2.1 the projected values for the sea level rise at the Dutch coast for the year 2050 and 2100 compared to the year 2000 are summarized.

	Minimum	**Medium**	**Maximum**
2050	0.10 m	0.25 m	0.45 m
2100	0.20 m	0.60 m	1.10 m

Table 2.1: Sea-level rise projections along the coast of The Netherlands compared to the year 2000 (Hinkel et al., 2019)

As these projections are relative to the year 2000, already 20 years have passed since then. The sea level rise since 2000 needs therefore to be subtracted from the sea level rise projection of 2050 and 2100. According to (Centraal Bureau voor de Statistiek, 2018), the trend of the sea level at the Dutch coast has risen from a level of NAP + 2.5 cm in 2000 to NAP + 6.3 cm. This means that the estimated average rise of the sea level at the Dutch coast is 1.9 mm/year during the past century.

This rise of almost 4 cm over the past 20 years means that currently the actual sea level rise seems to follow the minimum projection as mentioned earlier. However, it should be noted that this seemingly linear trend probably does not hold for the coming decades and cannot be extrapolated without caution due to for instance the melting of the Greenland ice caps and the uncertainty of the many processes such as self-attraction and loading effects that are involved (Riva et al., 2017). Hence, it is wise not to discard the medium and maximum projections as these are very much viable sea level rises that might be reached due to an acceleration. As mentioned, the maximum sea level rise is also captured by the RCP's.

2.4.2. Storm surge level change

According to Sterl et al. (2009) storm surge heights at the Dutch coast are not expected to become larger for a changing climate. Currently, it is expected that only the intensity of south-western winds are going to increase. For north-western storms however, the wind speeds during storm events are not expected to change. Since these storms create the largest storm surges along the Dutch coast, the frequency curve for a changing climate is not going to change.

2.4.3. Increase of maximum Rhine discharge

As mentioned in Section 2.4, the maximum discharge in the Rhine is expected to become larger in the coming decades. Currently the return period for a discharge of 16,000 m^3/s at Lobith is 1000 years. For the near future (2050), there is a small tendency for this discharge to increase about 5 to 10 % and for 2100 this tendency to a higher discharge is estimated to be about 10 to 20 % (Görgen et al., 2010). The resulting maximum discharges in the river Rhine can be found in Table 2.2.

	Minimum	**Medium**	**Maximum**
2050	16,000 m^3/s	16,800 m^3/s	17,600 m^3/s
2100	16,000 m^3/s	17,600 m^3/s	19,200 m^3/s

Table 2.2: Maximum Rhine discharge projections (Stumpe and Tielrooij, 2000).

This increase of the maximum discharge in the Rhine at Lobith can be mainly attributed to higher temperatures (less water retained in the form of snow), more rainfall and a larger intensity of rainfall. Additionally, the maximum amount of water being able to flow through the Rhine at Lobith also depends largely on the flood protection measures undertaken in Germany. If the dikes at the other side of the border overflow this diminishes the downstream discharge, namely at Lobith (Görgen et al., 2010).

According to De Vriend et al. (2016), the maximum discharge of the Rhine at Lobith is limited to around 17,500 m^3/s. However, this is based on the assumption that the current German philosophy of reducing flooding consequences instead of dike reinforcements is going to stay the same in the coming decades. If it is decided to heighten the flood defenses of the German Rhine branches, the maximum Rhine discharge can become larger than 17,500 m^3/s. Hence, it is decided to keep Q_{1000} of the maximum projection equal to 19,200 m^3/s to account for such changes.

2.5. Setup of scenarios from future boundary conditions

This section sets up the scenarios that need to be examined in order to create an overview of the flood risk at the flood prone areas not protected by flood defenses at Dordrecht for different possible situations. These scenarios are set up using the climate projections given in Section 2.4.

The created scenarios are based on a projection for the year 2100. This is done, because most climate projections are based on this horizon. There are already many uncertainties for the sea level and discharge in the Rhine for this year and extrapolating any further does not give much more insight.

2.5.1. Scenarios: Hydraulic boundary conditions

This subsection discusses the various hydraulic boundary conditions for the scenarios. These conditions are based on the climate projections given in Section 2.4. The main conditions are the absolute sea level rise and the increase of high river discharges in the Rhine.

A set of three different sea level rise values is taken as the basis for the scenarios. To keep matters simple, the sea level rise in 2100 for the minimum, medium and maximum scenario are taken as the three scenarios to be assessed in this report. Regarding the RCP's this means that the lower bound of RCP 2.6 scenario and the upper bound of the RCP 8.5 scenarios are used (IPCC, 2019). The sea level rise of 0.60 meters falls within the uncertainty bands of all the RCP's and is therefore a more likely sea level rise than the lower and upper bound.

A set of two different maximum discharges of the Rhine are assessed. These are the values for the medium and the maximum scenario given by (Stumpe and Tielrooij, 2000) for 2100. Regarding the modeling of these scenarios this practically means that simply the probabilities of occurrence for the standard set of high river discharges are adapted accordingly.

2.5.2. Scenarios: Europoort barrier operation

The Europoort barrier can be chosen to operate as normal, the closure levels can be changed to attain the present Europoort closure frequency. Also it can be chosen to permanently close the barrier in case of a very large sea-level rise. As mentioned in Paragraph 1.2.1 this plan is called Plan Locks (Dutch: 'Plan Sluizen').

Two scenarios are examined for the operation of the Europoort barrier. The first one is a situation in which the current operation and reliability of the Europoort barrier are taken. This means a scenario with a closure decision level H_s of NAP + 3.0 m at Rotterdam and NAP + 2.9 m at Dordrecht and a critical Rhine discharge of 6,000 m^3/s. Additionally, the reliability of the barrier is kept equal to that of the reference situation.

For the second scenario Plan Locks is implemented. As discussed in Section 1.2.1 this means that the Europoort barrier is permanently closed and shipping can navigate to and from the Nieuwe Waterweg via locks in the Nieuwe and Oude Maas. Model outcomes can be obtained from Stijnen and Botterhuis (2015a). The minimum, medium and maximum scenarios of this research are however defined somewhat differently than in this report. The sea level rise values that are assessed are 0.07, 0.35 and 0.85 meters and the Rhine discharges with a return period of 1,000 years are 16,000, 17,000 and 18,000 m^3/s respectively.

In Stijnen and Botterhuis (2015a) Plan Locks allows for a negligible failure of closure probability of about 10^{-6} per closure attempt during high-water. So if a set of locks and doors were to be constructed, almost never a free passage of water from sea into the Nieuwe Waterweg would occur. Furthermore, the locks are constructed in the Oude and Nieuwe Maas with the addition of a pumping station that is able to discharge 1,000 m^3/s at the Oude Maas and 2,000 m^3/s at the Nieuwe Maas. Lastly the Volkerak locks are permanently opened and the Krammer locks connecting the Volkerak to the Oosterschelde are able make use of the Oosterschelde as extra water retaining area. To use the Oosterschelde for this purpose, the closing regime of the Oosterschelde barrier is changed and it is made sure that less water leaks through the cracks of the gates.

2.5.3. Overview reference situation and scenarios

To summarize, a reference situation and a set of scenarios is created that is used to assess what the influence of climate projections are on the flood risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht Dordrecht in Chapter 3. In Chapter 5 the same reference situation and scenarios are used to assess the influence of the addition of Delta21 to the flood protection system of the Rhine-Meuse delta. In Table 2.3 the boundary conditions of the current flood protection system for the reference situation and the scenarios of the year 2100 can be found.

	Reference situation	**Minimum**	**Medium**	**Maximum**
Mean sea level [m + NAP]	0.06	0.20	0.60	1.10
Maximum Rhine discharge [m^3/s]	16,000	16,000	17,600	19,200
Probability of failure [-]	10^{-2}	10^{-2}	10^{-2}	10^{-2}

Table 2.3: Boundary conditions current flood protection system for reference situation and scenarios of the year 2100

The scenarios used for the calculation of Plan Locks Van Waveren et al. (2015) can be found in Table 2.4 below. The minimum scenario is the present situation and the medium and maximum scenario are scenarios for the year 2100.

	Minimum	**Medium**	**Maximum**
Mean sea level [m + NAP]	0.07	0.35	0.85
Maximum Rhine discharge [m^3/s]	16,000	17,000	18,000
Probability of failure [-]	10^{-6}	10^{-6}	10^{-6}

Table 2.4: Boundary conditions Plan Locks for scenarios of the year 2100

3

Flood risk flood prone areas at Island of Dordrecht without the Delta21 project

This chapter aims to create an overview of the flood risk at the flood prone areas not protected by flood defenses of the Island of Dordrecht for the reference situation and the scenarios that have been set up in Chapter 2. This is done for both the current flood protection system without the Delta21 project and Plan Locks. First the flood risk calculation method is explained in Section 3.1, then an inventory of the flooding consequences is made in Section 3.2, after this the high-water modeling of the current flood protection system is explained in Section 3.3, then the computed present and future high-water levels are given in Section 3.4, subsequently the computed present and future flood risk is presented in Section 3.5 and finally some concluding remarks are made and presented in Section 3.6.

3.1. Flood risk calculation method for flood prone areas not protected by flood defenses

3.1.1. Flood risk definition

Flood risk can be described by the expected damages per year or average annual value at risk (R). This value at risk is defined as the annual frequency of an event times the consequences of the event. For the specified case of flood risk, the annual frequency is the annual frequency of a flood event and the consequences are damages (direct and indirect) and loss of life.

The average annual frequency of a flood event and the consequences of such a flood event can be combined to create the average annual value at risk as can be seen in Equation 3.1.

$$R = \int_{f_{min}}^{f_{max}} D(f) \cdot df \tag{3.1}$$

Where:

R - average annual value at risk [€/year]

f - average annual frequency of flood event [year^{-1}]

$D(f)$ - consequences of flooding event as function of annual frequency [€]

The average annual value at risk or annual flood risk is the average amount of money that is at risk during a random year. As there is a discrete number of flood events that is evaluated in this report, the total annual flood risk can be calculated using Equation 3.2. The assumption here is that the damages for flood event i are the same as for event $i-1$. This means that there is a small underestimation of the total flood risk for this method. This underestimation can be reduced to be marginal by reducing the step size of the event frequency.

$$R = \sum_{i+1}^{N} (f_i - f_{i-1}) \cdot D_i \tag{3.2}$$

Where:

R - annual value at risk [€/year]

f_i - annual frequency of flood event i [year^{-1}]

D_i - consequences of flooding event i [€]

In this report the annual flood risk is the same as the average annual value at risk (R) or the annually expected damages. These terms are used interchangeably. To determine the average annual value at risk, the frequencies of certain flood events need to be determined as well as the consequences of these events.

For the flood prone areas not protected by flood defenses at the Island of Dordrecht only flood depths were used to assess the potential consequences of the flood event. During the flooding of these flood prone areas typically no breaching event occurs. Hence, these areas flood very gradually. A gradual flood means that the rising velocity of the water is almost negligible and hence the horizontal flows that occur during flooding are also very small. Waves that are generated on the river body due to the high wind velocities were not taken into account for the flood risk assessment method as high waves are not able to intrude onto the flooded land, because of the small water depths.

3.1.2. Inventory of consequence types

For flood prone areas not protected by flood defenses specifically, potential loss of life was not accounted for in the flood risk determination. The reason for this was that high water levels can be predicted days ahead and therefore these areas can be evacuated well in time (Huizinga et al., 2011). Additionally, due to the low flow velocities, potential loss of life is limited even if proper evacuation has not been met (Jonkman, 2007). Hence, only damages were assessed for the flood risk assessment of the flood prone areas not protected by flood defenses.

The damages due to flooding of the flood prone areas not protected by flood defenses can be divided into two categories: direct and indirect damages. Direct damages can be described as loss of value and the indirect damages as loss of revenue due to a flooding event. Such a loss of value or revenue could be economical, cultural, environmental and societal. For flooding of flood prone areas not protected by flood defenses, the indirect damages or a loss of revenue due to a halt to economic activity is largely dependent on the region type, local infrastructure and preventive measures (Nicolai et al., 2016). As is illustrated in Ledden and Visch (2016), the flood damages of an industrial area such as the Botlek become more dominated by the indirect damages for extremer situations. For the Botlek specifically the indirect flood damages are about 10 % of the total damages for a return period of 1,000 years, but rise to 90 % for at 10,000 years. In this report however, the indirect damages are not quantified for the flood risk calculations. Because of this, in this report, it should be noted that the found damages at the industrial areas of the Island of Dordrecht might be underestimated. However, for the average annual value at risk, extreme events with a return period of 10,000 years have only a small contribution. Hence, the underestimation of the flood risk should be limited.

In this report it is assumed that the present investment level and value apply to the future situation in the year 2100, which is the same approach as followed in Nicolai et al. (2016).

3.1.3. Frequency of occurrence of flooding events

The frequency of occurrence of a flooding event is defined as the number of occurrences in a random year. This means that a certain water level with an average frequency of occurrence of 10^{-2} year^{-1} occurs on average once every 100 years. By combining a multitude of (hydraulic) boundary conditions and calculating water levels at the Island of Dordrecht, an overview can be found of water levels at the Island of Dordrecht and the corresponding frequencies of occurrence. More on this method can be found in Appendix B.

3.2. Inventory of flooding consequences

3.2.1. Functional analysis flood prone areas not protected by flood defenses

The flood prone areas not protected by flood defenses at Dordrecht can be divided into several regions based on their functions and land-uses. From Van Herk et al. (2011) the following regions have been defined: the historical harbor, the flanks and the Biesbosch. Where those regions are located can be found in Figure 1.4.

Historical harbor

The historical harbor area is one of the most well-known areas of the city of Dordrecht. Many monumental and historical buildings are situated in this area and therefore potential damages are relatively high compared to other residential areas in the city when comparing their sizes. Because the region is relatively small, also the number of inhabitants is limited. After the Biesbosch it is also the most low-lying part of the flood prone areas not protected by flood defenses on the Island of Dordrecht. As mentioned, a large portion of the potential damages to due flooding of the flood prone areas not protected by flood defenses may be attributed to this region.

Flanks

The flanks comprise a much larger portion of the island and are also largely build upon with residential areas and industry. This region is located at larger elevations than the historical harbor and is therefore better protected against flooding. The flanks are home to many high-value objects, but most of these are situated at large elevations above NAP + 3.5 m. This means that only during very extreme storm events of return periods in the order of 10,000 years flooding of these areas might take place. However, in the future these events might become less extreme. There are also some parts of the flanks that are located at smaller elevations that are flooded in less extreme events. Such parts contain residential areas as well as some industry (Van Herk et al., 2014).

Biesbosch

The last and largest portion of the Island of Dordrecht that is not protected by flood defenses is the Biesbosch. The Biesbosch is almost entirely Natura 2000 and in addition to serving as a nature reserve, a few old polders have been transformed into drinking water reserves. These are however not situated on the Island of Dordrecht, but at the Brabantse Biesbosch situated on the south side of the Nieuwe Merwede. As mentioned, the part of the Biesbosch on the Island of Dordrecht is almost entirely Natura 2000 area with the exception of some residential neighborhoods and industry at the second Merwede harbor. According to Wouters et al. (2015) such nature areas are quite resistant against occasional flooding, as long the duration of the flood is not too long, low flow velocities are present and the flood does not occur not during the growing season. Additionally, the flood event should not bring in any additional nutrients that can disturb the survival of local species. As long as the future flooding frequencies of the Biesbosch do not increase significantly and rapidly, most species in the area are most likely going to be able to adjust (Wouters et al., 2015).

3.2.2. Land subsidence at Island of Dordrecht

The land in the western part of the Netherlands subsides, because the soil consists largely of clay and peat. These materials are compressed and oxidize when they rise above the groundwater table. Especially in polder areas this is a large problem that is of large influence on the flood risk. In such areas the groundwater table is kept artificially low in favor of for instance agriculture (Halsema and Kooij, 1996).

By definition, flood prone areas not protected by flood defenses are not polders. Therefore, the groundwater table in these areas is not managed artificially. However, land subsidence can still be a real issue here because the clay and peat layers can still consolidate by for instance heavy loading of the soil due to construction (Halsema and Kooij, 1996).

From Figure 3.1 it is obvious that there is quite some deviation in land subsidence over these different parts of the flood prone areas at the Island of Dordrecht. It is however obvious that for the largest portion of the land is subsiding instead of rising.

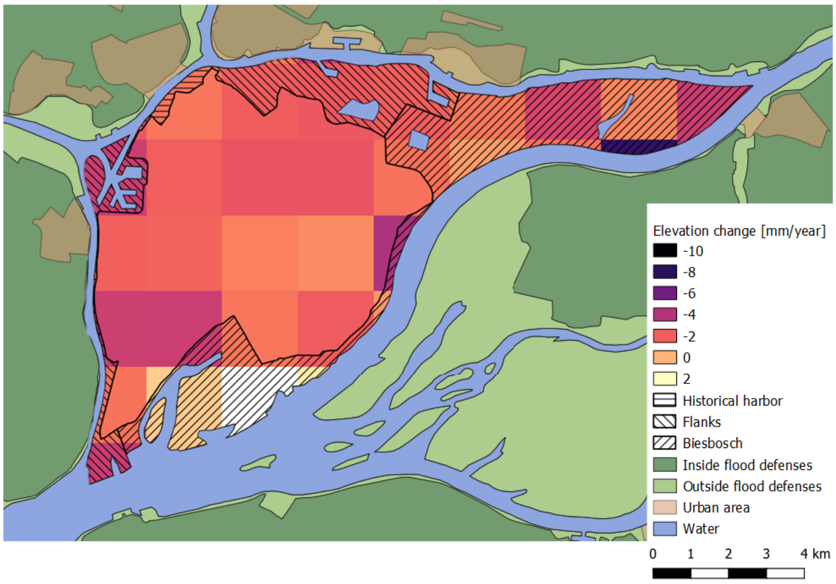


Figure 3.1: Land subsidence (negative change in elevation) at the Island of Dordrecht (NCG, 2020)

A distinction is made between the three regions of the flood prone areas not protected by flood defenses. By doing so, an average land subsidence for each of these sections is found. These values can be found in Table 3.1.

	Land subsidence (mm/y)
Historical harbor	1
Flanks	4
Biesbosch	1

Table 3.1: Land subsidence per region of flood prone areas not protected by flood defenses

All together this means that these land subsidence values need to be accounted for in order to assess the scenarios set in Section 2.5. As these scenarios are based on the year 2100, the annual land subsidence rates need to be multiplied by 80 years. Here it is assumed that the rate of subsidence stays constant over the coming decades. Accounting for land subsidence means that by 2100 the elevations of the Island of Dordrecht can be significantly different from those in 2020. It is assumed that for each flood prone region not protected by flood defenses, the land subsidence rate is unique and uniform.

3.2.3. Flood damage profiles

The damage types were identified for each of the functionalities of the flood prone areas not protected by flood defenses, i.e. economic, social, societal and cultural damages (Huizinga et al., 2011). An overview was created with the potential damages in Euros for each flood depth.

For every water level around the Island of Dordrecht the potential flood damages were assessed. This was done by creating an elevation map of the flood prone areas not protected by flood defenses as can be found in Figure 1.6 and applying a certain flood depth on it. These flood depths were linked to the various land uses of the flood prone areas not protected by flood defenses and their corresponding damage functions. Here, a higher flood depth for a certain land-use means more damage. In the program SSM-2017 the flood depth map and all the different land-use maps were overlapped to find the total flood damage. This process is explained in more detail in Appendix A.

In Figure 3.2 one can see the total damage profile of the flood prone areas not protected by flood defenses at the Island of Dordrecht for every region. Here, a range of water levels from NAP + 2.0 m to + 3.6 m was taken. A maximum of NAP + 3.6 m was chosen, because after this the flood damage curves start to show a linear behavior on a semi-log scale and the relative damage per category does not change anymore. Assessing water levels larger than NAP + 3.6 m did not give any more information as at this point a clear mathematical extrapolation is possible. This means that the flood damages given in blue in Figure 3.2 are for the present terrain elevations of the Island of Dordrecht and due to land subsidence the graph of the future terrain elevation shifts slightly leading to the orange graphs.

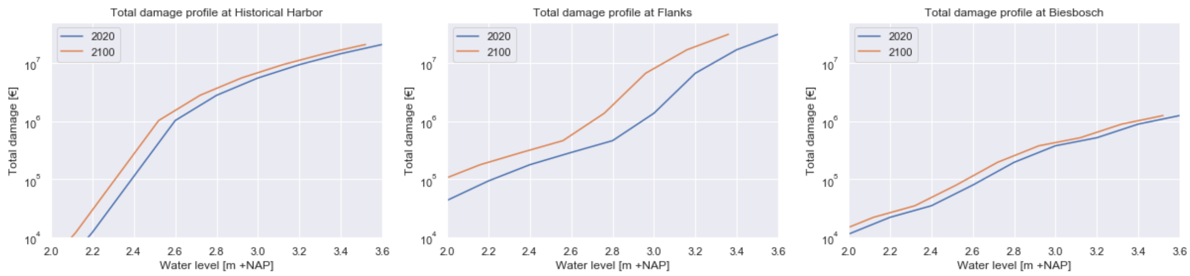


Figure 3.2: Damage profiles for every flood prone region not protected by flood defenses for the year 2020 and 2100

The most obvious conclusions that can be taken from Figure 3.2 is that the potential damages at the Biesbosch is much smaller than at the historical harbor and the flanks, just as predicted in Section 3.2.1. Furthermore, one can see that due to the high land subsidence rate at the flanks, the damage profile for the year 2100 for this region differs much more than at the historical harbor and the Biesbosch. This development by itself can already mean a significant increase in this region's flood risk.

The total damages can be divided into four main damage types: companies, infrastructure, residences and other. It is important to know to which category the damages fall into, since residents and companies of the flood prone areas not protected by flood defenses are responsible for damages to their own property, but not for the local infrastructure for instance. The damage types that make up the total damage profile can be observed in Figure 3.3. In Appendix A one can find a complete overview of all the sub-categories that are assessed. The damages per category for the year 2100 are not included to make Figure 3.3 more clear. Essentially, just as Figure 3.2 the curves are shifted 80 years of land subsidence to the left.

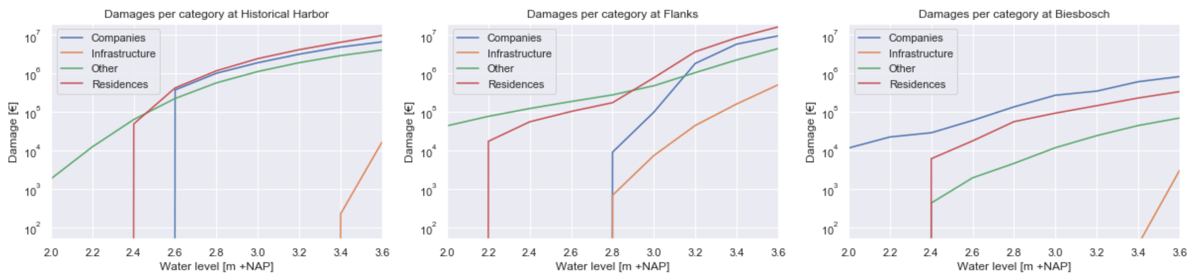


Figure 3.3: Flood damages per category for every region for the year 2020

Interesting to see is that for each of the regions the contribution of the damage categories varies largely. For water levels higher than NAP + 3.0 m the contributions of damages to companies, residences and other seem to converge. For small water levels not all damage categories contribute to the total damages. For instance, houses located in the historical harbor are not damaged for water levels lower than NAP + 2.4 m and companies do not experience damages due to flooding up until the water level exceeds NAP + 2.6 m. These values are different for the flanks and the Biesbosch. These variations make it even more logical that for a fair assessment of the flood risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht, the three regions need a separate examination.

It should be noted that these damage profiles assess only flood prone areas not protected by flood defenses at the Island of Dordrecht and any damages that may occur for the same water levels inside the flood defenses are not accounted for in Figures 3.2 and 3.3.

3.2.4. Indirect flooding consequences

According to experts regarding flood safety at the municipality of Dordrecht, the indirect consequences due to flooding of flood prone areas not protected by flood defenses are also of importance rather than just the direct flood damages (Gersonius, B., personal communication, September 7 2020). Mainly the historical harbor is a region of the city that is regarded as essential regarding indirect flooding consequences. Currently some streets in the historical harbor experience minor flooding every 2 years on average. As can be seen in Figure 3.4, the water level that belongs to this frequency is about NAP + 2.0 m. Inhabitants are urged to remove cars and sand bags are facilitated to prevent houses from being flooded. If flooding frequencies were to rise much more in the coming decades, such measures might decrease the living standard of the area and current residents might move away. Such a migration away from the historical harbor area would mean that the value of the houses decreases. In that case new residents with smaller financial means might not be able to take care of the culturally valuable houses in the historic heart of the city. Hence, an increase in flooding frequencies at the historical harbor could decrease the overall historical and cultural value of the city of Dordrecht.

It is hard to quantify such possible future negative developments. Such developments are dependent on many variables such as the housing market, economic developments and public perception of flooding frequencies. These variables are very uncertain for the present situation, which means that it is next to impossible to predict them for the year 2100. Hence, the indirect consequences due to flooding are not quantified as mentioned in Section 3.1.2, but they are taken into account for the optimization of the use of Delta21.

The consequences can be qualitatively predicted with the quantification of the frequency of flooding. As can be seen in Figure 1.6, the quay levels at the historical harbor have an elevation between NAP + 1.7 m and + 2.5 m. This means that from water levels at NAP + 2.5 m almost all of the region is flooded. This level is therefore also often regarded as a critical water level that should not be exceeded too often. At this water level almost all of the historical harbor is flooded and real damages to historical buildings and household effects start to take place (Heinen, R., personal communication, September 23 2020). If this value is exceeded too often, this may negatively impact the value of the region and is therefore considered an indirect consequence.

3.2.5. Maximum allowable flood risk and frequencies

There are two criteria that are used to assess the flood risk and frequency of the flood prone areas not protected by flood defenses at the Island of Dordrecht:

- **Percentage of annual value at risk compared to the income per household**
  The annual value at risk of the flood prone areas not protected by flood defenses can be divided into risk per region. This risk can then be compared to the annual income per household to assess the significance of the value at risk. The annual value at risk compared to the average annual income per household at the historical harbor is a specification within the total flood risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht. The maximum of this specification is based on the analogy with the Dutch average healthcare premium in the year 2020, which is equal to about €1440 per year with an excess deductible (Dutch: 'eigen risico') of €385 (Koenraadt, 2020). By dividing the healthcare premium by the income per household, one can find that a household at the flood prone areas not protected by flood defenses at the Island of Dordrecht spends about 1 % of its annual income on its healthcare premiums. Since a premium of 1 % of the annual income is a reasonable amount for households to pay, this same premium can be set for flood risk as well. Hence, the critical value of flood risk per household is set at a 1 % limit.

- **Flood frequency (water level > NAP + 2.5 m) at the historical harbor**
  As mentioned in Section 3.2.4, a water level larger than NAP + 2.5 m is regarded as a critical value. Hence, it is important to evaluate the frequency at which this water level is exceeded. This limit is set at 1 year^{-1} to make it a graspable value that can be communicated easily.

3.3. High water modeling of current flood protection system

3.3.1. High water modeling method

As mentioned in Section 3.1.1, the probability of occurrence of different magnitudes of flooding needed to be determined. This meant that the water level frequency curves at the Island of Dordrecht had to be found. This was done using the program Normative High Water processor (MHWp5) in combination with the program Hydra. MHWp5 runs a SOBEK 1D flow model of the Rhine-Meuse delta for a combination of hydraulic boundary conditions and failure states of the Europoort barrier. The outcomes of this model are water levels for the specified computation period. Hydra uses the known probabilities of occurrence and correlations of the hydraulic boundary conditions and failure states to find a probability of occurrence of each of the computed water levels at the Island of Dordrecht. In Appendix B a more elaborate explanation of the way these programs work and how they intertwine is described.

3.3.2. High-water modeling uncertainties

The goal of using a high water modeling program such as MHWp5 is to accurately forecast hydraulic conditions with a small probability of occurrence. Some of these extreme weather events have never happened and any attempts to predict such events are bound to be imprecise to some extend. As an example, Figure 2.3 can be taken. The largest storm to be recorded is the one with a return period of 100 years, namely the storm surge of 1953. It can be observed that the water level of this event is about 0.3 meters higher than what marginal distribution functions of the sea level at Hook of Holland currently expect it to be. As such distributions are used to calculate the probability of occurrence of each of the events modeled in MHWp5, this distribution uncertainty definitely impacts the accuracy of the model. These uncertainties are dealt with partly by adding an uncertainty margin obtained by using the confidence margins of marginal extreme value distributions and testing the sensitivity of the high water results to some parameters and variables.

There are several other types of uncertainty that have to be noted to correctly interpret the outcomes given in this chapter. A couple of the more notable ones are as follows:

- **Schematization uncertainties**
  Schematization uncertainties are errors that are created by simplifying a three dimensional system such as the Rhine-Meuse delta as a one dimensional model. In reality, flow in the river branches is in all directions with in- and out fluxes all over and ever-changing river cross-sections. To simplify the situation and reduce computational times significantly, the real life situation has been simplified as a one dimensional model without continuously changing characteristics. This imposes some differentiation from the real-life situation, hence the schematization uncertainty.

- **Model uncertainties**
  Model uncertainties are uncertainties that are imposed by model parameters that are derived from empirical relations with observations and any errors that are resultant from numerical schemes used to solve the shallow water equations. An example of errors imposed by model parameters is the bed friction coefficient that is calibrated for a certain range of water depths and locations in the computational grid. This value actually differs for every location, but it is kept uniform, creating errors along the grid. The numerical scheme used in D-Flow1D is the Delft scheme, which is robust so that it does not create unstable results. However, just like every numerical scheme, it has a certain deviation from the analytical solution. This error is dependent on the time and spatial step of the model. But as these steps cannot be too small so that the computational time does not increase too much, the error that is imposed is not negligible.

- **Forecast uncertainties**
  As mentioned earlier in this section, there is a difference between the real-life occurrence of certain extreme events and the expectation derived from extreme value analyses. This is called forecast uncertainties. As an example the water level at Hook of Holland was given, but other variables that are prone to a deviation from their forecast value. The Rhine discharge, storm duration and failure probability of the Europoort barrier are some of the more notable ones in this report. A deviation of the real-life value

from the modeled value can significantly change the outcome of the high water modeling results.

- **Calibration and validation uncertainties**
The D-Flow1D model of the Rhine-Meuse delta as used by the MHWp5 software is calibrated and validated to the WBI database, since this is currently the legal instrument to test the Dutch flood defenses. This calibration of the D-Flow1D model of the Rhine-Meuse delta is therefore done for the normative high-water levels at numerous locations in the delta. This is shown in the validation plots of Appendix B, where the discrepancies between the WBI database and the MHWp5 model are minimal and in the order of 0.05 meters for return periods in the order of 1,000 years. Since the model is calibrated for such normative return periods, using the same model for high-water calculations for flood prone areas not protected by flood defenses can lead to underestimations for very small (10 years) and very large (100,000 years) return periods in the order of 0.10 m.

It can be concluded that the uncertainties as listed above should be taken into account when interpreting the flood risk and flood frequency outcomes of this report. High-water levels at the Island of Dordrecht can be predicted with a reasonable accuracy, but with an uncertainty in the order of a few decimeters.

3.4. Computed present and future high-water levels

The water level frequency curves for the reference situation have been created from the high water modeling results created by the MHWp5 model. These frequency curves can be found in Figure 3.4.

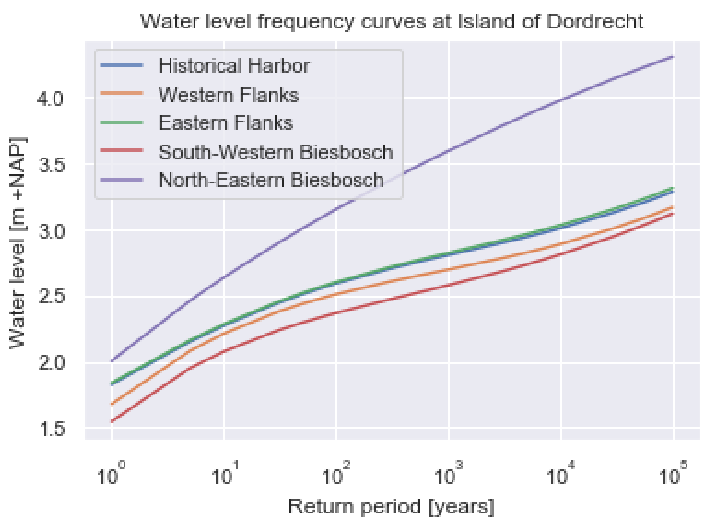


Figure 3.4: Reference situation: Frequency curves of water levels at Island of Dordrecht

It is apparent that the water level frequency curves for most (sub-)regions show a similar shape, whereas the north-eastern Biesbosch curve is shaped differently. This can be explained as the observation point linked to this sub-region is located further upstream where the water level is dominated by river discharges. This differs from the other curves that show a mixed influence of sea and river water levels.

On the left side of Figure 3.5 the water level frequency curve envelopes of the scenarios with the current flood protection system can be found. For all (sub-)regions the range of water levels for the year 2100 are shown. As one can observe, the possible range of future water levels is quite large with difference between the minimum and maximum water level at a specific return period of about 1.0 to 1.5 meters. The largest part of this uncertainty comes from the sea level rise value. The solid lines that run through the middle of the envelopes are the medium scenarios that have been described in Section 2.5. The lower bound of the uncertainty band can be associated with the minimum scenario and the upper bound of the uncertainty band with the maximum scenario.

The occurrence of high-water at the Island of Dordrecht is also assessed for the flood protection system with the implementation of Plan Locks. The water level frequency curves of Plan Locks can be seen on the right side of Figure 3.5. As can be observed, the differences in water levels are quite large and especially the water levels for the more western regions are affected largely. Also, the shape of the frequency curves of all regions is more similar to that of the North-Eastern Biesbosch, i.e. river discharge dominated. Additionally, the range of water levels created by the scenarios is quite a bit smaller for Plan Locks than for the current flood protection system. The sea level rise and maximum Rhine discharge values used for Plan Locks can be found in Section 2.5.3.

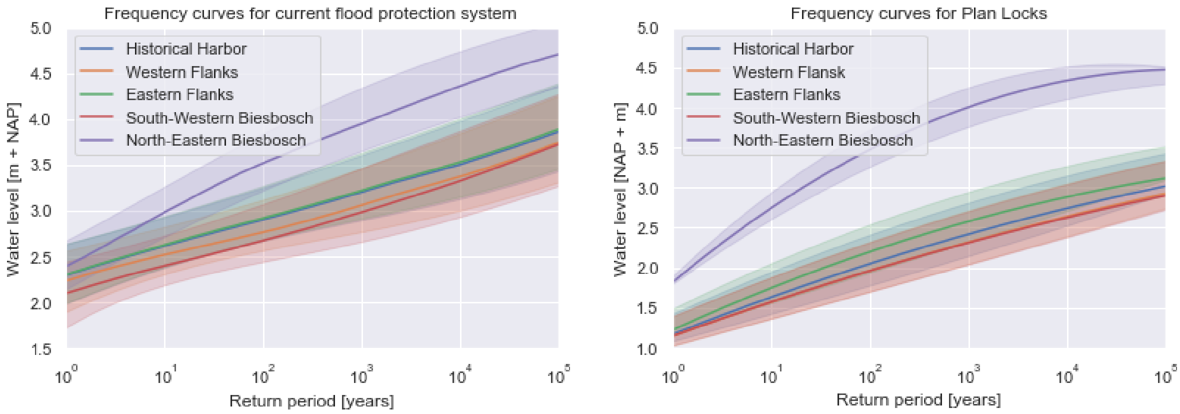


Figure 3.5: Scenarios: Current flood protection system frequency curves envelopes of water levels in 2100

From the graphs in Figure 3.5 the flooding frequency of the historical harbor can be found. As explained in Section 3.2.5, the water level at Dordrecht may not exceed NAP + 2.5 m more than once per year. Hence, for both the current flood protection system and Plan Locks the flood frequencies for each of the scenarios can be found in Table 3.2. Note that the scenarios of the current flood protection system and Plan Locks are not the same. However, Table 3.2 does give an insight into the completely different order of magnitude of the flood frequencies at the historical harbor.

	Present	**Minimum [year^{-1}]**	**Medium [year^{-1}]**	**Maximum [year^{-1}]**
Current system	0.05	0.07	0.3	3
Plan Locks	$8 \cdot 10^{-5}$	10^{-4}	$5 \cdot 10^{-4}$	$7 \cdot 10^{-3}$

Table 3.2: Flood frequency at historical harbor (water level > NAP + 2.5 m)

3.5. Computed present and future flood risk

In this chapter research step two is elaborated. The flood risk for the reference situation and the scenarios was determined by combining the probabilities of certain water levels with the damage corresponding with those same water levels. More information on the method and more elaborate results can be found in Appendix C.

3.5.1. Flood risk reference situation

Combining the water level frequency curves from Figure 3.4 with the current damage profiles from Figure 3.2 lead to the flood risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht for the reference situation. This flood risk was split up for the three regions of flood prone areas. This means that the flood risk for the western flanks and the eastern flanks has been calculated separately and combined as a final step. The same process has been undertaken for the south-western and north-eastern Biesbosch. The flood risk curves for the reference situation can be found in Figure 3.6.

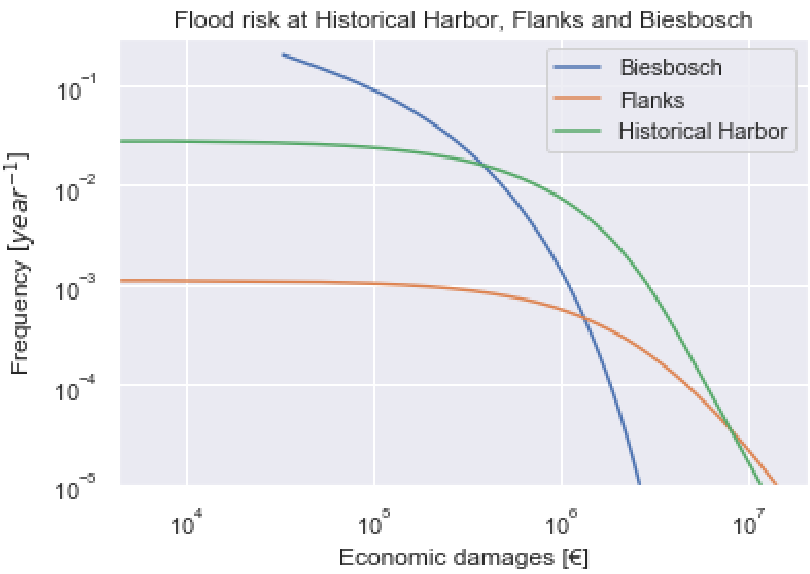


Figure 3.6: Reference situation: flood risk at the flood prone areas on the Island of Dordrecht

The total flood risk or annual value at risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht can be found per region in Table 3.3 below. These values have been determined using 3.2. As can be seen, the historical harbor shows the largest yearly value at risk due to flooding, whereas the annual value at risk at the Biesbosch and more so the flanks are less. The main reason for this large discrepancy between the flood risk values of the different areas is that the historical harbor and the Biesbosch are located at much lower elevations than the flanks. Also, since it is located more upstream, water levels at the north-eastern Biesbosch are quite a bit higher than at the rest of the Island of Dordrecht as can be seen in 3.4.

Flood prone area not protected by flood defenses	**Flood risk [€/year]**
Historical harbor	$5.6 * 10^4$
Flanks	$9.3 * 10^3$
Biesbosch	$4.4 * 10^4$
Total	$1.1 * 10^5$

Table 3.3: Reference situation: flood risk flood prone areas not protected by flood defenses at Island of Dordrecht

3.5.2. Flood risk scenarios

As mentioned before, the flood risk of the flood prone areas not protected by flood defenses is divided into three regions: the historical harbor, the flanks and the Biesbosch. In Figure 3.7 below the total flood risk curves of these regions combined can be seen for both the current flood protection system and Plan Locks. It is obvious that the value at risk for the scenarios is much higher than for the reference situation. Another phenomenon that stands out is that the potential damages for set frequencies are about 10 times as small for Plan Locks compared to the current flood protection system, though it should be noted that these curves are not deduced from the same scenarios.

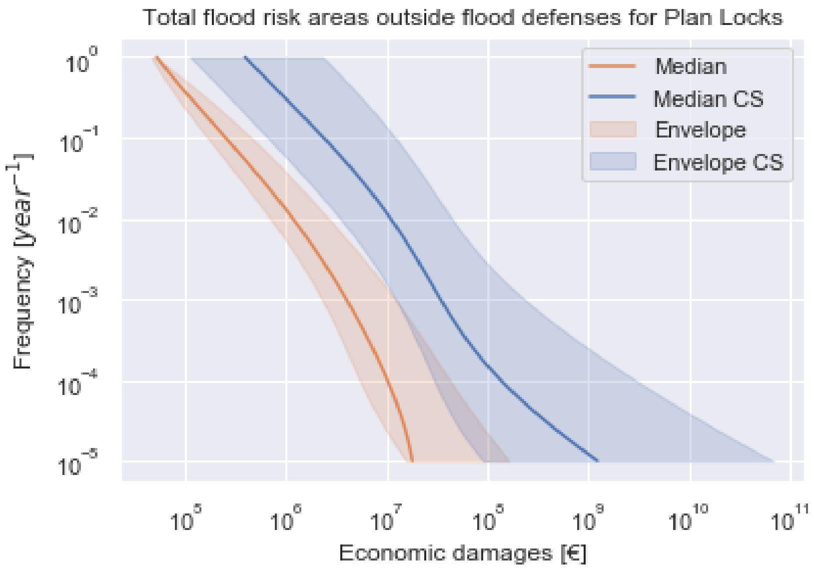


Figure 3.7: Total flood risk curves for the current system and Plan Locks

From Van Waveren et al. (2015) the relative flood risk reduction of Plan Locks compared to the current flood protection system can be found in Table 3.4. These reductions are found for both the Island of Dordrecht, but also more northern regions and therefore a comparison of the absolute potential damage values does not hold up. However, to validate the relative decrease of the flood risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht, the research by Van Waveren et al. (2015) can be used. It should be noted that the medium scenario of Plan Locks used in the report is not the same as used for the current flood protection system. Hence, the average damage of the medium and maximum scenario for Plan Locks was compared to the medium scenario of the current flood protection system.

	Plan Locks	**Plan Locks (Stijnen and Botterhuis, 2015b)**
1/10 year^{-1}	-78%	-67%
1/100 year^{-1}	-76%	-70%
1/1000 year^{-1}	-65%	-75%

Table 3.4: Decrease in damages due to flooding of flood prone areas not protected by flood defenses for Plan Locks

Since the reductions in potential damages are very similar in order of magnitude, it may be concluded that the flood risk results from this report are determined in a similar fashion as in Van Waveren et al. (2015) and can thus be compared.

In Tables 3.5 and 3.6 an overview of the average annual value at risk for the current flood protection system and Plan Locks can be seen. The tables show the minimum, medium and maximum flood risk values per flood prone area not protected by flood defenses as well as the total for each scenario. Also, it can be observed that for the future situation, the largest flood risk contributor is the historical harbor, which is about five times more than the Biesbosch for the medium scenario. Interestingly, the flanks were the region with the least flood risk for the reference situation by far, but by the year 2100 this is going to change slightly and shift from the Biesbosch to the flanks.

The reason for the shifts of the contribution of flood risk among the different flood prone areas not protected by flood defenses can be most easily observed in Figure 3.6. The Biesbosch shows economic damages already for small return periods, but for more extreme events these damages do not increase too much. The flanks do not show any damages up until quite large return periods after which the damages start going up the fastest of all three areas. The historical harbor shows a behavior with characteristics of both the Biesbosch and the flanks. Hence, this, along with the fact that the land subsidence of the flanks is the largest, explains why the flanks are so perceptible to sea level rise and an increase of the extreme Rhine discharges and the

Biesbosch is the least perceptible.

Flood prone area	**Minimum [€/year]**	**Medium [€/year]**	**Maximum [€/year]**
Historical harbor	$1.6*10^5$	$7.0*10^5$	$5.7*10^6$
Flanks	$1.1*10^5$	$3.9*10^5$	$1.7*10^6$
Biesbosch	$1.2*10^5$	$2.0*10^5$	$7.0*10^5$
Total	$3.9*10^5$	$1.3*10^6$	$8.1*10^6$

Table 3.5: Scenarios: Flood risk for current flood protection system for the year 2100

Flood prone area	**Minimum [€/year]**	**Medium [€/year]**	**Maximum [€/year]**
Historical harbor	$5.5*10^4$	$7.0*10^4$	$1.0*10^5$
Flanks	$6.4*10^3$	$1.3*10^4$	$5.2*10^4$
Biesbosch	$4.4*10^4$	$6.8*10^4$	$1.1*10^5$
Total	$1.0*10^5$	$1.5*10^5$	$2.6*10^5$

Table 3.6: Scenarios: Flood risk for Plan Locks for the year 2100

The total flood risk values as given in Tables 3.5 and 3.6 are tough to interpret and the relevance of these values is not clear. This risk is however largely the responsibility of the inhabitants of the flood prone areas not protected by flood defenses. Specifically damages to residences are fully the responsibility of the owners. At the historical harbor and the flanks, the total damages are largely due to damages to residences, as can be seen in Figure 3.3. In Table 3.7 it is shown how the flood risk for residences increases relatively more than the total flood risk for more extreme scenarios. It is therefore interesting to see how these annual values at risk or flood risk values to residences compare to the income of the inhabitants of the flood prone areas not protected by flood defenses.

	Present	**Minimum**	**Medium**	**Maximum**
Portion of damages to residences [%]	0.4	0.4	0.5	0.7
All residences [€/year]	$4.4*10^4$	$1.6*10^5$	$7.0*10^5$	$5.7*10^6$
Residences in historical harbor [€/year]	$2.2*10^4$	$6.6*10^4$	$3.8*10^5$	$4.0*10^6$

Table 3.7: Flood risk to residences for present situation and all scenarios for current flood protection system

Firstly, the annual value at risk to residences is compared to the average annual income per household at all the flood prone areas not protected by flood defenses at the Island of Dordrecht, as can be found in Table 3.7. From CBS (2020) it can be found that the average income per person at the flood prone areas not protected by flood defenses is about €25,000 per year. This means that the average income per household is around €40,000 per year. Dividing the total annual value at risk to residences at the flood prone areas not protected by flood defenses by the amount of households, namely around 13,000, one can come to the percentages of average values at risk compared to the total income per household of the flood prone areas not protected by flood defenses for the current flood protection system and Plan Locks can be found in Table 3.8. It can be found that the percentage of risk to residences compared to income at the flood prone areas not protected by flood defenses slightly exceeds the 1 % limit as set in Section 3.2.5 for the maximum scenario.

	Present [%]	**Minimum [%]**	**Medium [%]**	**Maximum [%]**
Current system	0.01	0.03	0.2	1.2
Plan Locks	0.01	0.02	0.03	0.05

Table 3.8: Percentage of annual value at risk to residences compared to income per household

Secondly, it is interesting to see how the percentages as shown in Table 3.8 change if only the historical harbor is examined. Since the annual value at risk at this region is relatively large compared to the number of inhabitants, the same computations as done above are performed for the historical harbor. From CBS (2020) it can be found that the income per person in the historical harbor, lies at around €35,000. The total income per household was found to be around €50,000 per year. By dividing the annual value at risk to residences at the historical harbor by the amount of households, namely around 1,500, one can come to the values as found in Table 3.9 (CBS, 2020). It shows that, on average, every household in the historical harbor needs to put away around 1 % of the annual income for flood damages to their house and household effects for the medium scenario of the year 2100. For the maximum scenario, this percentage might rise up to 7 to 8 %. Also the risk compared to the income per household for Plan Locks is incorporated in Table 3.9. Plan Locks is able to keep this percentage well under 1 % for all scenarios.

	Present [%]	**Minimum [%]**	**Medium [%]**	**Maximum [%]**
Current system	0.07	0.2	0.9	7.6
Plan Locks	0.06	0.07	0.09	0.1

Table 3.9: Percentage of annual value at risk to residences compared to income per household at historical harbor

3.6. Concluding remarks

There are three main conclusion remarks to be made regarding the results that have been obtained in this chapter.

- **The present average annual value at risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht is equal to about €110,000 per year. By the year 2100 this value at risk is going to rise to €390,000, €1,300,000 and €8,100,000 per year for the minimum, medium and maximum scenario respectively.**
  This means that the flood risk increases with a factor of 3 compared to the present situation for the presently observed sea level rise rate and a factor 12 and 70 for the medium and maximum scenario for the year 2100 as defined by the IPCC respectively

- **The flood risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht is going to shift from the Biesbosch more towards the flanks. The historical harbor, flanks and Biesbosch are going to constitute to about 50, 30 and 20 % respectively for the medium scenario of the year 2100 compared to the present distribution of 50, 10 and 40 %.**
  Due to the limited potential damages in the Biesbosch and relative large potential damages at the flanks, for the year 2100 the risk distribution for the flood prone areas not protected by flood defenses is going to shift more towards the flanks along with the historical harbor. The value at risk remains the largest at the historical harbor and due to the limited number of inhabitants, the average annual value at risk can constitute up to 7 or 8 % of the annual income per household by the year 2100.

- **With the implementation of Plan Locks, the annual value at risk at the flood prone areas not protected by flood defenses can be kept near present values until a sea level rise of at least 0.85 m.**
  All the measures that Plan Locks incorporates lead to a significant lowering of the high-water levels at the Island of Dordrecht. The placement of pumping stations at the Oude and Nieuwe Maas does give a large decrease of water levels at the Island of Dordrecht and also the usage of the Oosterschelde as a storage area slightly decreases the water levels (Stijnen and Botterhuis, 2015a).

4

Future boundary conditions in the Rhine-Meuse delta with the Delta21 project

This chapter elaborates on research step 3 by determining the future boundary conditions that belong to the new flood protection system with Delta21. Furthermore, the way in which Delta21 is modeled into the D-Flow1D SOBEK model and into the SingleRunner, the program that allows for a control of the SOBEK model for various hydraulic boundary conditions and operation settings, is explained. To come to an optimum use of the Delta21 project several configurations are assessed based on a number of criteria. These configurations are also inventorized in this chapter.

4.1. Introduction to flood protection system with the Delta21 project

4.1.1. Need for new flood protection system

The computed future flood risk values from the high water calculations made in Chapter 3 show that even for the minimum scenario the total annual value at risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht becomes three times larger than the current annual value at risk. For the maximum scenario this value at risk is even 70 times larger than for the present situation. Additionally, for the maximum scenario it is determined that the annual value at risk per household with respect to the income per household will exceed the 1 % limit that has been defined in Section 3.2.5. Apart from showing that the flood risk increases are extremely large, it also shows that the exact increase is very hard to predict and largely depends on how the water level in the North Sea rises in the coming decades. This is also addressed in Chapter 3.

Nevertheless, since the value at risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht is going to increase, there are solutions needed. As mentioned in Chapter 1, the flood prone areas not protected by flood defenses are not protected by dikes that can be heightened. To decrease the annual value at risk due to flooding for these areas there are two options. The first one is to limit the potential damages during flooding events and the second one is to limit the occurrence of such events.

Limiting the potential damages can for instance be done by placing water retaining obstacles such as sand bags around valuable objects during a flood event, heightening the foundation of buildings and moving objects to areas with larger elevations or areas within the flood defenses among other things. Placing sand bags or other obstacles can be relatively effective and not always too expensive. Adapting foundations and rebuilding houses is fairly expensive. Since inhabitants and companies of flood prone areas not protected by flood defenses are responsible for any damages due to flooding, they also need to make such investments themselves. As flood events occur with low frequencies, individuals might not be too willing to make such investments. Additionally, the direct damages are not the only unwanted consequence of high water events. Also relevant is the possibly unattractive situation where inhabitants are forced to leave or protect their property too frequently, which can be categorized under indirect consequences as described in Section 3.2.4. Hence limiting the damages of flood events is only part of the solution and also the limitation of the occurrence of high water events might be necessary.

Limiting the occurrence of high water events means that water levels for extreme situations need to be lowered. An example of an intervention to lower extreme water levels in the Rhine is the Room for the River project (Eijgenraam, 2005). One problem with this is that this means that the upstream part of the widened river has lower water levels during large discharges, but it has little effect on downstream areas. The Room for the River project did make some adjustments to the Rhine-Meuse delta around the Island of Dordrecht. Those were however only small measures and as the western part of the Rhine-Meuse delta has many cities and industry at the river, drastic measures that were made in the eastern part of the delta could not be taken in the western part around Dordrecht. Additionally, the impact of such a measure is only limited to upstream areas.

It has been determined in Chapter 3 that Plan Locks has a large influence on the water levels at the Island of Dordrecht, but also has the disadvantage that free shipping from sea to the port of Rotterdam and other ports on the Rhine-Meuse delta is more often blocked. A more preferable situation would be an adjustment to the flood protection system in which the Nieuwe Waterweg could preserve its storm surge barrier. Hence, Delta21 is proposed to lower extreme water levels in the Rhine-Meuse delta. The idea is to lower water levels all the way at the Haringvliet mouth and therefore lowering all upstream locations; for example the Island of Dordrecht.

The Delta21 project is only examined for the future scenarios of the year 2100 because of two reasons. The first reason is that the project is still in its exploratory stage and by the time that it is potentially in operation the present day boundary conditions are not valid anymore. The second reason is that the present day flood risk and flood frequency values at the flood prone areas not protected by flood defenses at the Island of Dordrecht do not exceed the limits as set in Section 3.2.5. Hence, no changes in the flood protection system are required.

4.1.2. Changes made to the project area

The current flood protection system that has been evaluated in Chapters 2 and 3 is supplemented by the Delta21 project. In Figure 4.1 the change from the current flood protection system in the Haringvliet estuary to the new flood protection system with Delta21 can be observed.

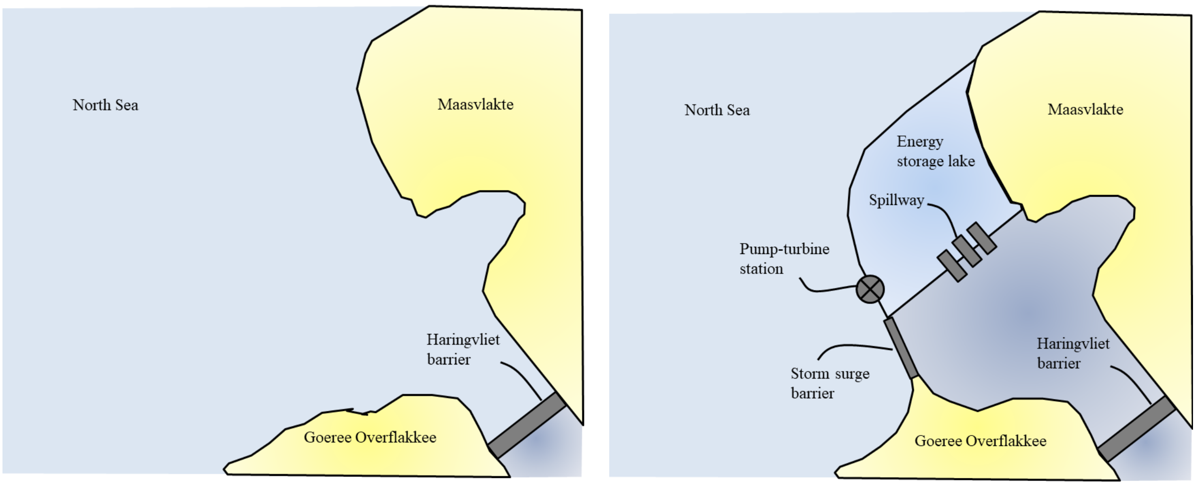


Figure 4.1: Haringvliet estuary without and with Delta21.

As discussed in Section 1.2, Delta21 consists of an energy storage lake with an accompanying pump-turbine station, a spillway (siphons) and a new storm surge barrier. By introducing these structures, the Haringvliet barrier can be permanently opened. The Haringvliet barrier does still limit the opening of the Haringvliet. However, if the new storm surge barrier in opened state has an opening smaller or equal to that of the opened Haringvliet, this does not matter. If the new opened storm surge barrier has an entrance area larger than that of the Haringvliet barrier, an option is to demolish the Haringvliet barrier; resulting in large costs and also redundancy regarding the reliability of the new flood protection system with Delta21. If the new storm surge barrier fails to close, the Haringvliet barrier can always still be closed.

The idea of the Delta21 project is to lower the water level in the Haringvliet estuary (for the situation with Delta21 this area is renamed to the 'Tidal Lake'). By lowering this water level, the flow pattern within the Rhine-Meuse delta is adjusted to direct more water towards the Haringvliet. By doing so, for a closed Europoort barrier the piling up of water is limited and the maximum water levels during a combination of storm surge and high river discharges are lowered.

The four main components of the Delta21 project are the new storm surge barrier, the energy storage lake, the spillway (siphons) and the pump-turbine station. During storm surge and high river discharges the storm surge barrier is closed, the spillway is opened, water is let into the energy storage lake and this water can subsequently be pumped out onto the North Sea. Currently the energy storage lake is designed to be able to store enough water that 10,000 m^3/s can be let in for 12 hours. This leads to a total storage volume of 430 million m^3 (Berke and Lavooij, 2019). This means of course that if a storm lasts for more than 12 hours or if the lake is not completely empty at the start of the opening of the spillway, water needs to be pumped out of the energy storage lake.

Lastly, the Haringvliet barrier remains at its current location with the only change being that there will be a more permanent opening to let in tidal flows during normal conditions. This is however not important to this study. It is vital to keep in mind that even if the storm surge barrier is not closed, the Haringvliet barrier does close whenever inward directed flows become too large.

4.2. High water modeling of flood protection system with the Delta21 project

4.2.1. One-dimensional schematization of Delta21 implementation

The new flood protection system set-up needed to be modeled adequately to represent its physical properties. This process consisted of three main parts: adding a storage area representing the energy storage lake, including the new storm surge barrier by closing off the estuary further downstream with a new barrier and adding an entrance to and exit from the storage lake representing the spillway and pump-turbine station.

As mentioned in Chapter 3, the water levels in the Rhine-Meuse delta during extreme events were modeled by a 1D SOBEK flow model run by the Normative High Water processor (MHWp5). This meant that the 2D representation in Figure 4.1 needed to be translated to a 1D schematization. To do so, an extra node was added downstream of the Haringvliet barrier that contained the new storm surge barrier. Additionally, a new branch was added to this node that was followed by a large storage area; the energy storage lake. By adding a new fixed weir and a set of pumps on this same node, the spillway (siphons) and pump-turbine station of Delta21 were schematized. The storm surge barrier was modeled as a controllable gate just downstream of the node with the spillway and pump-turbine station. More information on the 1D schematization of the 2D representation of Delta21 can be found in Appendix D.

4.2.2. Set-up control systems of hydraulic structures

The hydraulic structures that were modeled in the D-Flow1D model of the new flood protection system with Delta21 needed to be controlled by the Singlerunner module of MHWp5. In Appendix D more information on this process can be found. The pump and storm surge barrier are the two components of the Delta21 project that needed to be controlled by a control system. As mentioned in Appendix D, these components are controlled through a real-time control module. The exact set-up of the control systems depend on the configuration of Delta21. As mentioned in Section 4.3, the most fundamental difference between the configurations is the dependency of Delta21 on the Europoort barrier.

Since this study is on the application of the Delta21 project for the flood prone areas not protected by flood defenses at the Island of Dordrecht, the control system of the storm surge barrier and pumping station checks whether the expected water level at Dordrecht exceeds a certain level (e.g. NAP + 2.9 m). If this is the case, the storm surge barrier is closed and then, and only then, the pumping station is turned on. The discharge of the pumping station is dependent on the discharge in the Rhine and can change according to water levels in the Haringvliet. This is done to create a maximum hydraulic slope towards the Haringvliet and redirect as much water as possible to the tidal lake. If the water level gets too low, the discharge of the pumping station is lowered. Once the water level at Dordrecht drops below about NAP + 2 m, the barrier is opened again and the pumping station is turned off. In Figure 4.2 this process is very roughly schematized. As explained in Appendix B, the water level for every time step in one day time is calculated. Whenever the water level is expected to exceed an initiation level (h_{init}), the storm surge barrier is closed and the pumping station is turned on. For the duration of the run, the expected water levels are calculated. Whenever the water level at Dordrecht is expected to drop below a stop level (h_{off}), the Delta21 components are turned off.

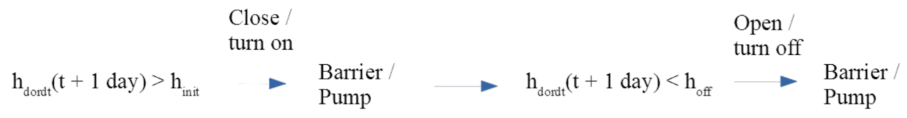


Figure 4.2: Basic control of storm surge barrier and pumping station

The control system of the Delta21 components can be set up in two ways: inclusive with and independent from the Europoort barrier.

An inclusive control system means that the Delta21 components can only work in case the Europoort barrier is closed. Additionally this means that the initiation levels of the new storm surge barrier and pumping station are equal to the closure level of the Europoort barrier.

An independent control system means that the Delta21 components are operated independently from the Europoort barrier. The initiation height of the Delta21 components are not conditioned to the closure levels of the Europoort barrier, but instead lowered so that Delta21 may be initiated in case of an open Europoort barrier.

4.3. Delta21 configuration variants and resulting boundary conditions

4.3.1. Creation of Delta21 configurations

The operation of Delta21 can be varied in an endless number of ways. Initiation and closure levels can be changed, its cooperation with other structures in the flood protection system of the Rhine-Meuse delta and operation intensity and duration can be altered.

Presently, the most important structure that determines the water levels in the Rhine-Meuse delta is the Europoort barrier. Especially the cooperation of the new Delta21 components with the Europoort barrier is important to assess with the addition of the Delta21 project. A decision has to be made as to whether the Delta21 is a separate project that is operated on its own or if it should be closely integrated into the current flood protection system and therefore with the Europoort barrier.

Hence, two configuration variables have been created that assess the question if the Delta21 project is to be used if and only if the Europoort barrier is in operation or if the Delta21 project can be operated separately from the Europoort barrier. The two control system set-ups are:

1. Inclusive with Europoort barrier
2. Independent from Europoort barrier

The control system set-ups are crucial to the way in which the Delta21 project aims to lower water levels in the Rhine-Meuse delta. These set-ups can be obtained by adjusting two variables that in their turn can be adjusted to create a number of Delta21 configuration variants. These two variables are:

- Europoort barrier closure level
- Delta21 initiation level

The closure level of the Europoort barrier was adjusted as such that the closure frequency could remain equal to about 1/10 per year. For one situation the closure level at Rotterdam and Dordrecht was kept the same and for the other situation the closure level was adjusted so that the closure frequency stayed the same.

In Table 4.1 the closure levels and frequencies of the Europoort barrier for all sea level rise scenarios can be found. The table consists of two columns: one that shows the closure frequency of the Europoort barrier if the closure level were not adjusted and one shows the adjusted level that is needed to obtain the same closure frequency as is currently given by the WBI (Botterhuis et al., 2012).

	Closure frequency for h = NAP + 2.9 m	**Closure level for f = 1/11 year^{-1}**
SLR = 0.2 m	1/6 year^{-1}	NAP + 3.1 m
SLR = 0.6 m	1.1 year^{-1}	NAP + 3.4 m
SLR = 1.1 m	10.4 year^{-1}	NAP + 3.8 m

Table 4.1: Closure frequency for original closure levels and adjusted closure levels

The relation between the initiation level and the initiation frequency of the Delta21 components is the same as that of the Europoort barrier as shown in Table 4.1. This means that the Europoort barrier closure and the Delta21 initiation are set to the same water levels and the resulting frequencies are the same. For each of these variables two values were chosen in order to keep computation times reasonable. This means that in total four different Delta21 configurations were modeled. In Table 4.2 the closure and initiation levels of the Europoort barrier and Delta21 at Dordrecht are given for each of the four Delta21 configurations are presented. The closure level of the Europoort barrier of configurations 3 and 4 depend on the respective scenario for which it is implemented. The three values therefore represent the closure level for the minimum, medium and maximum scenario respectively. The same goes for the initiation level of Delta21 for configuration 4. Currently, the Delta21 project is proposed to be implemented as configuration 2, where the Europoort closure level is equal to the present one and Delta21 is only initiated when the Europoort barrier is closed.

Configuration	**Closure level Europoort [m + NAP]**	**Initiation level Delta21 [m + NAP]**
1	2.9	2.3
2	2.9	2.9
3	3.1/3.4/3.8	2.3
4	3.1/3.4/3.8	3.1/3.4/3.8

Table 4.2: Configuration variants of flood protection system with Delta21

The initiation level of Delta21 for configurations 1 and 3 was set at NAP + 2.3 m, because of the current water level at the historical harbor of Dordrecht that causes the so called 'water on the quay' situation. This water level that should not occur too frequently is about NAP + 2.5 m (Heinen, R., personal communication, September 23 2020). Hence, keep the water level below NAP + 2.5 m and to assess a larger range of operation possibilities, the initiation level of Delta21 was chosen as NAP + 2.3 m for configurations 1 and 3.

4.3.2. Assessment of new boundary conditions

For each of the four configurations given in Section 4.3 some of the boundary conditions are changed. Technically the water level boundary conditions at the Haringvliet have remained similar to those associated with the current flood protection system. What has changed is that due to the construction of the energy storage lake some of the tidal channels of the Haringvliet mouth have been built over. Additionally, the tidal inlet cross section has been made smaller by the construction of the new storm surge barrier. Hence, the tidal signal during normal conditions is somewhat changed in amplitude and phase compared to the current flood protection system. This change in tidal signal can be seen in Figure 4.3. It shows the tidal signal in the new tidal lake. This change is for a specific combination of river discharge and storm surge and serves therefore only as an indication.

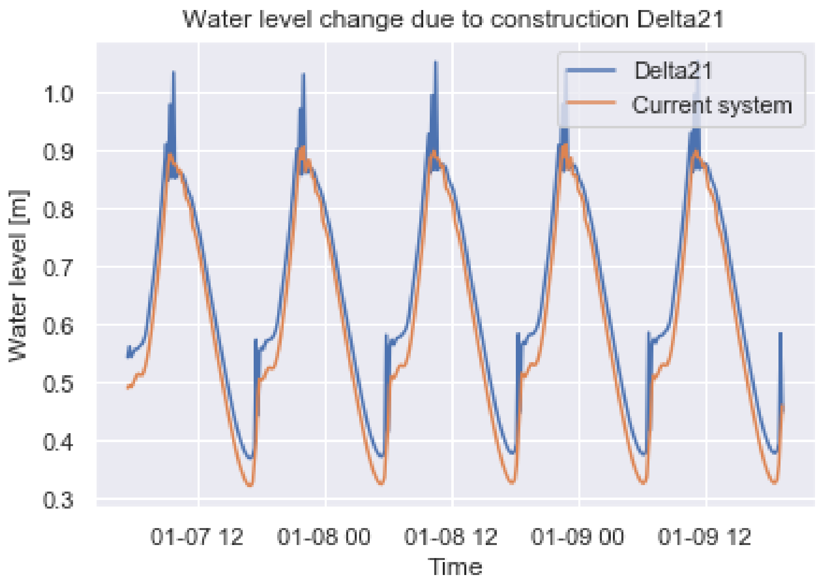


Figure 4.3: Change of tidal signal due to construction of Delta21 in the new tidal lake (Haringvliet)

As can be observed, the mean water level during normal conditions is actually a few centimeters higher for the new flood protection system with Delta21. Also, the tidal range is slightly larger. This might be explained by the fact that the number of channels of the Front Delta becomes smaller. In the short term this might lead to an amplification of the water level as the same amount of water needs to enter the Haringvliet through a smaller opening.

5

Optimizing the operation of Delta21 for flood prone areas at the Island of Dordrecht

This chapter elaborates on research step four. It aims to optimize the operation of the flood protection system with Delta21 for the flood prone areas not protected by flood defenses for the future scenarios of the year 2100 based on a set of criteria consisting of requirements and limitations. Additionally, the changes in the governing processes in the Rhine-Meuse delta due to the implementation of Delta21 are analyzed.

5.1. Defining an optimal operating regime

5.1.1. Optimizing Delta21 for flood prone areas at the Island of Dordrecht

The Delta21 project aims to lower high-water levels in the Rhine-Meuse delta. However, the optimization that is performed in this chapter is based solely on requirements as defined for the flood prone areas not protected by flood defenses at the Island of Dordrecht. This means that the optimal operating regime, which is the result of this chapter, is specified for this specific location in the Rhine-Meuse delta.

There are main two factors of the optimization that is performed in this report that may cause a differentiation from an optimization from the perspective of the entire Rhine-Meuse delta. These factors are the geographic location of the Island of Dordrecht and the assessment of flood prone areas not protected by flood defenses instead of protected areas.

The Island of Dordrecht is located in the so-called transition region of the Rhine-Meuse delta as can be seen in Figure 1.2. This means that high-water levels are influenced by both the water level at sea as the Rhine discharge during extreme events. The influence of Delta21 is therefore very different at for instance Rotterdam, which is located in the sea dominated region and where the extraction of river water has very little effect on high-water levels. On the other hand, an optimization based on a locations along the Haringvliet would lead to very low requirements for the Delta21 frequency of initiation and discharge capacity as such locations are very directly affected by the Delta21 project.

Since the Delta21 is optimized for the flood prone areas not protected by flood defenses, certain aspects are different than when doing the same for protected areas. For flood prone areas not protected by flood defenses high-water levels with relatively high frequencies are of larger importance. Though such more frequent high-water levels can contribute to the failure probability of dikes for failure mechanisms such as piping, the most relevant goal of Delta21 would be to lower the Normative High-Water level (MHW) of the dike section in question. Using the Delta21 project for the flood prone areas not protected by flood defenses means that it is of larger importance to lower high-water levels for all frequencies. An optimization for flood prone areas not protected by flood defenses therefore focuses more on the overall high-water reduction rather than mainly the water level for a specific return period. This also means that the optimal operation as given in this chapter is probably not the most optimal one when looking at protected areas.

Moreover, the optimal operating regime, as is defined in this chapter, does give a good insight into the relevant processes and influence of the flood protection structures on the high-water levels in the Rhine-Meuse delta. However, its settings cannot be directly translated to the optimal operation for the protected areas in the whole of the Rhine-Meuse delta.

5.1.2. Definition of the optimal operation of Delta21

To define an optimal operation of the Delta21 project, an inventory needs to be made of the operation variations. The Delta21 system can be operated in many different ways and the number of configurations is endless. A configuration is a combination of initiation levels and closure levels of the components within the flood protection system. An infinite amount of combinations of such water levels can be created, but in this report only four configurations have been assessed as is elaborated in Section 4.3. To come to the so called optimal operation one needs to define what such an optimal operation is. It can be concluded that the most important factors are the flood frequency at the flood prone areas not protected by flood defenses at the Island of Dordrecht and the accompanied flood risk. However, as is discussed in Chapter 2, it is expected that the closure frequency of the Europoort barrier is going to be too high for the more extreme climate change projections. As an alternative to a storm surge barrier such as the Europoort barrier, Plan Locks has been proposed as it might be a better option for extreme sea level rise values. Having a set of locks permanently closing the Oude and Nieuwe Maas from the sea would then hinder shipping less than a frequently closing Europoort barrier. By introducing Delta21 as an alternative to such a permanent closure, the relation with the Europoort barrier needs to be assessed as it is one of the most vital components of the current flood protection system. The way in which the initiation level of Delta21 and the closure level of the Europoort barrier influence the extreme water levels at the Island of Dordrecht and generally the governing processes in the Rhine-Meuse delta is essential for a complete analysis.

An optimal operation of the flood protection system with Delta21 for the flood prone areas not protected by flood defenses at the Island of Dordrecht is therefore defined as an operation strategy that is able to keep flood frequencies and flood risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht within checks. Additionally, it should be able to keep the closure frequency of the Europoort barrier and the initiation frequency of the Delta21 project reasonable. In Section 5.2 it is defined what the limits for these criteria are. It is therefore chosen to only model the Delta21 project for future situations. For the present situation no problems with flood risk at the flood prone areas not protected by flood defenses exist. Also the potential implementation of Delta21 will only take place in several decades meaning that an analysis with the present hydraulic boundary conditions are not too meaningful.

5.2. Set-up of criteria regarding optimal operation

As set in Section 3.2.5 there are a few requirements which need to be met by the flood protection system for the flood prone areas not protected by flood defenses at the Island of Dordrecht. These requirements are the percentage of flood risk to residences compared to the income per household being smaller than 1 % and the flood frequency at the historical harbor not being allowed to exceed 1 year^{-1}. As shown in Sections 3.4 and 3.5, the percentage of flood risk compared to the income per household is not smaller than 1 % for all regions and also the flood frequency of the historical harbor does not stay below the limit of 1 year^{-1} for all scenarios of the year 2100. As these requirements are not met with the current flood protection system, it is important to assess if the Delta21 can fill these requirements. The Delta21 project may be able to lower high-water levels enough so that these requirements can be complied with for all scenarios of the year 2100. To do so, it is important to know the limitations of the new flood protection system with Delta21.

The main limitations of the Delta21 project are the closure frequency of the Europoort barrier and the initiation frequency of the Delta21 project. As mentioned in Section 2.2.2, there is a physical limit to the closure frequency of the Europoort barrier as well as economical downsides to very frequent closures. This physical limit is based on both structural problems as well as the required yearly maintenance period during which no closures can occur. The initiation frequency of the Delta21 project cannot be too large either. The configuration cannot lead to situations in which the Delta21 components operate at maximum capacity too often. It is not possible to compare the exact costs of pumping and closing the storm surge barrier against the flood risk reduction values, because of the different spatial scales of the costs and benefits. However, it can still be determined if the initiation frequency is at a reasonable value. Besides the flood protection function of the Delta21 project, also an improvement of the Haringvliet ecology is an important aspect. This improvement is largely based on the opening of the Haringvliet sluices and the construction of the Delta21 storm surge barrier. If the storm surge barrier were to be closed very often and the water level in the Tidal Lake or Haringvliet is drastically lowered, the ecological benefit of Delta21 is largely vanished. Therefore, since the initiation of Delta21 has an impact on the surroundings and mainly ecology, but this impact is limited to lower water levels and higher flow velocities, it is decided that the initiation frequency of Delta21 may not exceed 10 $year^{-1}$.

All in all, a trade-off develops between the requirements and limitations of the Delta21 project that impose a set of criteria on the Delta21 configurations:

- Requirements

  Flood risk as percentage of income per household < 1 %

  Flood frequency at the historical harbor < 1 $year^{-1}$

- Limitations

  Closure frequency of the Europoort barrier < 3 $year^{-1}$

  Initiation frequency of Delta21 < 10 $year^{-1}$

The (non-)compliance of the Delta21 configurations to the requirements and limitations as given above is presented in Sections 5.3 and 5.4. After this an optimal operation of the flood protection system with Delta21 for each of the scenarios is defined in Section 5.5. These optimal operations are created as such that proper balance between the requirements and limitations of the flood protection system with Delta21 is present.

5.3. Computed future high-water levels, flood risk and flood frequencies with Delta21

5.3.1. Computed future high-water levels

In the same manner as has been explained in Section 3.3, the future high-water levels at the Island of Dordrecht have been computed for the flood protection system with Delta21. The implementation of the project into the high water modeling software is explained in Section 4.2 as well as in Appendix D. The modeling of the flood protection system with Delta21 for the future minimum, medium and maximum scenario leads to water level frequency curves for all locations at the Island of Dordrecht. In Figure 5.1 below the water level frequency curves the location Dordrecht can be found for each configuration and in Appendix F an overview of the water level frequency curves for all the configurations and locations can be found. Additionally, the influence of sea-level rise, extreme discharge increase, Europoort barrier closure level change and Delta21 initiation level change are investigated and presented in Appendix F. As mentioned in Section 4.3, the currently proposed implementation of Delta21 is configuration 2 where the present Europoort barrier closure level and an equal Delta21 initiation level are used.

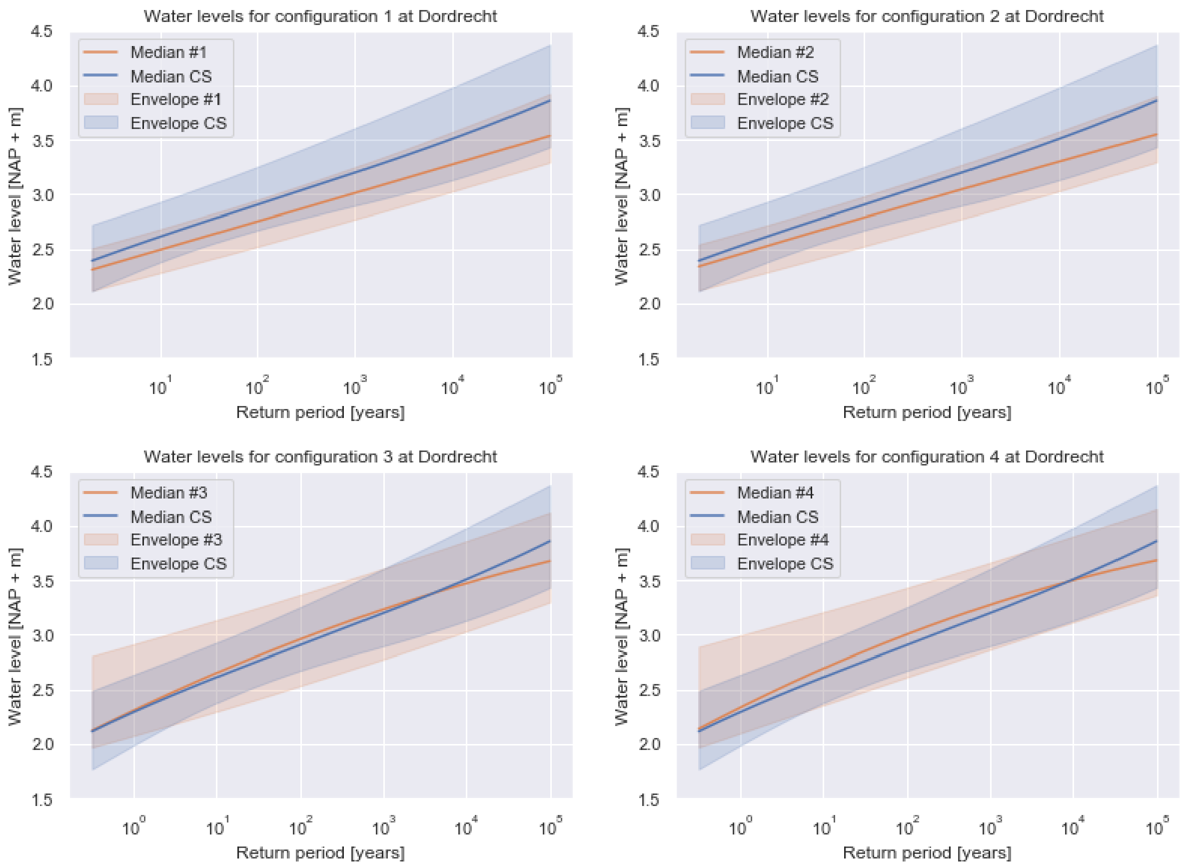


Figure 5.1: Future water levels with Delta21 for configurations 1 to 4 (from upper left to lower right)

The water level frequency curves for configuration 1 and 2 show a somewhat similar behavior, just like configuration 3 and 4 do. The difference between these configurations is the Europoort barrier closure level. It can therefore be immediately recognized that this variable has an enormous impact on the high-water behavior at Dordrecht; more than the Delta21 initiation level. The impact of the Delta21 initiation level mostly affects the relatively high frequencies. The reason for this is clear, since the difference between a low and high initiation level is all the situations that lie in between these water levels. All other situations experience the same influence of the Delta21 components.

5.3.2. Computed future flood risk

In Figure 5.2 the future total flood risk curves for each of the Delta21 configurations compared to the current flood protection system can be found. These flood risk curves have been created by combining the water level frequency curves for each location at the Island of Dordrecht with the flood damage curves as given in Figure 3.2 from Chapter 3. In blue the flood risk curve for the current flood protection system can be found and in orange each of the configurations of the Delta21 project.

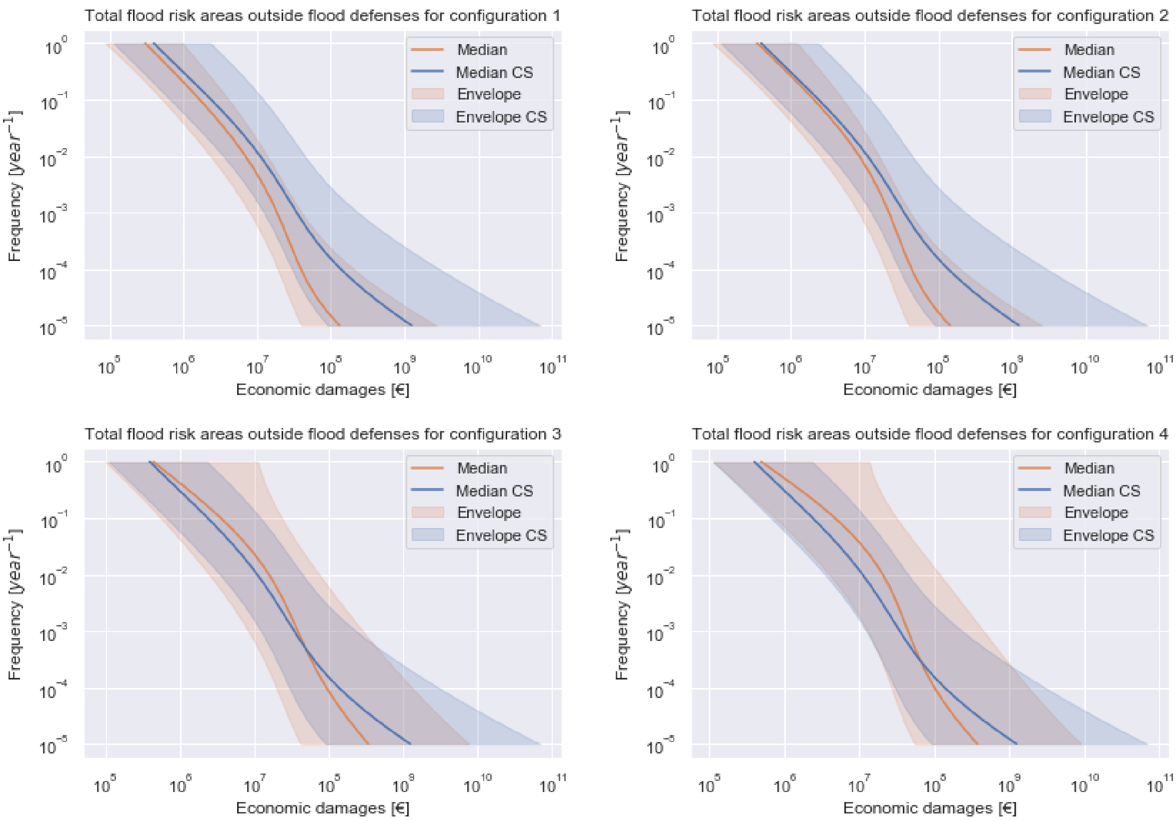


Figure 5.2: Future total flood risk curves for the Delta21 configurations

The total flood risk curves from Figure 5.2 identify the same system response as the water level frequency curves in Figure 5.1. For configurations 1 and 2 the potential damages are smaller for all return periods with the implementation of Delta21. When the Europoort barrier closure level is raised, the damages for low frequencies actually increase for the system with Delta21 compared to the current flood protection system. This is obvious for configurations 3 and 4. For these configurations the damages do become smaller for the highest frequencies. However, this cannot compensate for the increased damages for low frequencies and therefore the total flood risk for these configurations actually increases compared to the flood risk values of the current flood protection system.

In Table 5.1 the annual value at risk or flood risk for the configurations and scenarios can be found and in Table 5.2 the differences between the values at risk of the current flood protection system and the Delta21 configurations can be found.

	Minimum [€/year]	**Medium [€/year]**	**Maximum [€/year]**
Configuration 1	$2.9*10^5$	$9.1*10^5$	$2.4*10^6$
Configuration 2	$3.0*10^5$	$1.1*10^6$	$2.9*10^6$
Configuration 3	$3.1*10^5$	$1.8*10^6$	$1.7*10^7$
Configuration 4	$4.2*10^5$	$2.2*10^6$	$2.2*10^7$

Table 5.1: Total annual value at risk at flood prone areas not protected by flood defenses for Delta21 configurations

	Minimum [%]	Medium [%]	Maximum [%]
Configuration 1	-25	-30	-70
Configuration 2	-23	-15	-64
Configuration 3	-21	+38	+110
Configuration 4	+28	+69	+172

Table 5.2: Change in total annual value at risk at flood prone areas not protected by flood defenses for Delta21 configurations

In Table 5.3 the change in potential damages compared to the current flood protection system for certain frequencies can be found. The values are for the medium scenario, i.e. a sea level rise of 0.6 meters and a Q_{1000} of the Rhine equal to 17,600 m^3/s.

	Configuration 1	Configuration 2	Configuration 3	Configuration 4
1 $year^{-1}$	-25%	-25%	+13%	+23%
1/10 $year^{-1}$	-30%	-13%	+3%	+104%
1/100 $year^{-1}$	-37%	-24%	+45%	+82%
1/1000 $year^{-1}$	-44%	-38%	+12%	+29%

Table 5.3: Change in potential damages of each configuration for several frequencies for medium scenario

In Table 5.4 the ratio between the annual value at risk to residences versus the annual income per household at the historical harbor can be found. This is determined in the same manner as explained in Section 3.5.

	Minimum [%]	Medium [%]	Maximum [%]
Current system	0.2	0.9	7.6
Configuration 1	0.2	0.7	2.3
Configuration 2	0.2	0.8	2.7
Configuration 3	0.2	1.3	16
Configuration 4	0.2	1.6	20

Table 5.4: Percentage of annual value at risk to residences compared to income per household at historical harbor for Delta21 configurations

It can be concluded that both the closure level of the Europoort barrier as the initiation level of Delta21 are of large importance to the flood risk at the flood prone areas not protected by flood defenses of the Island of Dordrecht. Additionally, the influence of Delta21 on a reduction of the potential damages for a set frequency actually increases for smaller frequencies. Partly, the reason for this is that events with smaller frequencies have larger Rhine discharges and therefore the pumping discharge at the Haringvliet is also much larger.

However, changing the initiation level of the Delta21 components only influences the larger frequencies. If the initiation level is chosen to be heightened from NAP + 2.3 m to + 2.9 m, only events that lie in between these values (relatively high frequencies) are affected. This is because for all events that lead to water levels higher than NAP + 2.9 m the components are already initiated.

5.3.3. Computed future flood frequency at historical harbor

From Figure 5.1 the frequency of occurrence of each water level at the location Dordrecht (historical harbor) can be identified. As mentioned in Section 5.2, the frequency at which a water level of NAP + 2.5 m at the historical harbor is exceeded, is one of the criteria regarding an optimal operation of the flood protection system with Delta21. In Table 5.5 below this frequency is given for each of the Delta21 configurations.

	Minimum [year^{-1}]	Medium [year^{-1}]	Maximum [year^{-1}]
Current system	0.05	0.2	3.3
Configuration 1	0.02	0.1	0.7
Configuration 2	0.02	0.2	1.3
Configuration 3	0.02	0.4	1.7
Configuration 4	0.07	0.4	2.5

Table 5.5: Return period of water level higher than NAP + 2.5 m at Dordrecht for all configurations and scenarios

Table 5.5 shows that the future flood frequency at the historical harbor can be lowered significantly with the use of Delta21 with an exception for configuration 4. It should be noted that the flood frequency for the maximum scenario is about a factor three too large for the current flood protection system. The reduction that the Delta21 project can provide still leads to flood frequencies of about once or twice a year. Another thing that is obvious is that raising the Europoort closure level (as has be done for configurations 3 and 4) leads to similar or even higher flood frequencies than the current flood protection system of which the Europoort closure level at Dordrecht is set at NAP + 2.9 m.

From the figures and tables above a few main phenomena can be identified:

- The Europoort closure level is the most influential factor on the high-water levels at the Island of Dordrecht.
- Implementing the Delta21 project leads to lower water levels for all return periods and its influence increases for larger sea levels and extreme Rhine discharges.
- The flood risk reduction due to the implementation of Delta21 cannot compensate for the flood risk increase due to a rise in the Europoort barrier closure level as is done for configurations 3 and 4.
- Changing the initiation level of the Delta21 components only affects situations with return periods that can be associated with water levels in between these initiation levels.

5.4. Computed future closure and initiation frequencies of the Europoort barrier and Delta21

5.4.1. Closure frequency Europoort barrier

The future closure frequency of the Europoort barrier depends on the sea level rise value of the scenario and the closure level of the barrier. In Table 5.6 the closure frequencies of the Europoort barrier by the year 2100 can be found for the three scenarios that have been created in Chapter 2. On the left column each of the values of the Europoort barrier closure level at Dordrecht relative to NAP can be found. The value of the closure level at Rotterdam is set at 0.1 m above that of Dordrecht, as is currently the case.

	Minimum [year^{-1}]	Medium [year^{-1}]	Maximum [year^{-1}]
2.9 m	0.2	0.9	10.4
3.1 m	0.1	-	-
3.4 m	-	0.1	-
3.8 m	-	-	0.1

Table 5.6: Frequency of closure of the Europoort barrier for all closure levels at Dordrecht and scenarios

It can be seen that the closure frequency increases substantially for the scenarios. For the minimum scenario the frequency doubles relative to the present situation and for the medium and maximum scenario it is the tenfold and hundredfold of the present situation. The adjusted closure levels lead to the present closure frequency of once per ten years as is given in Section 2.2.3.

5.4.2. Initiation frequency of Delta21

The future initiation frequency of the Delta21 project depends, just like the Europoort barrier closure frequency, on the sea level rise value of the scenario and the initiation level of the Delta21 components. In Table 5.7 the initiation frequencies for each initiation level and scenario can be found. The initiation frequencies are largely the same, because the Delta21 initiation is controlled in the same manner as the Europoort barrier. However, as configuration 1 and 3 take an initiation level of NAP + 2.3 m into account, these frequencies also need to be assessed. This initiation frequency leads to, as can be expected, very high frequencies for a rising sea level. The maximum scenario shows a frequency of almost 90 times per year. This would mean that the Delta21 storm surge barrier is closed about once every four days along with an opening of the siphon system and the initiation of the pumping station. As mentioned in Section 5.2, this defeats the purpose of an open Haringvliet for ecology.

	Minimum [year^{-1}]	**Medium [year^{-1}]**	**Maximum [year^{-1}]**
2.3 m	1.2	7.8	89
2.9 m	0.2	0.9	10.4
3.1 m	0.1	-	-
3.4 m	-	0.1	-
3.8 m	-	-	0.1

Table 5.7: Frequency of initiation of Delta21 for each initiation level and scenario

5.5. Optimal operation of the flood protection system with Delta21

The optimal operation of the flood protection system with Delta21 is defined per scenario. This can be done as the only variables between the configurations are closure levels and initiation levels that require no physical changes to the flood protection system. Hence, the operation settings of the system can be adjusted when more information on the actual sea level rise and increased maximum Rhine discharge is available. Below the optimal operation can be found for each scenario.

Optimal operation for minimum scenario
For the minimum scenario, regarding the total flood risk and flood frequency at the historical harbor, it can be accepted to raise the closure level of the Europoort barrier to NAP + 3.1 m at Dordrecht and the initiation level of the Delta21 components to the same level. This would mean a 28 % increase in the total value at risk, which does not lead to a significant increase in the percentage of flood risk to income per household at the historical harbor. This stays at 0.2 %, whereas the flood frequency increases slightly to of 1/14 year^{-1} at the historical harbor. By accepting this slight increase in flood risk and flood frequency, the closure and initiation frequency of the Europoort barrier and the Delta21 components can both be kept at around 1/10 year^{-1}.

Optimal operation for medium scenario
For the medium scenario the same operation settings are used as for the minimum scenario, hence the closure level of the Europoort barrier and the initiation level of Delta21 are both set at NAP + 3.1 m. The closure level is not set at NAP + 3.4 m, because this would lead to a 30 % increase in the total flood risk. This increase would be acceptable, but not desirable. A closure level of NAP + 2.9 m would lead to an Europoort closure frequency of 1 year^{-1}, which is already quite high and not necessary as the total flood risk does not need to be decreased significantly.

Optimal operation for maximum scenario
For the maximum scenario, the maximum percentage of the value at risk compared to the local income per household may be around 1 %. This means that the closure level of the Europoort barrier and initiation level of Delta21 need to be set at NAP + 2.9 m and still it exceeds 1 % with a value of about 2 %. The closure and initiation level of NAP + 2.9 m leads to closure and initiation frequencies of 10 year^{-1}. Hence, the third criterium, the closure frequency of the Europoort barrier, is not complied with as this does not allow for a closure frequency larger than 3 year^{-1}.

In Table 5.8 an overview is given of all the Europoort barrier closure levels and Delta21 initiation levels for the optimal operation of Delta21 for the flood prone areas not protected by flood defenses at the Island of Dordrecht. In Appendix G the specifications of among others the flood risk and flood frequency at the historical harbor can be found for the optimal operation of Delta21.

	Minimum	Medium	Maximum
Closure level Europoort [m + NAP]	3.1	3.1	2.9
Initiation level Delta21 [m + NAP]	3.1	3.1	2.9

Table 5.8: Optimal closure and initiation levels of Europoort barrier and Delta21

The optimal operation as presented in Table 5.8 leads to the following total flood risk curve as can be seen in Figure 5.3.

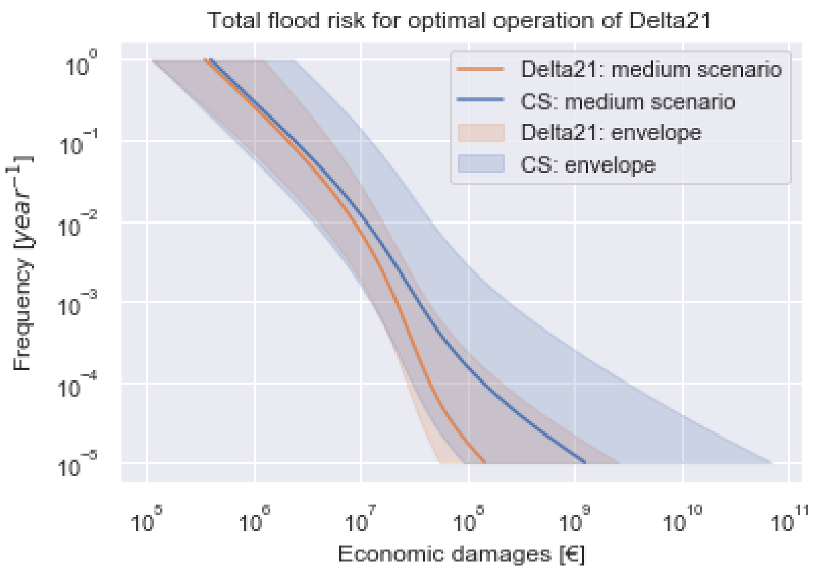


Figure 5.3: Total flood risk at the flood prone areas not protected by flood defenses for optimal operation as given in Table 5.8

	Minimum [%]	Medium [%]	Maximum [%]
Current system	0.2	0.9	7.6
Plan Locks	0.07	0.09	0.1
Optimal operation Delta21	0.2	1.1	2.3

Table 5.9: Percentage of annual value at risk compared to income per household at historical harbor

5.6. Examination of changes in flows and governing processes in the Rhine-Meuse delta

5.6.1. Changes in flows of the Rhine-Meuse delta

The Delta21 project introduces major changes to the flood protection system of the Rhine-Meuse delta. The addition of the Delta21 components influences the behavior of the system and therefore the flows and water levels that are present during extreme conditions. This influence can be divided into three main parts: the influence on the project area, the Island of Dordrecht and other regions in the Rhine-Meuse delta.

In case of an activation of Delta21, water levels in the project area are largely reduced due to the closure of the storm surge barrier and the opening of the spillway. However, water levels are kept above NAP - 4.0 m to avoid that certain areas in the Haringvliet run dry. Water levels at the Island of Dordrecht are also reduced due to the use of Delta21. This is the goal of Delta21 and the water level reduction increases for larger values of sea level rise. Delta21 also influences the flow distribution in the Rhine-Meuse delta. Flows through the Hollands Diep and Spui increase when Delta21 is implemented, which means that the total flow reaching the Delta21 project area is larger than the total amount of water entering the delta through the Rhine. This means that the total amount of water in the system decreases due to the activation of Delta21.

The changes in average flow discharge during high-water at sea for extreme events in the Rhine-Meuse delta due to the implementation of Delta21 are made visible in Figure 5.4. This is for the situation with a correctly functioning Europoort barrier. It is apparent that the flows are directed more to the south-western part of the delta compared to the current situation. This flow is concentrated through the Spui and Dordtse Kil. The large flow through the Dordtse Kil is the reason why the influence of Delta21 is relatively large for the western part of the Island of Dordrecht. In Appendix E more information can be found on the influence of the Delta21 project on the physical processes in the Rhine-Meuse delta.

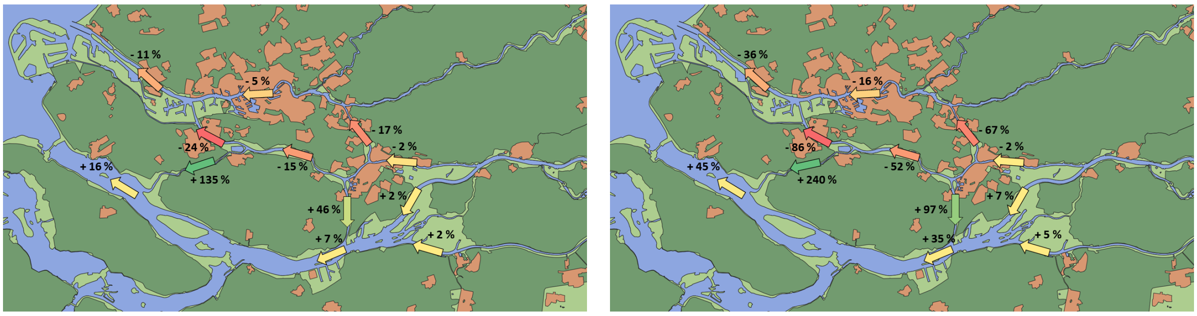


Figure 5.4: Change in mean discharge during storms in the Rhine-Meuse delta compared to current system for minimum and maximum scenario

From Figure 5.4 it can be deduced that the discharges through the Spui and Dordtse Kil are going to increase during storms with the implementation of Delta21. Such an increase in discharges leads to larger peak velocities through these branches as well as an increase in the duration of these peak velocities. In Table 5.10 the increase of the mean peak flow velocities in the Spui and Dordtse Kil during storms can be found. It is clear that for more extreme scenarios the relative increase in these peak velocities becomes larger.

	Minimum scenario	**Medium scenario**	**Maximum scenario**
Spui	+ 22 %	+ 28 %	+ 43 %
Dordtse Kil	+ 8 %	+ 13 %	+ 29 %

Table 5.10: Mean increase of peak flow velocities during storms for a closed Europoort barrier

These high flow velocities already lead to problems with bed erosion and large scour holes in the connecting branches between the northern and southern part of the Rhine-Meuse delta, i.e. the Spui, Dordtse Kil and Noord (Platform Rivierkennis, 2019). Though flows through the Noord are actually reduced significantly, flows through the Dordtse Kil and Spui are much larger after the implementation of the Delta21 project. The accompanied higher flow velocities are only expected to enlarge the erosion problems in these river branches.

5.6.2. Changes in governing processes at the Island of Dordrecht

For each set of high-water calculations using the high-water modeling software (MHWp5) the most nominal combination of water level at sea, discharge in the Rhine and operation of the Europoort barrier for a certain return period can be found. This means that Hydra determines for each wind direction the most probable combination of water level at sea and discharge in the Rhine. It does this for a closed and opened Europoort barrier. All of these situations have a certain probability of occurrence and the one with the largest probability is regarded as the so called 'illustration point'. Assessing these illustration points gives a closer look into the most normative processes of each region and the changes that the Delta21 project imposes on these processes. By understanding the underlying processes, this also gives a better insight in the optimization of

Delta21.

In Table 5.11 the influence of a closed Europoort barrier on the water levels at Dordrecht can be found for configuration 1 of Delta21. For each cell of the table two values are given. The first one represents the relative influence of a closed Europoort barrier on the total probability of occurrence of the high-water level for the corresponding scenario and return period for the current flood protection system. The second value represents the same, but only for the Delta21 project. Hence, if these values are smaller than 50 %, the corresponding high-water level is most likely reached through a situation in which the Europoort barrier is opened. If the value is larger than 50 %, this water level is most likely due to a situation in which the Europoort barrier is closed.

CS/D21 [%/%]	**T = 1 y**	**T = 10 y**	**T = 100 y**	**T = 1,000 y**	**T = 10,000 y**
Minimum scenario	1.6/0.4	6.9/1.8	9.6/13.4	66.2/37.4	84.2/42.3
Medium scenario	11.3/4.8	11.3/4.8	52.1/26.6	90.1/26.4	86.3/18.1
Maximum scenario	18.8/7.9	48.5/6.0	90.0/7.3	89.7/8.6	82.7/1.2

Table 5.11: Influence of closed Europoort barrier on total probability of occurrence of high-water levels at Dordrecht

The main difference that can be observed from Table 5.11 is that the influence of a closed Europoort barrier is largely reduced from its original value by implementing Delta21. This is the case for all return periods and sea level rises. The larger the sea level rise, the larger the impact of implementing Delta21 becomes. The reduction of the impact of a closed Europoort barrier does not mean that the Europoort barrier closes less often; for this to happen the closure level of the barrier needs to be altered. What does happen is that during a storm for which the Europoort barrier needs to be closed, the resulting water levels are smaller, because a large amount of water is removed from the Delta21 through the Delta21 spillway and pumping station. Hence, the problem of water being retained and piling up has been alleviated largely with the implementation of Delta21 to the flood protection system.

These findings do mean that the influence of a non-closing Europoort actually becomes larger for the system with Delta21. This includes both a correctly opened barrier and a barrier that has failed to close. The latter is visualized in Figure 5.5.This influence of a failing Europoort barrier only starts to become of significance from return periods larger than 1,000 years. It can be concluded from this that the improvement of the failure probability of the Europoort barrier could benefit the reduction of the high-water levels at the Island of Dordrecht, although the benefit is limited to about 0.10 meters for the most extreme situation.

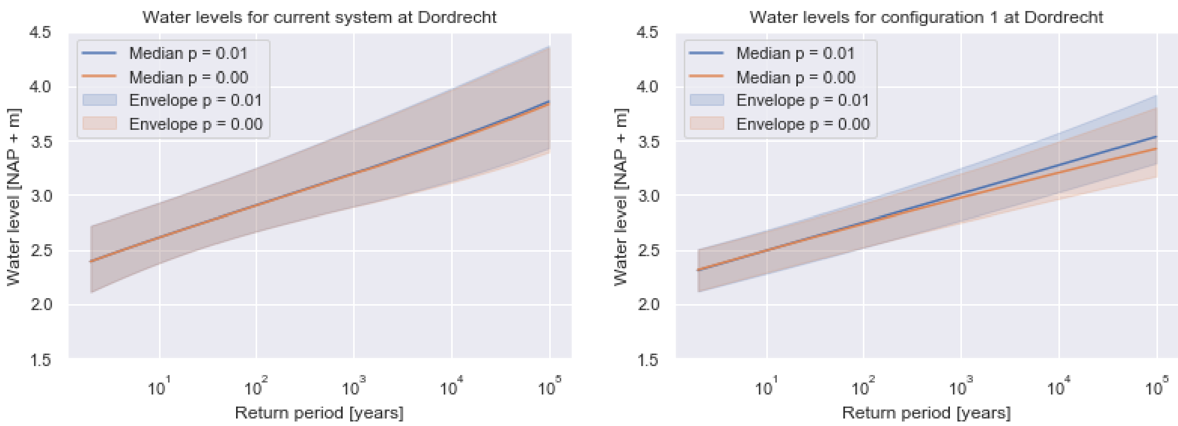


Figure 5.5: Influence of failing Europoort barrier on water levels at Dordrecht for current system and configuration 1

5.7. Concluding remarks

There are four main conclusion remarks to be made regarding the results that have been obtained in this chapter.

- **The implementation of the Delta21 project in the current flood protection system with an Europoort closure level of NAP + 2.9 m at Dordrecht can reduce the value at risk at flood prone areas not protected by flood defenses with 23, 15 and 64 % for the minimum, medium and maximum scenario respectively relative to the current flood protection system.**

- **The implementation of the Delta21 project in the current flood protection system with the Europoort barrier cannot decrease flood frequencies and flood risk at the flood prone areas not protected by flood defenses at Dordrecht enough while also keeping the Europoort barrier closure frequency below three times per year for all scenarios of the year 2100.**
  It is determined that the flood risk per household in the historical harbor can only stay below the 1 % limit if the closure level of the Europoort barrier is at NAP + 2.9 m, just as the 1 $year^{-1}$ limit for the flood frequency at the historical harbor (water level above NAP + 2.5 m). The closure frequency of 10 $year^{-1}$ accompanied by the closure level of NAP + 2.9 m exceeds the current limit of 3 $year^{-1}$. To make the implementation of the Delta21 feasible, the Europoort barrier closure frequency issue needs to be fixed or the barrier needs to be replaced by a more reliable barrier or locks.

- **Positioning all the Delta21 discharge capacity in the mouth of the Haringvliet leads to the Spui and Dordtse Kil becoming bottlenecks for the efficiency of the high-water level reduction function of Delta21. Additionally, the flow discharges through these branches increase up to twofold for the minimum and threefold for the maximum scenario.**
  The flow velocities in the Dordtse Kil and Spui that are up to 30 and 40 % higher respectively may lead to additional erosion and scour holes. To counteract this phenomenon, part of the Delta21 discharge capacity could be relocated or a wider connection between the Oude Maas and Hollands Diep and Haringvliet should be realized.

- **The water levels at the Island of Dordrecht become more dependent on a situation where the Europoort barrier fails to close with the implementation of Delta21.**
  Decreasing the failure probability of the Europoort barrier could lower water levels at the Island of Dordrecht more effectively than for the current flood protection system, though still limited to about 10 centimeters maximum.

6
Impact of reliability Delta21 project on high-water levels

In this chapter, the reliability of the new flood protection system with Delta21 and its impact on the high-water levels at the Island of Dordrecht is determined. This is done for the most frequent operation strategy regarding the flood prone areas not protected by flood defenses that has been determined in Chapter 5. First in Section 6.1 the method through which the impact of the reliability is assessed is given. After this the allowable uncertainty that the reliability of Delta21 introduces onto the water levels at the Island of Dordrecht is determined in Section 6.2. Then an inventory is made of the relevant failure mechanisms and correlations in Section 6.3. After this the failure gradations are discretized in Section 6.4. Finally, it is assessed whether or not the impact of the reliability is normative and if more research is needed regarding the failure probability of one or more components of the new flood protection system with Delta21 in Section 6.5 and the sensitivity to the assumptions made is assessed in Section 6.6.

6.1. Method for determining impact of reliability Delta21 project

In Chapter 5 the optimal operation for the Delta21 project is defined and here only a situation in which all the Delta21 components work as they should is assessed. In reality however, there are situations imaginable where one or more of the Delta21 components is not able to fulfill its function. As this report focuses solely on the high-water reduction function of the Delta21 project, only the reliability of this function is investigated in this report.

For the reliability analysis as performed in this chapter, only the new components of the Delta21 project are taken into account. Though the reliability of the gates of the Haringvliet barrier and even more so the Europoort barrier, as shown in Appendix E, also influence the high-water levels at the Island of Dordrecht, these are not assessed in this chapter. Additionally, the possible correlations between te failure mechanisms of the current flood protection structures of the Rhine-Meuse delta and the structures introduced with the Delta21 project are therefore not evaluated. The reason for this is that the analysis as performed in this chapter should give a clear insight into the sole influence of the Delta21 components and the extra analysis needed for a link between the failure mechanisms of the Europoort barrier and the Haringvliet barrier lies outside the scope of this research. The failure mechanisms of the Europoort barrier are taken into account for the high-water and flood risk calculations of Chapter 5, but only as a factor that is fully independent from the Delta21 components.

The Delta21 project contains structures of unprecedented dimensions. Since the components such as the pumping station are a lot larger than anything that has been built up until this moment, there are many uncertainties that come with it; one of which is the reliability of the system. The reliability of the Delta21 project can be calculated through an extensive fault tree with all the different failure mechanisms. With such a fault tree come three main issues: it is next to impossible to include every single failure mechanism, accurately determining the probabilities of all the failure mechanisms and the correlations between them is not possible and not all failure mechanisms lead to a situation in which the function of the Delta21 system is lost to a normative degree.

Hence, this so-called bottom-up approach to determine the reliability of the Delta21 project is not the most efficient and accurate method for this particular problem. Instead a top-down approach is used. A schematization of this process can be found in the flow chart in Figure 6.1. Firstly, a decision on the allowable uncertainty induced by the reliability of the Delta21 project is made. After this an inventory of the most relevant failure mechanisms is made. Consecutively, a discretization of the degrees of failure of each failure mechanisms is made. These discretized mechanisms are then modeled into the high water calculation model and from this the allowable probabilities of occurrence of these mechanisms can then be found in an iterative manner. Working further up, the acceptable failure probabilities of the components of the Delta21 project can be found for varying correlations. Any assumptions that have been made to come to the maximum allowable failure probabilities per component are then tested in a sensitivity analysis. Finally, a conclusion can be made regarding the impact of the reliability of the flood protection system with Delta21 on the high-water levels at the Island of Dordrecht. If the acceptable probability of failure of a certain component is relatively small, it may be recommended to perform more research on the failure probabilities of and correlations between the components of a subsystem of Delta21.

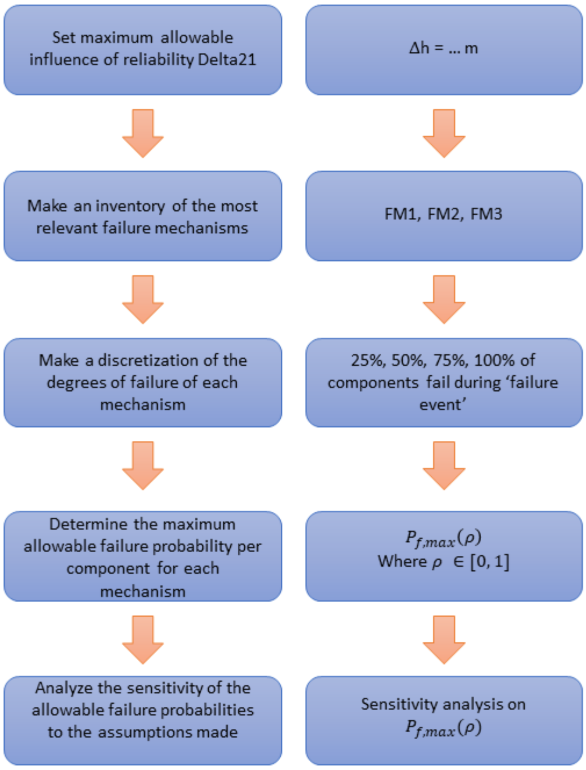


Figure 6.1: Flow chart of the reliability impact process

6.2. Determination of allowable influence of reliability Delta21

Firstly, the allowable uncertainty induced by the reliability of the Delta21 project can be set. As shown in Section 3.5, the range of water levels for all return periods for the year 2100 is fairly large. Though this range is smaller and equal to about 0.5 meters for return periods between 1 and 50 years, for return periods larger than 50 years the range only increases to about 0.8 meters. In Appendix B the validation of the high-water modeling software used for this report gives an insight into the uncertainty of the model results. These uncertainties can be in the range of 5-10 centimeters for very small return periods (< 10 years) and very large return periods (> 10^4 years). Hence, any uncertainty induced by the reliability of the flood protection system that is smaller than 0.10 m, can be regarded as non-normative.

It is therefore decided that the maximum increase of the water level for each return period may be 0.10 m. This means that first it is assessed whether any of the relevant failure mechanism induce such a water level increase and, if necessary, a combination of failure mechanisms could be analyzed.

6.3. Inventory of relevant failure mechanisms and correlations

6.3.1. Inventory of failure mechanisms

As mentioned in Section 6.1, new flood protection system with Delta21 can fail in its function to lower the water level at the Island of Dordrecht. Such situations are assessed in this section and together they form the fault tree of the Delta21 system. It is however of importance how this system is set up. This means it should be determined if these mechanisms are correlated and if they are in a parallel or series setup. The Delta21 project introduces four new main sub-systems: the new storm surge barrier, the energy storage lake, the siphons and the pumping station. All these sub-systems have their own functions within the system, but it is not necessarily the case that the loss of this function is equal to the loss of the function of the system as a whole. In Table 6.1 the functions of each of the sub-systems during high water and low water can be found.

Component	Function	Loss of function
Storm surge barrier	close HW / open LW	open HW / close LW
Pumping station	on HW / off LW	off HW / on LW
Siphons	open HW / close LW	close HW / open LW
Lake	intact	breached

Table 6.1: Functions of Delta21 components during high water (HW) and low water (LW) at sea.

Some of the functionality losses are only relevant when assessing operational costs, but not necessarily for flood risk. For instance, if the pumps are not turned off during low water at sea, more water is discharged from the energy storage lake than necessary. This leads to unnecessary costs, but not to higher water levels at the Island of Dordrecht. Hence, such a failure to provide its function is not relevant to the high-water problems that are assessed in this report. There are two main ways in which the Delta21 project can fail to provide its function: failing to stop water at sea from entering the Rhine-Meuse delta and failing to discharge excess river water towards sea. In Figure 6.2 the fault tree can be found. On the left one can see the failure of Delta21 to stop the water from sea from coming into the Rhine-Meuse delta and on the right the failure of Delta21 to discharge the excess river water.

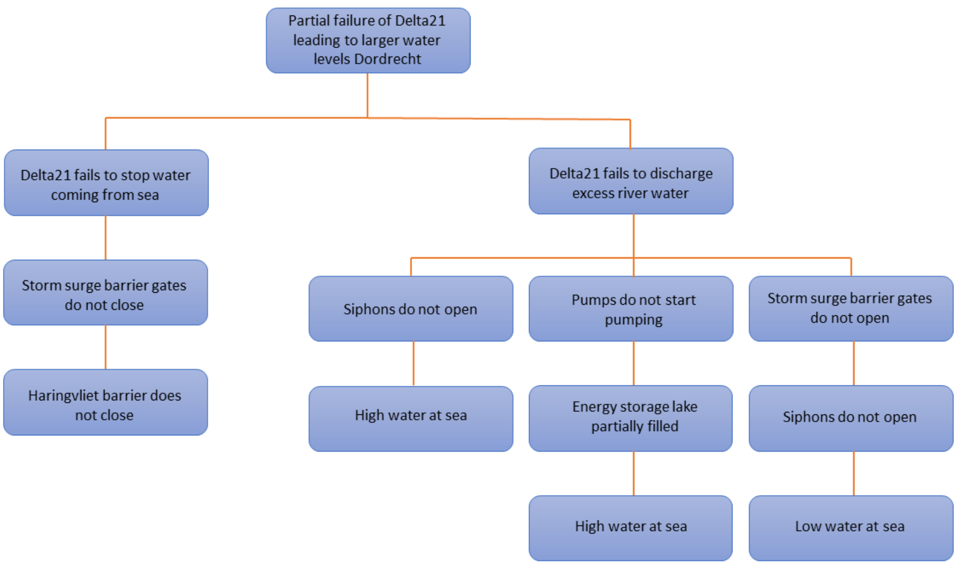


Figure 6.2: Fault tree for the Delta21 project

Both of these failures of the Delta21 system to provide its function lead to higher water levels at the Island of Dordrecht than when the system is functioning properly. It should be kept in mind that there are structural issues regarding for example the new storm surge barrier and the energy storage lake that can lead to higher water levels at the Island of Dordrecht. Given the fact that this report focuses on the flood prone areas not protected by flood defenses, events with relatively small return periods are of the largest interest. Such events could for instance occur multiple times in the lifetime of the Delta21 project. Structural failure mechanisms such as those mentioned would require for large reconstructions that may lead to new findings and hence a reduction in the future failure probabilities. This is not within the scope of this report and is therefore not included in the reliability assessment of Delta21.

6.3.2. Curtailment to relevant failure mechanisms

The fault tree as can be found in Figure 6.2 contains a number of failure mechanisms that either have too little an influence on the water levels at the Island of Dordrecht or the probability of occurrence is far too small to be taken into account. It can be quickly concluded that the inability of the new flood protection system with Delta21 to stop sea water during storm surge from entering the Haringvliet has a very small probability of occurrence. Both the new storm surge barrier as the Haringvliet barrier need to be opened (partially) when they should be closed, which is too improbable to include in this assessment.

This leaves only the inability of the Delta21 system to discharge the excess river water. There are, as can be seen in Figure 6.2, three main failure mechanisms that lead to this inability. All of the failure mechanisms involve extreme conditions such as storm surge at sea or high river discharges. However, the timing of the failure mechanisms within such an extreme event is different. As can be seen in Figure 6.2, the inability of the siphons to open and the pumps to work both are both normative for a situation where high-water levels at sea are present. The inability of the storm surge barrier to open and the siphons to open sufficiently is normative for a situation with low water at sea.

By eliminating the failure mechanisms that involve the inability of Delta21 to stop sea water during storm surge, the three most relevant failure mechanisms that need to be assessed in the reliability analysis are:

1. Siphons not opening during high water at sea
2. Pumps not working during high water at sea
3. Storm surge barrier and siphons not opening during low water

6.3.3. Inventory of failure mechanism correlations

There are two types of correlations that are important within the fault trees shown in Figure 6.2: correlation between the sub-systems and between the components of which each sub-system is made. The first type of correlation can be between the closure of the storm surge barrier and the Haringvliet barrier, whereas the second type of correlation can be between the various gates that make up the new storm surge barrier. It is assumed that each of the failure mechanisms shown in Figure 6.2 cannot occur at the same time and are therefore mutually exclusive. This is an assumption that is made to allow for a simplification in the high-water modeling calculations.

Therefore, only the system set-up of the components and the correlations between these components are of interest. All the sub-systems that are important to the reliability analysis have components that are in a parallel set-up. The Delta21 storm surge barrier and the Haringvliet both are made up of a multitude of gates and the same principle counts for the spillway and pumping station that both consist of many siphons and pumps. The correlation of a failure of closure and/or opening between these components is unknown at the moment. As a means of creating a lower and upper bound for the maximum allowable failure probability per component, it is possible to determine this probability based on a fully dependent or independent system. This means that for a fully dependent system the probability of occurrence of ten pumps not working is equal to that of one pump not working. For a fully independent system this probability would be equal to the probability of one pump not working to the tenth power.

Though correlation between failure of the components is not known, it can be determined what the allowable failure probability per component may be for varying values of correlation. This is further elaborated in Appendix H.

6.4. Discretization gradations of failure mechanisms

Each of the most relevant failure mechanisms as presented in Section 6.3 is a sum of all the different gradations in which the mechanism can occur. For instance, only one siphon can fail to open, which has a relatively large probability of occurrence, but also a very small impact on the water level at the Island of Dordrecht. The other extreme would be that all the siphons failed to open. In its turn this has a very small probability of occurrence, but the effect on the water level at the Island of Dordrecht would be rather large. To accurately describe the influence of this failure mechanism one can either model all of the possible gradations of this failure mechanism as seen in Figure 6.3 or for the sake of simplicity and time-efficiency some middle ground can be chosen. This discretization is done for both the pumping station in failure mechanism 1 and for the spillway in failure mechanisms 2 and 3.

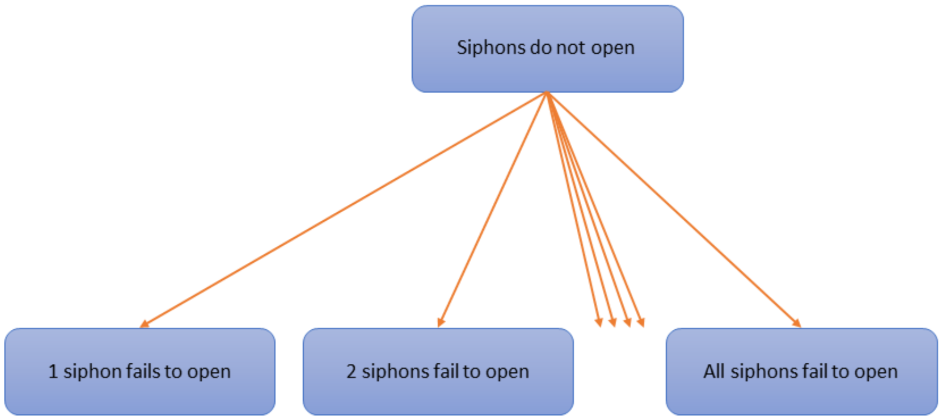


Figure 6.3: Overview of all gradations of failure of siphons component

To limit the amount of calculations that are needed, there are five gradations of failure that are evaluated for each of the failure mechanisms. This means that the case of fully functioning and fully failing component is computed in addition to a failure of 25, 50 and 75% of the components. For each of these gradations the probability that leads to an 0.10 m increase of the water level frequency curve can be found. This in turn is used to calculate the accessory failure probability of a single component.

By analyzing a discretized range of degrees of failure, it can be determined what the most nominal situation is for the high-water levels at the Island of Dordrecht. This approach may lead to an underestimation of the maximum allowed probability of failure per component. However, since the goal is to find the smallest maximum allowed probability of failure, this is the correct method to do so.

6.5. Impact of reliability flood protection system on high-water levels

The three main failure mechanisms as obtained from Section 6.3.2 all influence the water levels around the Island of Dordrecht. This influence varies on the location and the return period of interest. For this analysis the maximum water level increase for return periods between 10 and 100,000 years at any location due to a failure mechanism was obtained. In Figure 6.4 one can find an example of failure mechanism 1 and its influence on the water level frequency curve at Dordrecht. The curves have been created for other locations around the Island of Dordrecht and failure mechanisms 2 and 3.

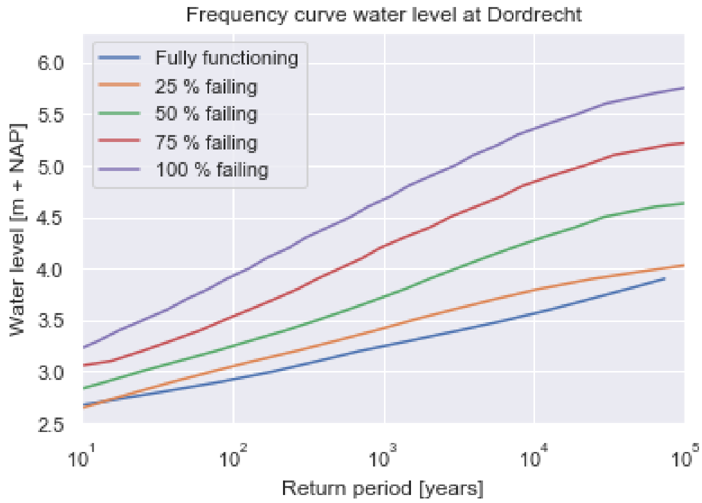


Figure 6.4: Water levels for (partial) failure of spillway at Dordrecht

As mentioned, the maximum impact of the failure mechanisms may be 0.10 m at any location around the Island of Dordrecht. Firstly, the maximum allowable probability of occurrence of the (partial) failures was determined by using the program Hydra-BS in which probabilities of occurrence of a working and failing system could be varies so that the difference with a totally functioning system is equal to 0.10 m maximum for any return period and any location. In Table 6.2 the acceptable probabilities of occurrence of a (partially) failing system for the three main failure mechanisms can be found.

For both the siphon system and the pumping station it is assumed that each component, i.e. each pump and each siphon has a capacity of 100 m^3/s, so both the siphon system and the pumping station consist of 100 components.

	FM1	**FM2**	**FM3**
25%	0.25	0.36	0.73
50%	0.08	0.11	0.23
75%	0.05	0.08	0.15
100%	0.04	0.06	0.11

Table 6.2: Acceptable probability of occurrence of (partial) failure

From the acceptable probabilities of failure in Table 6.2 the maximum allowable failure probabilities per component can be determined. This is done for a completely dependent and independent system to create a lower and upper bound regarding the correlation between the components. In Figure 6.5 the allowable failure probabilities per component can be found.

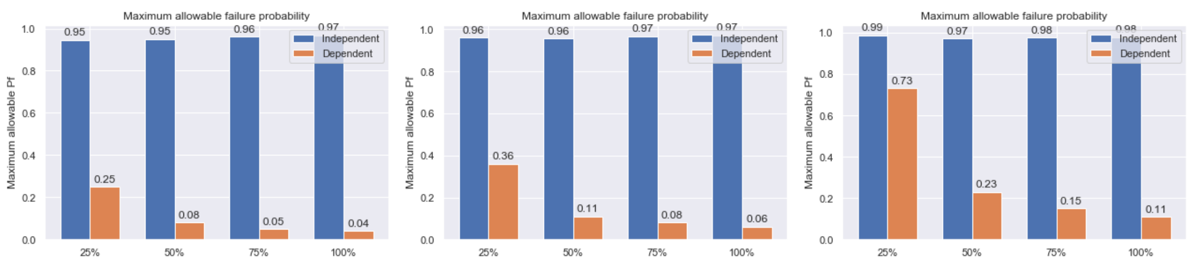


Figure 6.5: Maximum allowable failure probabilities per component for failure mechanisms 1, 2 and 3

The lower and upper bounds of the maximum allowable failure probabilities per component lie very far apart, especially for the more extreme gradations of failure. Hence, the influence of the correlation between the components on the allowable failure probability is determined. These calculations, of which the calculation method is explained in Appendix H, lead to the curves as can be found in Figure 6.6.

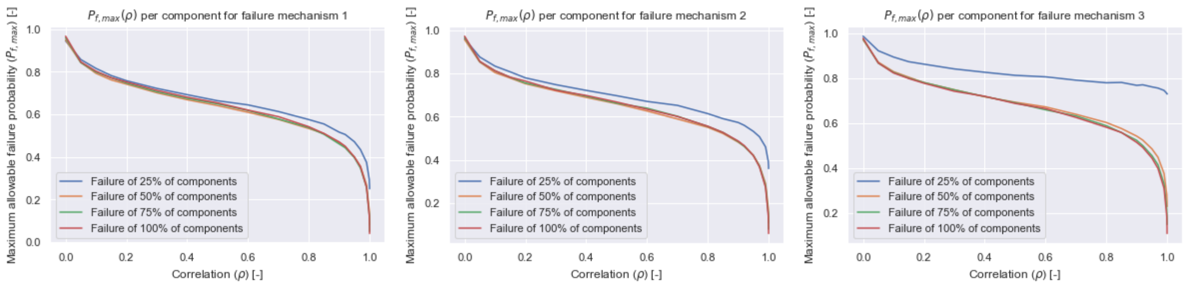


Figure 6.6: Maximum allowable probability of failure per component vs. correlation for failure mechanisms 1, 2 and 3

It is clear that for correlation values larger than 0.9 the maximum allowable probability of failure per component starts to drop rapidly. Hence, if a sub-system such as the spillway or the pumping station were to be designed so that this correlation is not above 0.9, the requirements regarding the probability of failure for the components may be much lower.

6.6. Sensitivity analysis reliability of the flood protection system

A few assumptions have been made in the determination of the impact of the reliability of the Delta21 project on the water levels at the Island of Dordrecht. These assumptions are the following:

- Capacity of siphons at 100 m^3/s
- Capacity of pumps at 100 m^3/s
- Energy storage lake halfway filled at pump failure
- Fully failing storm surge barrier

A sensitivity analysis was performed to test the validity of these assumptions. This means that the assumptions that have been made are changed to assess if this affects the conclusions that follow from this chapter.

For each of the assumptions as mentioned above, the sensitivity analysis concludes that the assumptions do not have a nominal influence on the eventual maximal allowed probability of failure per component. As of the siphon system and pumping station the system consists of many components, the difference between 100 and 200 components is marginal. The method and results of the sensitivity analysis can be found in Appendix H.4.

In the bullets shown below, the maximum allowed probability of failure per component for each of the assumptions for a correlation equal to 0.9 can be found. Between brackets the change compared to the initial calculation is also given. This shows that the sensitivity analysis does not identify a large influence of the assumptions that were made in this chapter and well-founded conclusions can therefore be made based on the results found in Section 6.5.

- Assumption 1

  $P(\text{siphon})_{200\text{comp.}} = 0.52$ (+0.05)

- Assumption 2

  $P(\text{pump})_{200\text{comp.}} = 0.55$ (+0.03)

- Assumption 3

  $P(\text{pump})_{\text{empty}} = 0.55$ (+0.03)

  $P(\text{pump})_{\text{filled}} = 0.50$ (-0.02)

- Assumption 4

  $P(\text{siphon})_{50\%failbarrier} = 0.57\ (+0.03)$

6.7. Concluding remarks

There are three main conclusions to be made regarding the impact of the reliability of the Delta21 project on the extreme water levels at the Island of Dordrecht.

- **The reliability of the Delta21 components is non-decisive for flood risk assessments at the Island of Dordrecht if the correlation between the components of each of the sub-systems stays below 0.9.**
  Decreasing the correlation between the components of the sub-systems from 1 to 0.9 greatly increases the maximum allowable failure probability per component. For the most extreme cases, this allowed increase may be in the order of ten times as large. Hence, if the siphon system and pumping station are designed in such a way that the operation of the components is not fully dependent, the allowable failure probability per component may be relatively high.

- **Failure of the spillway during high water is the most influential failure mechanism, with a failure of the pumping station and a combined failure of the storm surge barrier and the spillway during low water coming at second and third most influential.**
  The lower bound for the maximum allowable failure probability per component for failure mechanisms 1, 2 and 3 are 0.04, 0.06 and 0.11 respectively. If the correlation between the components is at 0.9, the maximum allowable failure probability rises to 0.47, 0.52 and 0.54. This means that each component (pump or siphon) may fail half the times it is requested to discharge river water and the resulting water levels at the Island of Dordrecht do not rise with more than 0.10 m for any return period between 10 and 100,000 years.

- **The impact of the reliability of the pumping station and siphon system does not become significantly smaller by increasing the number of components.**
  Since the most influential gradation of failure of each of these sub-systems is the 100 % failure, it does not matter if the sub-system consists of 100 components with a capacity of 100 m^3/s of 200 of 50 m^3/s. This would only matter if the sub-system were to be comprised of much fewer components.

7

Discussion, conclusions and recommendations

7.1. Discussion

To optimize the use of Delta21 for the flood prone areas not protected by flood defenses at the Island of Dordrecht, multiple models and programs were used and assumptions and approximations were made. To make conclusions that are well founded and account for all uncertainties that the results are subject to, the work done in Chapters 2 until 6 needs to be thoroughly analyzed.

1. **Discussion of present and future boundary conditions without Delta21**

   There are four main factors that need to be investigated before any conclusions may be drawn from the present and future boundary conditions without Delta21, namely:

   - Europoort failure probability
   - Sea level rise
   - Increase of maximum Rhine discharge
   - Plan Locks scenarios and modeling

   (a) Firstly, the value for the Europoort barrier failure probability in this report is 0.01, which is equal to the value that is used in flood protection research as to this moment (Stijnen and Botterhuis, 2015a). However, this value is merely based on software, mechanical and other investigations. The barrier has never failed to close or open during an extreme weather event and so the estimate of 0.01 is a very uncertain one. However, since Dordrecht is located in the transition area between sea dominated and river dominated regions and as is shown in Figure 5.5, the difference between a failure probability of 0.01 and 0 is fairly small and less than just a few centimeters for all return periods. Increasing the failure probability will then increase the water levels, but this increase shall also be within the margins of error of such extreme events.

   (b) Secondly, the values of sea level rise that have been used in the high-water calculations in this report are based on the IPCC scenarios as set in Hinkel et al. (2019). The minimum and maximum scenario as used in this report do account for the lower and upper limit from Hinkel et al. (2019), but there it is also noted that the actual values for sea level rise in the year 2100 are still very uncertain. Hence, when the maximum scenario is mentioned in this report, it is still a maximum of current predictions for the year 2100, but not necessarily the maximum of all possible future realities.

(c) Thirdly, the future maximum Rhine discharge, or the Q_{1000} of the Rhine are taken as relatively large in this report. Though in Görgen et al. (2010) it is said that the maximum Rhine discharge might be about 10 to 20% higher by the year 2100, other researches such as Stijnen and Botterhuis (2015a) use a Rhine discharge of 17,000 m^3/s and 18,000 m^3/s for the medium and maximum scenario respectively and in De Vriend et al. (2016) a maximum of 17,500 m^3/s is used. As shown in Appendix C, the maximum Rhine discharge does have an influence on the water levels at the Island of Dordrecht, especially at the most eastern part (discharge dominated region). However, the regions that account for most of the damages due to flooding of the flood prone areas not protected by flood defenses show about 0.10 m or less for return periods smaller than 1,000 years. The overestimation of the water levels due to the larger Q_{1000} used in this report can therefore only be about 0.10 m maximum. For return periods that are most relevant for flood prone areas not protected by flood defenses, say 100 years, this difference is even smaller.

(d) Lastly, the scenarios and modeling of Plan Locks need to be discussed. As mentioned in Chapter 2, the scenarios for Plan Locks are different than that of the current flood protection system, since the calculations were done by Stijnen and Botterhuis (2015a). In this report, the current situation from Stijnen and Botterhuis (2015a) is used as the minimum scenario for visualization purposes. Also all results such as flood frequencies and flood risk are compared with the scenarios that are set up in this report. This choice was made to avoid any scientifically unfounded interpolations between the scenarios from Stijnen and Botterhuis (2015a). Though it must certainly be kept in mind that all results from Stijnen and Botterhuis (2015a) are based on smaller sea level rise and maximum Rhine discharge values.

2. **Discussion of flood risk without Delta21**

There are four factors that need to be discussed before any definitive conclusions can be drawn from the water levels and flood risk for the current flood protection system and Plan Locks, namely:

- Land subsidence
- Flood damage curves
- High-water modeling
- Flood risk per household at historical harbor

(a) Firstly, land subsidence levels that are used in Chapter 3 are based on averages of extensive areas that are sometimes larger (historical harbor) or smaller than the area of interest (Biesbosch). For the former, it is not known if regions outside the area of interest contribute relatively more or less to the average land subsidence level and for the latter the area of interest might be subject to various values of land subsidence. In this report, the land subsidence level is taken as constant for each area for the coming 80 years until 2100. For the historical harbor and Biesbosch the difference between the present damage profiles and the future ones is not that large. However, for the flanks, the difference in subsidence between the tiles from AHN (2019) can be up to a factor 5. As can be seen in Table 3.5, the influence of the flanks to the total flood risk decreases from about 30 % for the minimum scenario to about 20 % in the maximum scenario. This does mean that if the land subsidence at the flanks is somewhat smaller or larger, the total flood risk at the flood prone areas not protected by flood defenses can differ up to 10 % from the values given in this report. Hence, a significant uncertainty is induced by the unknown land subsidence at the Island of Dordrecht.

(b) Secondly, the flood damage curves of each of the flood prone areas not protected by flood defenses that are created using the program SSM-2017, are a relatively large factor of uncertainty to the flood risk calculations made in Chapter 3. The first factor of uncertainty is the creation of the flood maps as described in Appendix A. These flood maps are created by adding a certain water level to an elevation map of the Island of Dordrecht. In the analysis it was checked that no spontaneous floods occur, but on small scales it is very hard to accurately predict the flood damages in a specific area. For larger water levels, the flood damage curves start to follow a certain trend, but especially for smaller water levels (that are most relevant for flood prone areas not protected by flood defenses) this behavior is not yet to be found. Additionally, the SSM-2017 software does not include local measures and indirect damages due to flooding. However, since these measures have counteracting consequences, it can be deduced that the flood damage curves are accurate enough to give a global insight into the damages occurring at the flood prone areas not protected by flood defenses at the Island of Dordrecht.

(c) Thirdly, alongside the flood damage curves, the high-water modeling calculations that have been performed to come to the flood frequency curves in Chapter 3 are one of the most essential factors. The calculations were performed using the program MHWp5, which is different from the program used to create the WBI databases. In Appendix B the water levels determined for this report are compared to the WBI database, which shows that the results are very similar for nominal return periods, but for very small and very large return periods, the water levels start to deviate. Which of the two databases shows the correct water levels is very hard to say, but it can be concluded that the MHWp5 program is calibrated for nominal return periods. This makes it somewhat less ideal for relatively small storm surge and low discharge values. In this report the uncertainty factor that is normally added to the water level curves, was left out. The reason for this was that in this report no flood protections are tested. Adding an uncertainty factor of 5 to 10 centimeters to the water levels only distorts the flood risk and flood frequency values that are used to give a realistic insight into the state of the flood prone areas not protected by flood defenses for the present and future situation.

(d) Lastly, the flood risk per household at the historical harbor is one of the most important values that results from this report. This average annual value at risk was presented as a percentage of the annual income per household to put the flood risk values of the regions into perspective. The value that is presented in Table 3.9 solely incorporated damages to residential buildings and household effects. However, since the buildings in the historical harbor are largely historical and culturally valuable buildings, there is a lot of uncertainty regarding the true potential and actual damages during a high-water event. Additionally, the potential decrease in the value of these buildings is not taken into account. However, if a historical building of €500,000 were to lose 10% of its value due to very frequent flooding, this would constitute to about 30 years of flood risk. Hence, the percentage of the annual value at risk compared to the annual income per household at the historical harbor can be much higher. To determine this more accurately, the situation per house and its household effects should be investigated as well as the real-estate dynamics in the region.

3. **Discussion of future boundary conditions with Delta21**

There are two factors that need to be discussed before any definitive conclusions can be drawn from the inventory of the future boundary conditions with the Delta21 project, namely:

- Modeling of Delta21 project
- Delta21 configuration variants

(a) Firstly, the modeling of the Delta21 project is one of the most vital parts of this report. All the assumptions that have been made are mentioned in Chapter 4.3 and the most important limitations are discussed here. The first limitation is that the closure operation of the flood protection system with Delta21 is kept the same as the current system. Hence, the Europoort barrier closes the last low water before the storm and from 6,000 m^3/s the so called turnaround closure (Dutch: 'kenteringsluiting') is used. This is done so that the results from Chapter 3 could be compared with those from Chapter 5. However, for the actual flood protection system with Delta21 the closure operation of the Europoort barrier could be adjusted. For example, the barriers could close

12 hours earlier, so that during a longer period of time the water levels in the Rhine-Meuse delta can be lowered. Another part of the modeling that might lead to deviations from reality is that the Front Delta (Dutch: 'Voordelta') is changed from the current situation due to the implementation of Delta21, but the exact tidal inlet that remains after the construction of the storm surge barrier is uncertain and only an estimation of this has been made for the calculations made regarding this report. However, this tidal inlet is not as important as that at the Nieuwe Waterweg, since the Haringvliet barrier is still there.

(b) Secondly, the number of Delta21 configurations presented in Chapter 4 is fairly limited compared to the actual amount of configurations that are possible. However, in this report only a range of possibilities is presented to give an insight into the influencing factors of the new flood protection system.

4. **Discussion of optimizing the operation of Delta21 and the limitations of the effectiveness of Delta21**

There are three factors that need to be discussed before any definitive conclusions can be drawn from the optimization of the operation of Delta21, namely:

- Criteria regarding optimal operation
- Optimal operation of Delta21
- Change of flows in Rhine-Meuse delta

(a) Firstly, in this report a selection of four main criteria regarding optimal operation has been made. Especially the flood risk and flood frequency are focused on the historical harbor, as this is currently the most critical flood prone region not protected by flood defenses (Gersonius, B., personal communication, November 2 2020). However, if the report were more focused on natural preservation of the Biesbosch, the criteria used in the report would be much different. Hence, as in this report the focus lies on monetary damages, the choice of criteria is justified.

(b) Secondly, the optimal operation of Delta21 can be a subject of discussion. The optimal closure and initiation levels of the Europoort barrier and Delta21 are defined such that first and foremost the flood frequency at the historical harbor does not exceed 1 $year^{-1}$ and the annual value at risk per household does not exceed 1% of the annual income. These values are based on insight into the critical flood risk and flood frequencies obtained from (Heinen, R., personal communication, October 30 2020) and (Gersonius, B., personal communication, November 2 2020), but they provide only a first insight with limited scientific support. There is currently no uniform agreement on what is acceptable and from what situation the historical harbor is critically negatively impacted by high-water. Also the maximum Europoort closure frequency of 3 $year^{-1}$ is yet to be scientifically proven. A higher acceptable closure frequency along with higher acceptable flood risk and frequencies could give more room for the Delta21 project to be efficient for flood prone areas not protected by flood defenses at the Island of Dordrecht.

(c) Thirdly, the flows in the Rhine-Meuse delta are a subject for discussion. Firstly, the discharge changes during storms given in Figure 5.4 should be carefully interpreted. The values that are given as relative increases of discharge in the different branches of the Rhine-Meuse delta cannot be physically interpreted. These are merely a weighed average of the mean discharge through a branch during a high-water event. Hence, a less extreme situation is weighed less than a very extreme event. However, no conclusions can be drawn as to how the occurrence of high discharges through each branch is changed due to the implementation of Delta21. It just gives an insight into the overall distribution change and where potential bottlenecks in the system can occur.

There are also three main limitations to the effectiveness of the currently proposed Delta21 project in the current flood protection system for flood risk and flood frequency reduction at the flood prone areas not protected by flood defenses at the Island of Dordrecht, namely:

- Closure frequency and failure probability of the Europoort barrier
- Closure and initiation procedure of the Europoort barrier and the Delta21 project
- Location of the Delta21 discharge capacity

(a) Firstly, the limitation of the closure frequency and the relatively high failure probability of the Europoort barrier largely reduce the potential of Delta21. Regarding the Island of Dordrecht, mostly the limit of a closure frequency of three times per year is the most influential factor. The high failure probability of the Europoort barrier is less important for the high-water levels at the Island of Dordrecht, but it does eliminate the water level reduction at locations in the sea dominated region such as Rotterdam. Both these issues may be alleviated by either improving the existing Europoort barrier or constructing a new barrier so that the failure probability is lower and that mechanical and structural issues, that lie at the foundation of the limitation of the closure frequency, are dealt with. Also, a higher closure frequency may be allowed through such an improvement if the maintenance works that are performed outside the storm season take less time. Eventually, the construction of a lock complex could solve both problems. Though such a complex may lead to problems with shipping, actually for the maximum scenario one would be able to lower the closure level significantly while still allowing ships to and from the North Sea to pass.

(b) Secondly, the current closure procedure of the Europoort barrier is limiting the effectiveness of the Delta21 project. Here mainly the timing of the closure is meant. Currently, the Europoort barrier closes as late as possible to minimize the impact on shipping and limit the amount of river water that gets trapped by the closed barrier. However, by implementing Delta21 a large water level reduction can be made by closing the barrier much earlier, for instance one low water or 12 hours before the present closure time. By pumping away more water than is retained by the Europoort barrier, extreme situations in which the Europoort barrier is closed can become even less influential on the normative high-water levels.

(c) Thirdly, the location of the Delta21 discharge capacity is a limiting factor in its effectiveness to lower high-water levels at the Island of Dordrecht and the northern branches of the Rhine-Meuse delta. As mentioned in Section 5.6.1, flows through the Dordtse Kil and Spui increase significantly with the implementation of Delta21. Not only does this lead to more erosion of these branches, it also acts as a bottleneck in the lowering of water levels in the Rhine-Meuse delta. Moreover, to improve the effectiveness of the Delta21 project to lower high-water levels in the northern branches of the Rhine-Meuse delta (this includes the Beneden Merwede and Oude Maas along which the Island of Dordrecht is situated) it may be more efficient to locate some of the Delta21 discharge capacity to these northern branches. For instance, it could be located at the Hartel or Maeslant barrier, a new storm surge barrier or lock complexes in the Nieuwe and Oude Maas such as is proposed in Plan Locks (Van Waveren et al., 2015). By doing so, the distance from the pumping location to the area at which the water level needs to be lowered can be reduced. Also the amount of water that needs to be drawn through narrow branches such as the Dordtse Kil and Spui can be minimized. Placing a pumping station at the Maeslant barrier could have the additional advantage that the barrier does no longer need to be opened vertically during the turning of the tide, which could lower the probability of failure and increase the limit of the limit of the closure frequency as mentioned above.

As a first estimate of the required pumping capacity at the northern branches, one could look at a branch on which the Delta21 project has little influence such as the Lek. The normative Rhine discharge for a return period of 1,000 years at Schoonhoven is about 13,000 m^3/s. For such a Rhine discharge the average flow through the Nieuwe and Oude Maas is about 2,000 and 1,000 m^3/s respectively. Hence, the total pumping capacity in the Nieuwe Waterweg would have to be about

3,000 m^3/s. This is the same capacity as is proposed in Plan Locks (Stijnen and Botterhuis, 2015a).

Additional to relocating the Delta21 discharge capacity, the problem may be partly dealt with more upstream in the delta. The flow through the Lek during high Rhine discharges can for instance be limited. In that case more water can be diverted towards the Waal at the Pannerdense Kop, meaning that flood risk in the Lek drops and less water needs to go through the Dordtse Kil and Spui during the initiation of Delta21. However, this also leads to higher water levels along the Waal and the subsequent branches.

5. **Discussion of impact of reliability Delta21 on high-water levels**

There are three factors that need to be discussed before any definitive conclusions can be drawn from the determination of the impact of the reliability of the Delta21 project on the high-water levels at the Island of Dordrecht, namely:

- Reliability of Haringvliet and Europoort barrier
- Allowable uncertainty induced by reliability
- Failure of the Delta21 storm surge barrier

(a) Firstly, the impact of the reliability of the Delta21 project on high-water levels at the Island of Dordrecht, as determined in this report, is solely calculated for the Delta21 components. However, by introducing these components, a relatively strong dependency might be created with the current flood protection structures in the Rhine-Meuse delta such as the Haringvliet and the Europoort barrier. Such a dependency definitely influences the allowable probabilities of failure per component as presented in Chapter 6. A dependence can for instance be created through the changes that the Delta21 introduces to the flows and water levels in the delta. These changes may affect the opening frequency of the Haringvliet sluices and the duration that the Europoort barrier discharges river water during the turning of the tide. Most likely, due to this created dependency between the new and current components of the flood protection system, the values of maximum allowed probability of failure, as presented in Chapter 6, are prone to changes when also considering the Haringvliet and Europoort barrier.

Also the failure of opening of the Haringvliet barrier can influence the effectiveness of the Delta21 project. Though the Haringvliet sluices might be able to actually discharge more water if one of the gates were not to open due to the larger water level gradient between the Haringvliet and the tidal lake, it is still the case that for a full reliability assessment of the flood protection system with Delta21, the failure mechanisms of the Haringvliet barrier should be incorporated. However, noticing the very high allowed probability of failure per component for all failure mechanisms, the small uncertainty introduced by these two factors is not expected to change the conclusions that can be drawn from the performed calculations.

(b) Secondly, the allowable uncertainty that the reliability of Delta21 induces is set to be 0.10 meters. This is based on the uncertainty that is already present in the high-water level frequency curves, which is in the same order of magnitude. However, since it was assessed that the maximum influence may be 0.10 meters for all return periods between 10 and 100,000 years and all locations around the Island of Dordrecht, this might lead to a underestimation of the maximum allowable probability of failure per component. However, since the allowable probabilities of failure found in Section 6.5 are relatively high and not nominal, this underestimation is not a large issue.

(c) Thirdly, the Delta21 storm surge barrier is not analyzed all that specifically in this report, which is mainly due to the Haringvliet barrier that is still in operation. This is how the Delta21 project is currently designed and also modeled, but in case the Haringvliet barrier were to be removed from the Haringvliet, the reliability analysis would be somewhat different. In that case, the failure mechanism in which the Delta21 storm surge barrier does not (partially) close, high water would be able to intrude the delta. This is a situation that is possibly interesting to assess once the barrier is designed and more information is available on the future of the Haringvliet barrier.

7.2. Conclusions

In Chapters 2 to 6 the methodological steps as presented in Section 1.4 have been followed. The results and concluding remarks from these methodological steps are combined and form the main conclusions of the report. In the following points the main conclusions of this report are given and finally the conclusion regarding the objective of the report is presented.

1. **Conclusions from flood risk without Delta21**

   (a) The present flood risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht is equal to €110,000 per year. The future flood risk is equal to €390,000, €1,300,000 and €8,100,000 per year for the minimum, medium and maximum scenario of the year 2100 respectively. This means that the flood risk increases with a factor of 3 compared to the present situation for the presently observed sea level rise rate and a factor 12 and 70 for the medium and maximum scenario for the year 2100 as defined by the IPCC respectively.

   (b) The flood risk is going to shift from the Biesbosch towards the flanks. The historical harbor, flanks and Biesbosch are going to constitute to about 50, 30 and 20 % respectively for the medium scenario of the year 2100 compared to the present distribution of 50, 10 and 40 %. The large contribution of the historical harbor to the total flood risk means that for the medium scenario this risk can constitute up to 1 % of the average annual income per household and for the maximum scenario up to 8 %. This exceeds the limit of 1 % that has been set in this report.

   (c) The implementation of Plan Locks could significantly lower the high-water levels at the Island of Dordrecht and the resulting flood risk can be kept near present values until a sea level rise of at least 0.85 m.

2. **Conclusions from optimizing the operation of Delta21**

   (a) The implementation of Delta21 in the current flood protection system with an Europoort closure level of NAP + 2.9 m at Dordrecht can reduce the value at risk with 23, 15 and 64 % for the minimum, medium and maximum scenario respectively relative to the current flood protection system.

   (b) The implementation of the Delta21 project in the current flood protection system with the Europoort barrier cannot keep flood frequencies below once per year and the percentage of flood risk compared to income per household under 1 % while also keeping the Europoort barrier closure frequency below three times per year for all scenarios of the year 2100.

   (c) Positioning all the Delta21 discharge capacity in the mouth of the Haringvliet leads to the Spui and Dordtse Kil becoming bottlenecks for the efficiency of the high-water level reduction function of Delta21. The flow discharges in these branches increase up to twofold and threefold for the minimum and maximum scenario respectively. The increase of the flow velocities in the Spui and Dordtse Kil of up to 40 and 30 % may also lead to additional erosion and scour holes.

   (d) Due to the implementation of Delta21, high-water levels at the Island of Dordrecht become more dependent on a situation where the Europoort barrier fails to close. Decreasing the failure probability of the Europoort barrier is therefore more effective than in the current flood protection system.

3. **Conclusions from impact of reliability Delta21 on high-water levels**

   (a) The reliability the Delta21 components is non-decisive for flood risk assessments at the Island of Dordrecht if the correlation between the components of the spillway and the pumping station stays below 0.9. Increasing the correlation between the components from 0.9 to 1 means a extreme decrease of the maximum allowable failure probability per component.

(b) Failure of the spillway during high water at sea is the most influential failure mechanism of the Delta21 project. The maximum allowable failure probability per component for a spillway of 100 siphons with a capacity of 100 m^3/s is about 0.04 for a completely dependent system. This value rises to 0.47 for a correlation equal to 0.9. This means that each siphon of the spillway may fail about half the times it is request to discharge river water.

(c) The impact of the reliability of the spillway and the pumping station does not become significantly smaller by increasing the number of components from 100 with a capacity of 100 m^3/s to 200 with a capacity of 50 m^3/s.

Conclusions regarding the objective of the report

The inclusion of Delta21 in the current flood protection system with the present Europoort closure level can provide a significant reduction of the future flood risk of the flood prone areas not protected by flood defenses at the Island of Dordrecht. However, it is not possible to create an optimal operational scheme for all scenarios of the year 2100 in which the flood protection system with Delta21 complies with the flood requirements of the flood prone areas not protected by flood defenses and the limitations of the Europoort barrier. Finally, the reliability of the new Delta21 components is non-decisive for the flood risk assessments that have been made as long as the components are not fully dependent.

7.3. Recommendations

Based on the conclusions regarding the objective of the report, recommendations are given for the Delta21 project to meet the flood requirements of the flood prone areas not protected by flood defenses and to deal with the Europoort barrier limitations that prevent the possibility of an optimal operational scheme.

1. **Recommendations to meet flood requirements**

(a) **Investigate an adjusted closure and initiation procedure of the Europoort barrier and the Delta21 project.**
The Delta21 project may lead to larger water level reductions when the Europoort barrier is closed and Delta21 is initiated 12 hours earlier than what is used in this report. By closing the storm surge barriers one low water earlier than in the current closure procedure, the adaption time of the delta due to the sudden pumping discharge in the Haringvliet can be dealt with. In Figure 7.1 an insight in such an adjusted operation is given for configuration 1 for the minimum scenario. As can be observed, an additional 0.10 m of water level reduction may be realized if this closure operation were to be further optimized. Though problems will arise regarding closure frequencies and closure duration, the adjusted closure operation could make the water level reduction function of Delta21 up to 50 % more effective.

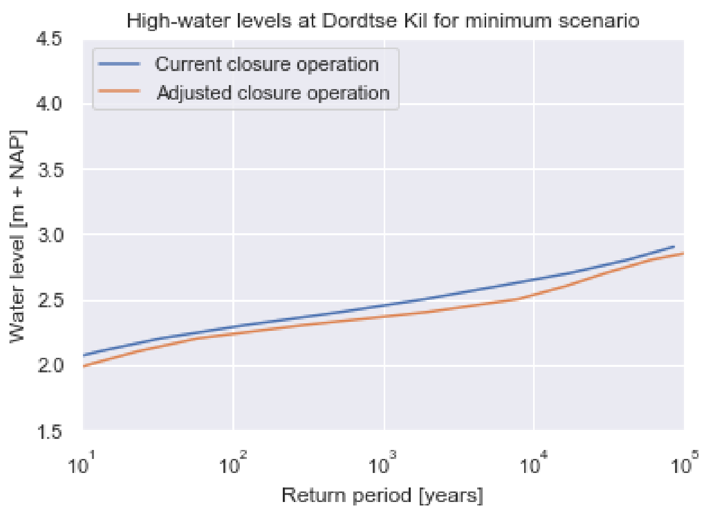


Figure 7.1: Water levels for an adjusted operation of Delta21 for configuration 1 for minimum scenario

(b) **Look into the option to either divert less water towards the Lek and more to the Waal at the Pannerdense Kop during high Rhine discharges or to move part of the high-water discharge capacity of the Delta21 project from the Haringvliet to the northern branches.**
One of the problems that arises from this report is that the distribution of the discharges in the Rhine-Meuse delta is not optimal for the implementation of Delta21 in its current form. The bottleneck in the system that occurs at the Dordtse Kil and Spui needs to be alleviated. It is recommended to look into the option to either divert more river water towards the southern branches (Waal) or to move part of the high-water discharge capacity of the Delta21 project from the Haringvliet to the northern branches. By doing so, the Delta21 pumping discharge and pumping duration may be decreased as the system becomes more responsive, i.e. water levels at Dordrecht are more directly impacted by the operation of Delta21. Furthermore, erosion of the bed of the Dordtse Kil and Spui that is currently happening leading to scour holes does not increase with the implementation of Delta21 if the increase of flows through these branches can be minimized.

(c) **Investigate the potential flood damages at the historical harbor in more detail to determine if a large scale project such as Delta21 can provide enough flood risk reduction or if local measures are necessary.**
The water level at the Island of Dordrecht is going to exceed NAP + 2.5 m more often by the year 2100. By assessing the acceptable flood risk and frequency at the historical harbor, it may be determined if the implementation of large scale projects such as Plan Locks and Delta21 are drastic enough or if local measures are needed. For instance, as is currently being investigated (Gersonius, B., personal communication, November 2 2020), the heightening of the quays or construction of flood walls at the historical harbor may be necessary if the flood frequencies and risk at this region exceeds what is ought to be acceptable. The once per year flood frequency and flood risk as 1 % of the income per household limits that are set in this report might not actually be the true critical values. This needs to be further investigated

2. **Recommendations to deal with Europoort barrier limitations**

(a) **Assess a combination of the Delta21 project with an upgraded Europoort barrier, a new storm surge barrier in the Nieuwe Waterweg or a lock complex as present in Plan Locks.**
Since the influence of the limited maximum closure frequency and failure probability of the Europoort barrier is largely defining the potential of the Delta21 project, the assessment of an upgraded Europoort barrier, a new storm surge barrier or a lock complex in combination with the Delta21 project can give new insights. Either one of these possibilities may lead to a increase in the allowable closure frequency. Maybe even a lower closure level might be possible to further decrease the flood risk of the flood prone areas not protected by flood defenses. The reassessment of the Europoort barrier is around the time that the Delta21 project might be implemented. Hence, it is essential to further investigate the Delta21 project in combination with alternatives to the current Europoort barrier.

Appendices

A

Flood damage profiles

This appendix explains the method that was used to create the flood damage profiles from Chapter 3. First the creation of the flood depth maps of the flood prone areas not protected by flood defenses on the Island of Dordrecht is explained, then how these flood depths were translated into flood damages and finally how the flood damage profiles were created.

A.1. Flood depth maps

To create the flood depth maps during high water at river branches around the Island of Dordrecht, the following steps needed to be followed:

1. Obtain elevation map
2. Manipulate elevation map
3. Create flood depth maps

A.1.1. Obtaining elevation map

From the General Height dossier of the Netherlands (AHN) different types of elevations maps can be obtained (AHN, 2019). The main types are the so called DSM (Digital Surface Model) and DTM (Digital Terrain Model). The unfiltered maps obtained from LIDAR observations are the DSM maps. These include all kind of objects such as buildings and trees. The DTM maps were created by filtering out those objects, creating an elevation map that could be used to calculate flood maps. In Figure A.1 the DSM and DTM map of the Island of Dordrecht can be seen. It is clear that the DTM model deleted any objects that are not terrain. The highest locations are shown in yellow.

Figure A.1: Digital Surface and Terrain Model map of the Island of Dordrecht.

As this report focuses on the flood prone areas not protected by flood defenses, all the areas that are protected by flood defenses were deleted from the elevation map. This lead to the final elevation map that needed to be manipulated to create flood depth maps. In Figure A.2 this digital terrain model map of the flood prone areas not protected by flood defenses of Dordrecht can be found.

Figure A.2: Digital Terrain Model map of the flood prone areas not protected by flood defenses

The elevation map given in Figure A.2 gives no values for places where objects such as buildings and trees were detected. However, by leaving them blank, an underestimation of the flood damages might occur. For instance, underneath trees infrastructural objects might be present. Another example might be that the objects of value as used in SSM-2017 are very small and because of uncertainties in their location, they might be placed on the grid cell of a building with no elevation. Hence, these gaps needed to be filled in to lead to the most accurate flood damage maps.

A.1.2. Manipulation elevation map

The gaps shown in Figure A.2 were filled by using the elevations surrounding the gaps. By doing so, the tiles with objects that were deleted from the Digital Surface Model can be flooded. This way the objects that actually account for the largest portion of the flood damages are not excluded from the flood damage calculations. Using an interpolation function of QGIS, a realistic elevation map was obtained. In Figure A.3 one can observe the resulting Digital Terrain Model elevation map of the flood prone areas not protected by flood defenses at the Island of Dordrecht.

Figure A.3: Digital Terrain Model elevation map with interpolated gaps.

A.1.3. Creation flood depth maps

The flood depth maps were created by setting a certain water level for the entire map and checking whether the water level exceeds the terrain elevation of the map as can be seen in Figure A.3. Here lies the problem that this could create 'spontaneous' flooding at areas that are located lower and away from the flooding open water bodies. To avoid such situations, it was checked if any tiles went from no flood depth to a small depth for each water level step. If this was the case, the specific tile was heightened just enough so that this spontaneous flooding would not occur anymore. Because this did not have to be done for many situations, it is assumed that the uncertainty from this is negligible.

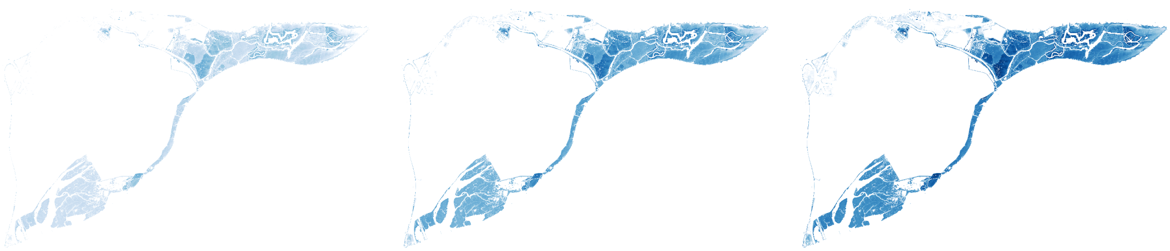


Figure A.4: Flood depths map for Rhine water levels of NAP + 2, + 3 and + 3.6 m

A.2. Translation flood depths to damages

The translation of the flood depth maps into total damages was calculated by the program SSM-2017. This program takes as input flood depths of a certain area, overlaps these with objects that are located at these grid points and calculates the flood damage that is resultant based on specific damage functions for each object type (see Figure A.5). There are different kinds of objects and damages that are used for the different methods the program implements (Slager and Wagenaar, 2017).

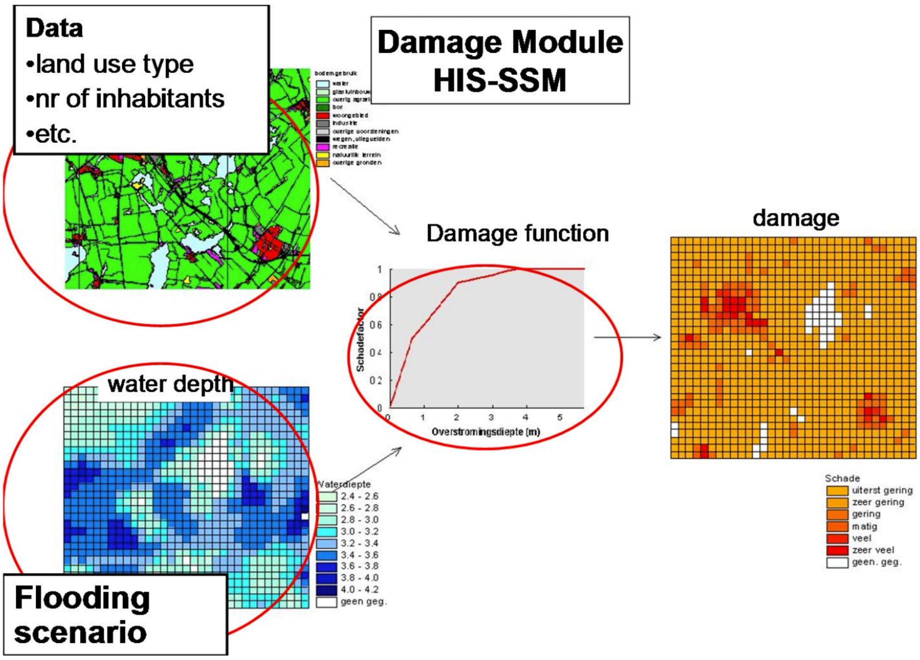


Figure A.5: Structure of SSM-2017 (Bruijn et al., 2015)

This program implements three main methods, namely: inside the main flood defenses, outside the main flood defenses (flood prone areas not protected by flood defenses) and inside regional flood defenses. For this report, the method for areas not protected by flood defenses was used. Flooding of flood prone areas not protected by flood defenses is fundamentally different from other types of flooding in a way that the flood depth is directly dependent on the water depth at the neighboring river. So as soon as the water level at the river drops again, the flood depth does as well, whereas for a breach of a flood defense and a flooded polder it takes much longer to make the area dry again (Slager and Wagenaar, 2017).

Hence, the method for flood prone areas not protected by flood defenses is a largely simplified method where only flood depths have to be given as input and the duration of the event and the flow velocities are not used. Therefore, the only damage that can identified for flooding of flood prone areas not protected by flood defenses is direct damage to properties. Damages due to a disruption to business does not have to be included, because of the aforementioned reasons (Slager and Wagenaar, 2017). Other indirect damages were not calculated by SSM-2017, but instead qualitatively determined based on flood frequencies.

A.3. Overview damages

The flood prone areas not protected by flood defenses at the Island of Dordrecht are split up into three regions, namely the historical harbor, the flanks and the Biesbosch. Hence, the potential damages due to flooding are divided into these three regions. Additionally, the water level along the Island of Dordrecht differentiates during a single event and therefore not a single uniform water level and resulting damage total can be created.

The damages due to a flooding event at one of the regions not protected by flood defenses can be divided into four main categories, namely businesses, infrastructure, residences and other. As Figure A.5 describes, combining the land uses provided by SSM-2017 and the water depths such as in Figure A.4 gives a damage map and eventually a total flood damage for each of the flood prone regions not protected by flood defenses. An example of such a damage map can be seen in Figure A.6. Along the historical harbor the damages are clear, but it is apparent that there is no damage reported in many other areas. This is due to the fact that SSM-2017 does not include any damages due to flooding of agricultural or Natura 2000 areas. The assumption is that timely evacuation of life stock is possible and that the relatively brief flooding of such areas does not impose for instance crop failure (Slager and Wagenaar, 2017). Additionally, the damages at the flanks and Biesbosch are less clear, because they are less concentrated in a small region such as is the case at the historical harbor.

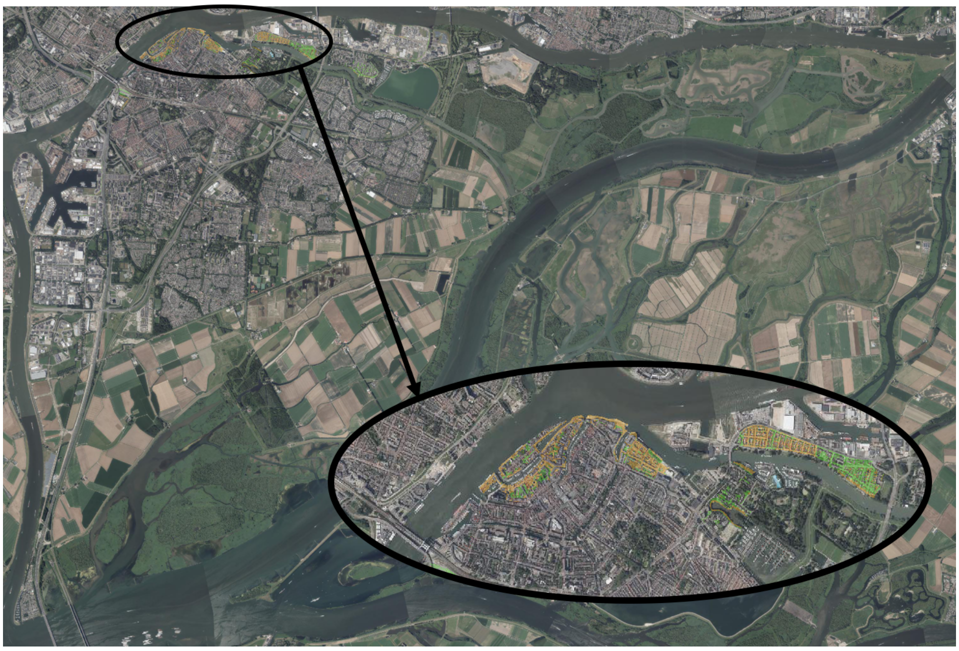


Figure A.6: Flood damage map for water level at NAP + 3.6 m

The flood damage map as seen in Figure A.6 leads to the creation of flood damage profiles. These flood damage profiles give the damage at a specific region for varying water levels near this region.

B

High-water modeling process

This appendix introduces the high-water modeling process that has been used for the high-water levels at the Island of Dordrecht as presented in this report. First an overview of the main modules of the whole process and the workflow is given and after that each of these modules is explained in depth.

B.1. Overview process and workflow

There are two main programs that are used in the high-water modeling process as performed in this report. These programs are MHWp5 and Hydra. Together these programs create an overview of the frequencies of occurrence of extreme water levels at one or more locations of interests for a specific sea level scenario and occurrence of high Rhine discharges.

The core of the process from MHWp5 is a D-FLOW 1D SOBEK model of the Rhine-Meuse delta. This model comprises all the river branches including hydraulic structures and their control system settings. A set of boundary conditions can be imposed on the model, which in turn returns the corresponding water levels at predefined locations from the 1D flow simulation for each time step. This includes the potential influence of the use of hydraulic structures such as the Haringvliet- and Europoort barrier.

In Figure B.1 the overall schematization of the high-water modeling process can be found. Firstly, a project is created and along with it the hydraulic boundary conditions such as the Rhine discharge at Lobith and the storm surge at sea. These boundary conditions are used to calculate the water levels at certain locations in the Rhine-Meuse delta using the SingleRunner module of MHWp5. The maximum water levels for each of the combinations are stored in a database that is used by the program Hydra. Hydra makes use of marginal extreme value distributions of sea water levels, wind speeds, wind directions and river flows along with their correlations to calculate the frequency of occurrence of a certain combination. By combining all these frequencies a water level frequency curve can be found for each location at which this is desirable.

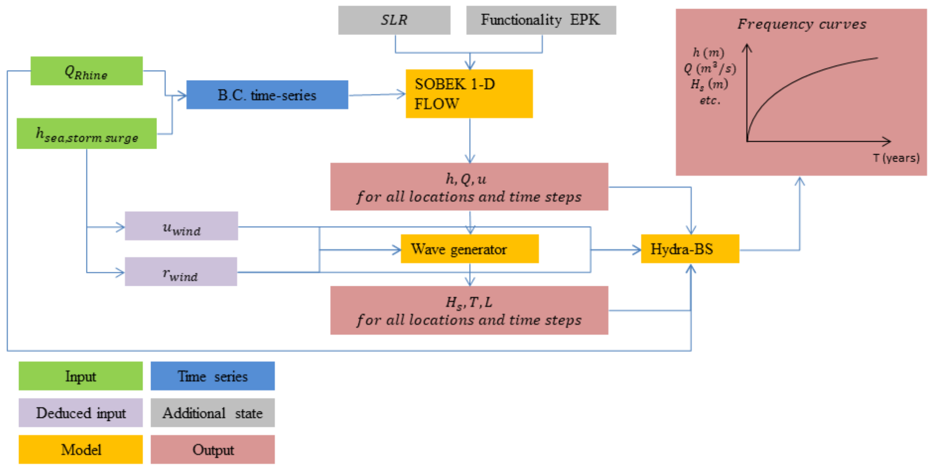


Figure B.1: Overall schematization from input to frequency curves

B.2. Creation of combinations and boundary conditions

B.2.1. Creation of combinations

As can be seen in Figure B.1, the process starts with the model inputs which are the boundary conditions that need to be used for each SOBEK simulation. This means that a set of Rhine discharges, storm surges and Europoort barrier states need to be defined. As an example if two different Rhine discharges, two storm surges and two Europoort barrier states were to be simulated, a total of eight SOBEK simulations would be needed. To capture the endless amount of possible combinations of these aforementioned factors, a discretization was needed. This means that the steps between the values of these factors need to be as small as possible, while still keeping the total amount of simulations reasonable. This leads to a set of nine Rhine discharges, six storm surges and three Europoort barrier states; hence 162 simulations.

B.2.2. Inventory of hydraulic boundary conditions

Since the water levels in the Rhine-Meuse delta need to be simulated for a period of about five days, the boundary conditions are transformed into time series. This means that the fixed values of Rhine discharges are changed into time series files with a constant value for every time step and that the normal tidal time series of the North Sea need to be combined with the storm surge values. Crucial to this process is however that the duration, timing and intensity of the storm is chosen correctly. In Figure B.2 below the storm surge function and its timing relative to the tidal signal can be found.

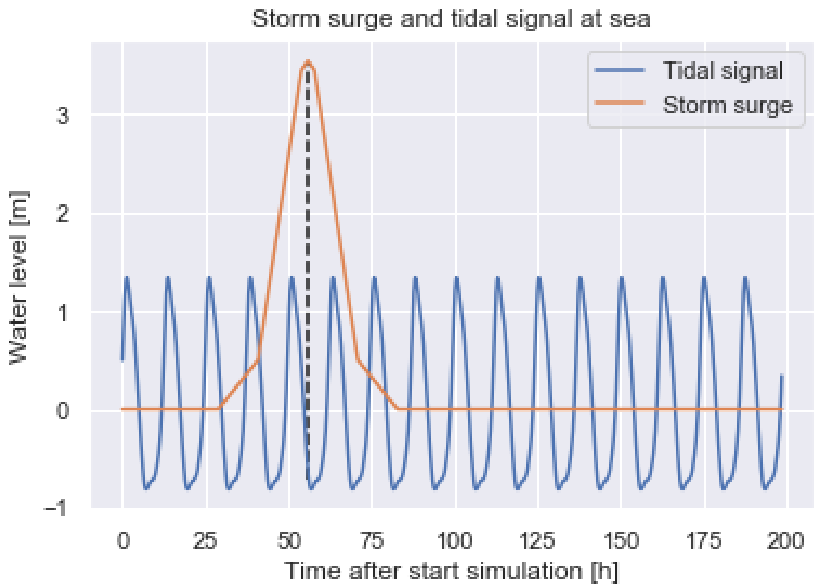


Figure B.2: Storm surge function

The peak of the storm surge actually coincides with a low tide. Since the duration of the storm is quite extensive, the surge during high tide is still relatively large. The tidal signal and storm surge create a total water level signal. The water level signal belonging to the storm surge in Figure B.2 can be observed on the left in Figure B.3.

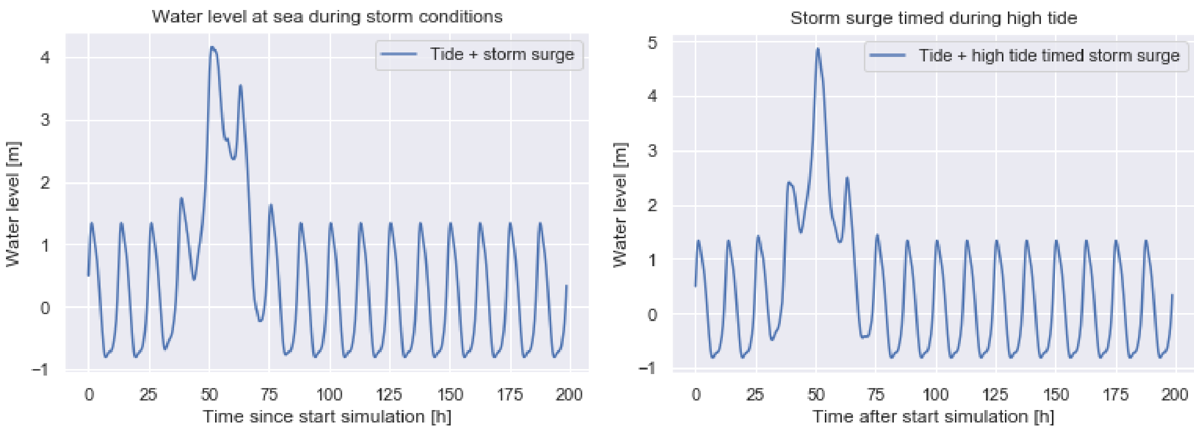


Figure B.3: Water level signal with storm surge at low and high tide

In Figure B.3 the water level signal with a maximum storm surge at low tide shows two peaks; coinciding with the two high tides that precede and follow this low tide. Storm surge timed at high tide gives one peak with small peaks to the side of it. The former has a much longer period during which high-water levels at sea occur, for the latter this period is smaller, but the intensity of the peak is much larger. As the MHWp5 calculations are based on situations of large storm surges in combination with large river discharges, it is interesting to see how the closure of the storm surge barriers influences the water levels at the rivers as the river water gets trapped. This phenomenon is more important for long closures of the storm surge barriers. It is clear that the timing of the storm surge is quite influential for the eventual high-water levels in the Rhine-Meuse delta and the influence of Europoort barrier failure mechanisms and closure operation may be changed a lot.

B.3. High-water modeling software: MHWp5 SingleRunner

The most vital and computationally expensive component of MHWp5 is the Singlerunner. The Singlerunner, as described above, controls a D-Flow 1D SOBEK model of the Rhine-Meuse delta. This D-Flow 1D model solves the De Saint Venant (de Saint-Venant et al., 1871) equations for one dimensional unsteady flow for the following assumptions (Cunge, 1980):

- The flow can be well modeled as one-dimensional and can therefore be represented as being uniform along the cross-section.
- Pressures within the water bodies can be assumed to be hydrostatic as there is little streamline curvature and vertical accelerations are negligible.
- Boundary friction and turbulence which normally depend on flow characteristics can be represented by resistance terms used for steady flow.
- Bed channel slopes are small enough so that $\sin(i) = i$ and $\cos(i) = 1$.

Hence, for this one dimensional flow the 1D continuity and 1D momentum equation need to be solved. This is done numerically using the Delft-scheme, which is designed specifically to be robust and deal with phenomena such as drying, flooding and super-critical flow. This way, a solution can be found for every time step (Deltares, 2019).

The Singlerunner part of MHWp5 consists of the 'water flow 1d' and 'real-time control' modules. The real-time control module uses water level predictions for the current system state to make a decision on any future state changes. If such a state change takes place that influences the hydrodynamic behavior of the system, new predictions need to be made as the system state has changed. For this new state all components controlled by the real time control module determine any future state changes. Hence, this process is very iterative and computational times depend largely on the amount of state changes of all components and the resulting number of predictions or "cached runs". The water flow 1d module is the actual water levels that result from the state changes within the system. These water levels are essentially a sum of portions of cached runs.

In Figure B.4 a simple schematization is given for the way cached runs are used to finally make up the actual water levels for the specific combination of hydraulic boundary conditions. The green lines represent the part of the cached runs that are saved and taken as the water levels belonging to the 1D flow results. The other parts are deleted as they are not valid anymore after the event that changes the hydrodynamic response of the system. It is clear that the calculation time greatly increases for a set of hydraulic boundary conditions for which a lot of hydrodynamic influencing events are triggered. Such events may be the closure of a barrier or the initiation of a pumping station.

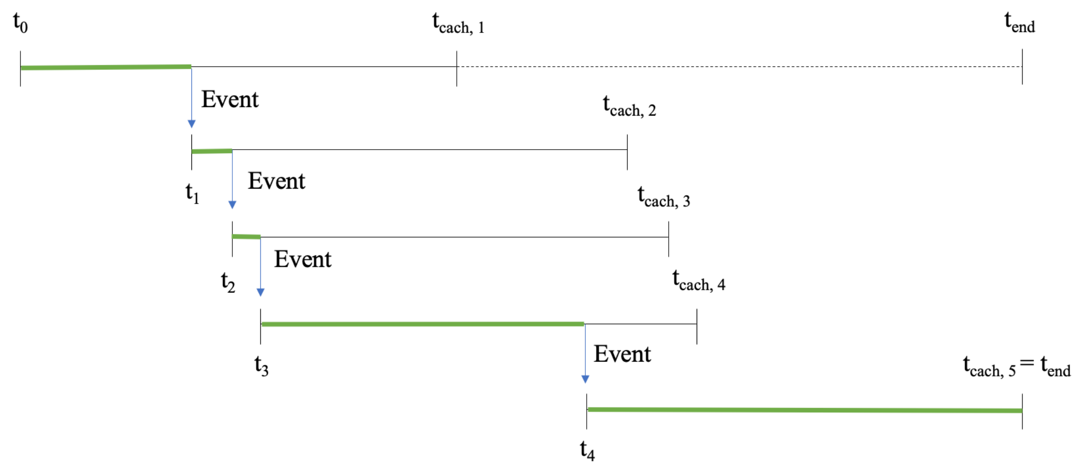


Figure B.4: Schematization of SingleRunner combined model of 1D Flow and real-time control

B.4. High-water modeling output

The Singlerunner module of MHWp5 gives as output the water level, water velocity and water discharge for all observation points in the SOBEK model during the duration of the run. In Figure B.5 below one can observe an example of the water levels at the sea side of the Nieuwe Waterweg (Maasmond), Rotterdam (RTTDM) and Dordrecht (DORDT). The vertical dashed lines represent states of the Maeslant barrier. Horizontal closure of the barrier is abbreviated as 'Hor. Sluit', the vertical closure of the barrier as 'Keren', vertical opening as 'Opdrijven' and horizontal opening as 'Hor. Open'.

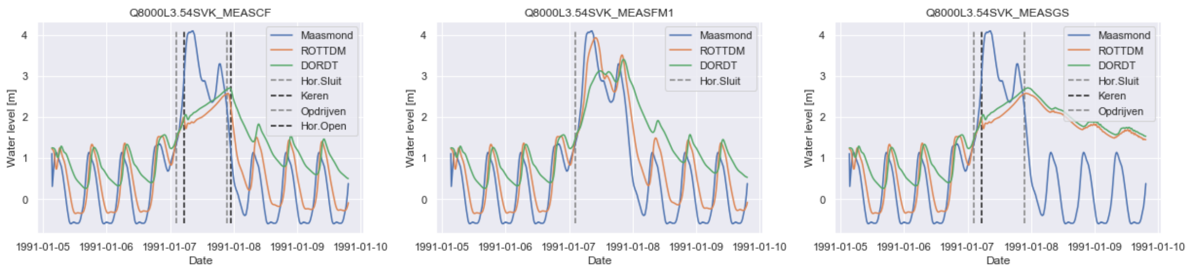


Figure B.5: Water level at sea, Rotterdam and Dordrecht for a discharge of 8,000 m^3/s and a storm surge equal to 3.54 m

It is clear that the water levels at Rotterdam and Dordrecht are very dependent on the failure mechanism of the Maeslant barrier. Water levels are significantly reduced by closing the barrier in case of a storm surge. Water levels at Rotterdam and Dordrecht do not keep rising during a failing to open Maeslant barrier (GS), because river water can be discharges at the Haringvliet sluices as well.

B.5. Creating water level frequency curves from high-water modeling output

The extreme water levels at specific locations are visualized in water level frequency curves. To create the frequency curves, the maximum water level at each observation point during each run is taken. Such a curve indicates for a series of increasingly rare scenarios what the accompanied water level at the location is. An example of such a water level frequency curve may be found in Figure B.6.

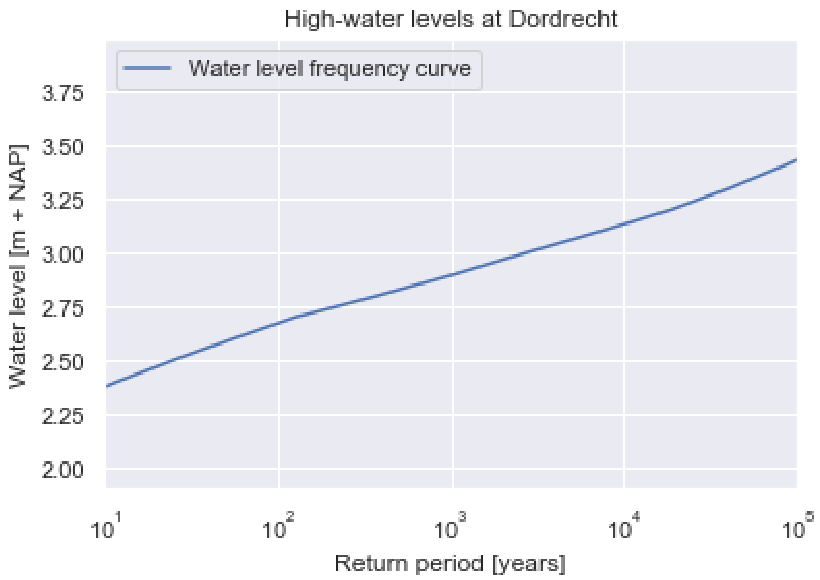


Figure B.6: Example of water level frequency curve at Dordrecht

Take for instance a water level of NAP + 2.5 m at Dordrecht. This water level can be obtained by a relatively high water level at sea or a high discharge in the Rhine. For each high-water level, twelve different situations are assessed, namely one for each possible dominant wind direction. For instance, during a moderate storm from the north-west, water levels at sea might rise to NAP + 3.1 m. This situation does not require the Europoort barrier to be closed and so along with a Rhine discharge of 4,000 m^3/s a water level of NAP + 2.5 m at Dordrecht is obtained. This is not a very unlikely situation, however there are also situations that are less likely that lead to the same water level. For instance, a south-western storm could lead to a water level at sea equal to NAP + 2.4 m and along with a Rhine discharge of 11,000 m^3/s a water level of NAP + 2.5 m at Dordrecht is once again obtained. From such an example it can be deduced that there are many different possible situations that lead to the same water level at Dordrecht.

From the high-water level output in Section B.4 one can find a set of discrete values of storm surge level at sea and river discharge in the Rhine along with failure mechanisms of the Europoort barrier that lead to a certain water level at Dordrecht. In Figure B.7 the maximum water level that occurs at Dordrecht for each combination of hydraulic boundary conditions can be found. For each Rhine discharge, six values of storm surge are assessed.

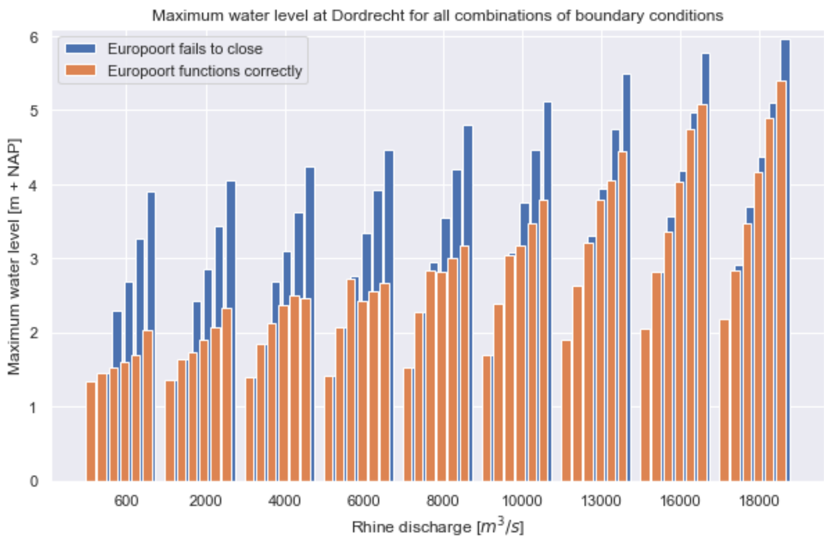


Figure B.7: Maximum water levels at Dordrecht for all combinations of boundary conditions

It can be seen that, the more extreme the set of hydraulic boundary conditions, the higher the water level at Dordrecht. The water level at sea is however influenced by a couple of other variables, namely the wind direction and wind speed at sea. That is why the high-water frequency curve water levels are split up for each of the twelve wind directions. For each wind direction, a certain water level at sea can be created.

The results as shown in Figure B.7 are put into a database from which Hydra-NL or Hydra-BS can create the water level frequency curves. To do so, firstly the discretization of the water level at sea and Rhine discharge needs to be made more continuous. From an interpolation process, not only the water level at Dordrecht for a Rhine discharge of 4,000 m^3/s, but also 4,300 m^3/s can be determined. Next from known relations of and between wind speed, wind direction and Rhine discharge, for each set of boundary conditions the probability of exceedance can be calculated. Doing this for each of the wind directions, gives a total probability of exceedance for each water level of interest, for instance NAP + 2.5 m as mentioned earlier. From the probability of exceedance the return period of the event can be easily calculated.

Lastly, the failure mechanisms of the Europoort barrier can be incorporated. As seen in Figure B.7 a situation in which the Europoort barrier fails leads to situations with larger water levels at Dordrecht. In Hydra the failure probability of the barrier can be given. The calculation of the twelve wind directions is simply split into two parts, one for an opened Europoort barrier and one for a closed Europoort barrier. An opened Europoort barrier can be either because the barrier closure level is not reached and therefore it is not attempted to be closed or the barrier closure fails. The latter has a very small probability of occurrence, because during such an extreme event, the barrier also needs to fail. However, it can still be a dominant process in case larger return periods are of interest.

B.6. Validation of high-water levels for current flood protection system

The high-water levels created by the high-water modeling process as performed using MHWP5 and Hydra are validated against the WBI database. Here it is assumed that this database is currently the best source of information regarding extreme water levels in the Rhine-Meuse delta. The results are validated at several locations around the Island of Dordrecht, which can be seen in Figure B.8 below.

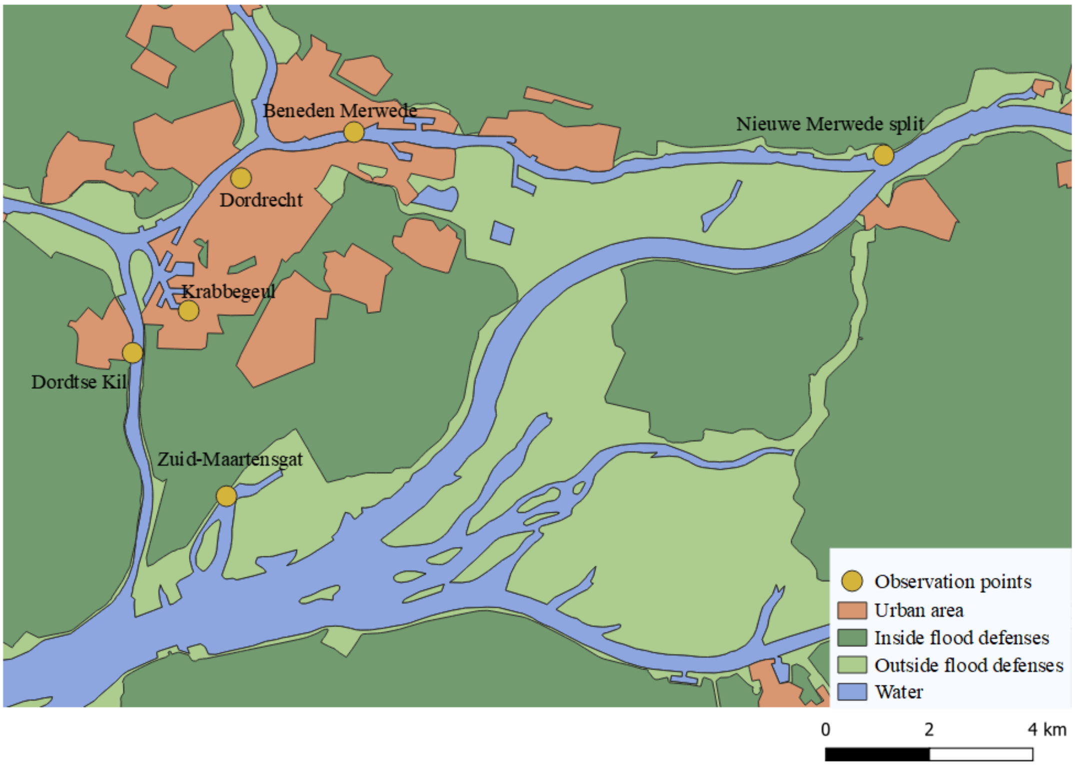


Figure B.8: Observation points around the Island of Dordrecht

In Figure B.9 below one can observe the water levels calculated by the MHWp5 model for several return periods and the frequency curves that are obtained from the WBI database. It is obvious that the frequency curves of the MHWp5 model overlap relatively well with the curves generated from the WBI database. There are however a few things to be noted from these results. For almost all locations, water levels for return periods larger than 10,000 years are larger for the WBI database than for MHWp5 except for the location 'Nieuwe Merwede split'.

One possible reason for this is that the WBI database frequency curve is generated by Hydra-NL instead of Hydra-BS. One difference between these programs is that Hydra-NL uses a total failure of the Europoort barrier, whereas Hydra-BS uses a partial failure of the Europoort barrier; namely only failure of the Maeslant barrier. The water levels for these extremely large return periods is larger for the WBI database. The reason for this is that for such return periods the influence of the scenarios with a (partially) failing Europoort barrier is relatively large. For the WBI database the failure probability of 0.01 per closure attempt of the Maeslant barrier is used as the failure probability of the Europoort barrier. As the failure of the Europoort barrier leads to higher water levels in the Rhine-Meuse delta than failure of the Maeslant barrier alone, the resulting water level for a set return period is larger using Hydra-NL compared to Hydra-BS.

Contrary to this analysis, it can be observed that the extreme water levels at the 'Nieuwe Merwede split' are quite a bit smaller. As this observation point is located all the way at the eastern tip of the Island of Dordrecht, it is no longer located in the transition region. This means that the influence of storm surge at sea is negligible compared to the influence of high-water levels due to extreme river discharges.

For relatively small return periods in the order of 10 years the frequency curves from MHWp5 and Hydra-BS deviates a bit from the WBI database frequency curves. As the MHWp5 model was originally created to assess situations that are normative for dikes along the rivers, it is calibrated for return periods in the order of 1,000 years. This means that for some validation stations, the difference between the MHWp5 model and the WBI database can be in the order of 0.10 to 0.20 meters for such small return periods.

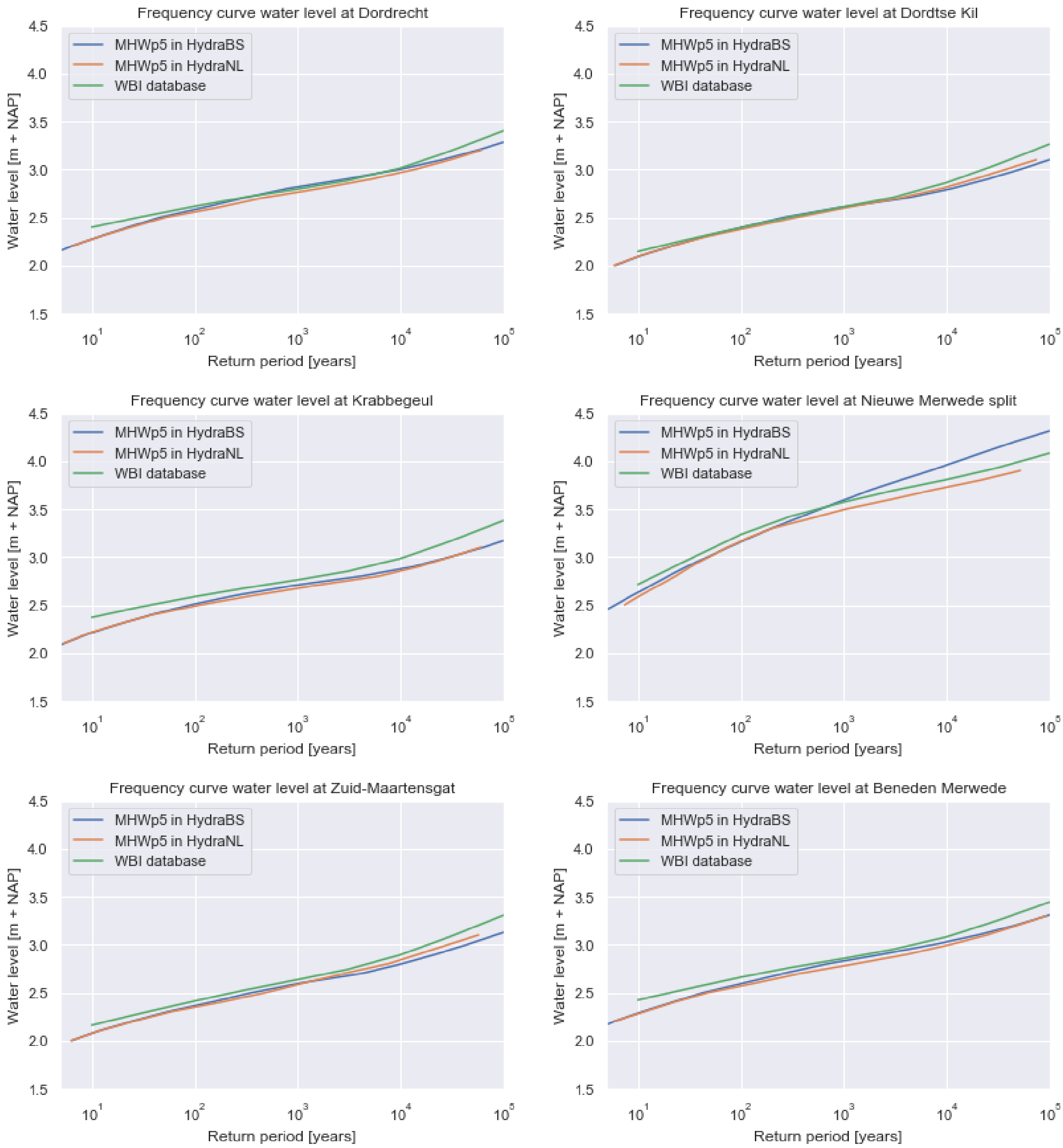


Figure B.9: High-water level curves from the WBI database vs. the MHWp5 model

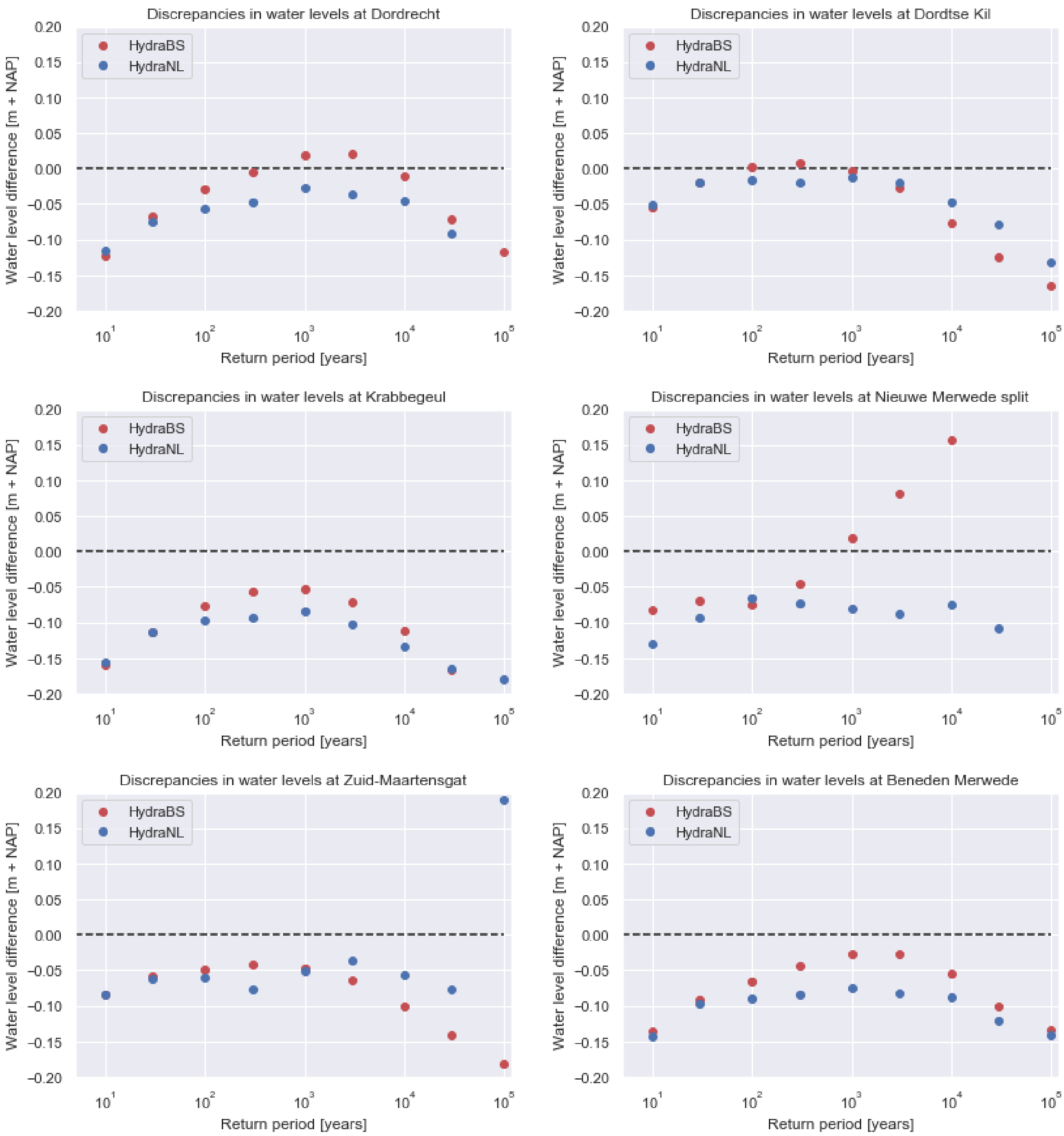


Figure B.10: Discrepancies between high-water level curves from the WBI database vs. the MHWp5 model

For return periods from 10 to 1,000 years, the difference between the Hydra-BS and Hydra-NL frequency curves are negligible compared to the overall uncertainty of the results. For the situation with a flood protection system with Delta21, the possibility of adding the failure probability of an additional barrier into the probabilistic calculation is required. Hence, in order to come to comparable results, also for the situation without Delta21 Hydra-BS is used to obtain the frequency curves.

C

Computed flood risk for flood protection system without Delta21

C.1. Water level frequency curves

To determine the flood risk at the three flood prone regions not protected by flood defenses at the Island of Dordrecht, the frequency curves for the six observation points need to be assigned to specific parts of these regions. Especially the Biesbosch and the flanks are spatially too different to be appointed to a single observation point. Furthermore, by averaging two or more observation points that lie far apart, area specific information might be lost. Hence, the Biesbosch is split up into south-western and north-eastern part and the flanks into a western and eastern part.

These (sub-)regions are assigned as follows:

(Sub-)Region	Observation point
Historical harbor	Dordrecht
Western flanks	Krabbegeul
Eastern flanks	Beneden Merwede
South-western Biesbosch	Zuid-Maartensgat
North-eastern Biesbosch	Nieuwe Merwede split

Table C.1: Linking the (sub-)regions to the observation points

C.1.1. Influence of sea level rise

In Figure C.1 the influence of sea level rise on the water level frequency curves around the Island of Dordrecht for the reference situation can be seen. It is obvious that the water levels increase a lot for various sea level rise values. This increase is not equal to the sea level rise, but for instance for 1.1 meter sea level rise, it is around 0.7 meters, depending on which location and what return period you look at. The influence of the sea level rise is larger at the downstream observation points (Dordrecht, Dordtse Kil) and less more upstream (Nieuwe Merwede split). Another property that stands out is that for downstream observation points the influence of sea level rise differs quite a bit for each return period, but for the upstream observation points, the water level difference between the reference situation and the sea level rise scenarios stays almost constant for each return period.

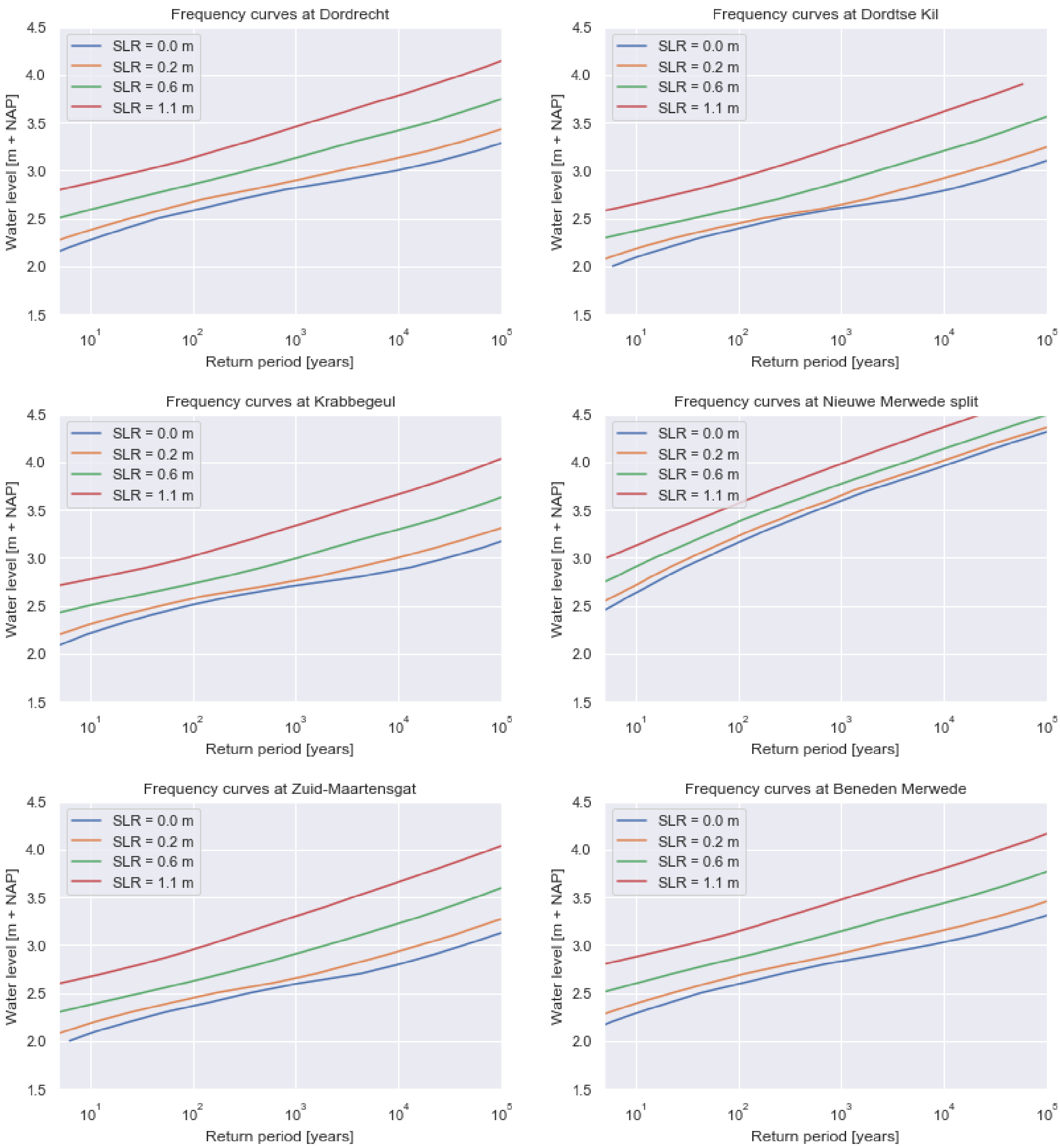


Figure C.1: Influence of sea-level rise on the water level frequency curves for various locations around the Island of Dordrecht

C.1.2. Influence of increase maximum Rhine discharge

The Rhine discharge Q_{1000} is not actually the maximum discharge, but the discharge in the Rhine that occurs on average once every 1,000 years. In Figure C.2 below the marginal distribution functions of Rhine discharges for the reference situation and the scenarios can be observed.

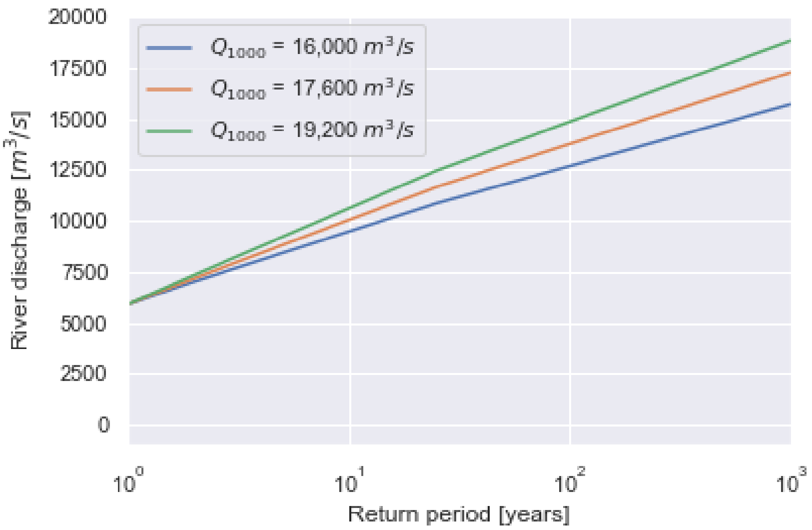


Figure C.2: Reference and possible future distribution of annual maximum Rhine discharge.

These marginal distribution functions are used to assess the influence of higher river discharges on the normative water level at the Island of Dordrecht during combinations of high river discharges and storm surge at sea.

The water level frequency curves for the reference situation can be seen in Figure C.3. It is clear that the influence of a larger Q_{1000} is most apparent for the upstream locations such as Nieuwe Merwede split. For more downstream locations such as Dordtse Kil the influence of larger river discharges becomes less as the influence of large sea levels increases. Furthermore, the water level deviation for an increasing Q_{1000} does impact small return periods, but it is clear that by far the largest increase in water levels is present for return periods larger than 1,000 years.

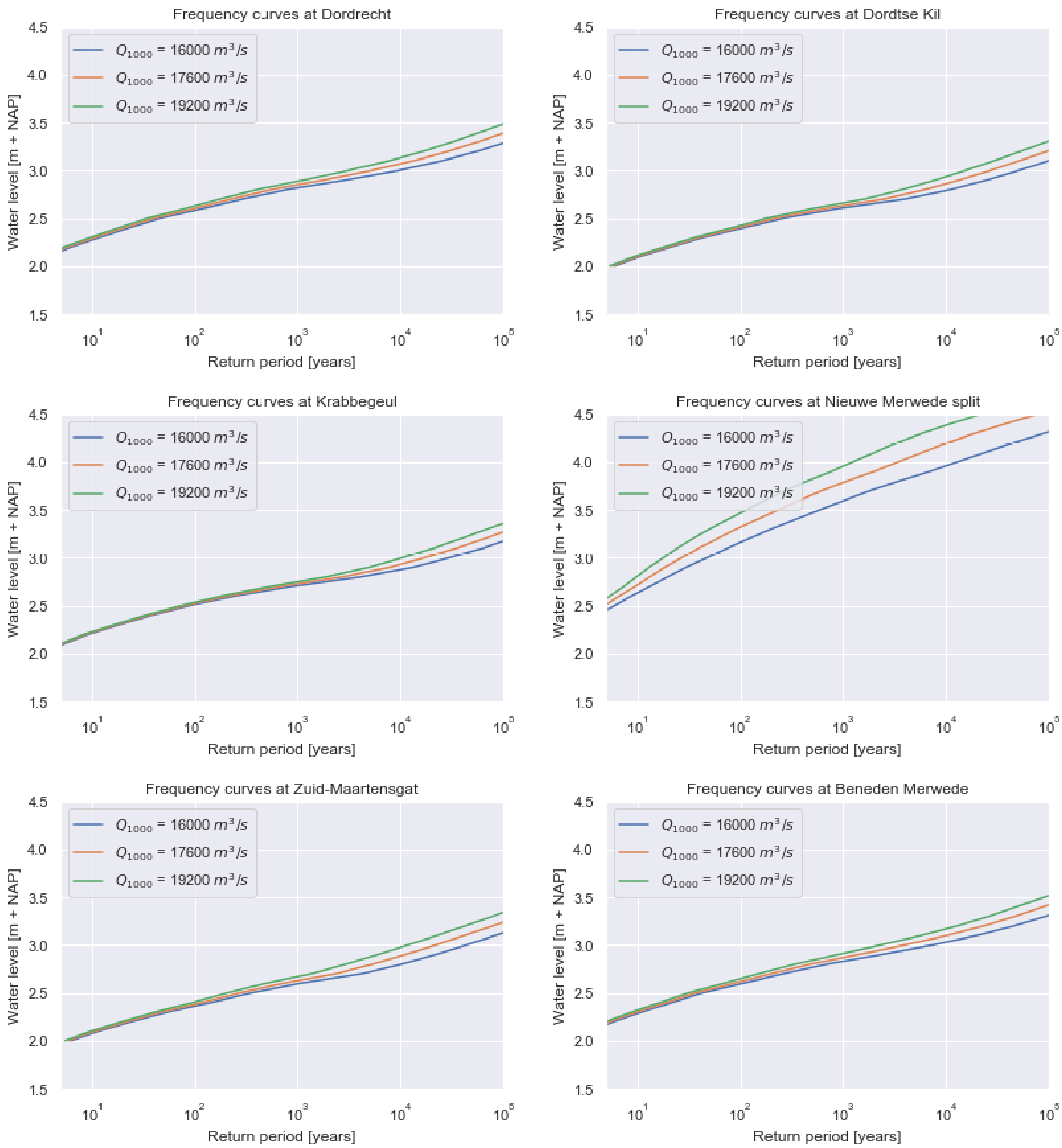


Figure C.3: Influence of increasing Rhine discharges on the water level frequency curves for various locations around the Island of Dordrecht

C.1.3. Water level prognoses

The influence of both sea level rise and the increase of extreme Rhine discharges can lead to a range of possible future frequency curves for each of the observation points. In Figure C.4 these ranges of possible future water levels for the year 2100 can be seen. It is obvious that water levels for Plan Locks are almost the same for all return periods with only a small reduction for most downstream observation points.

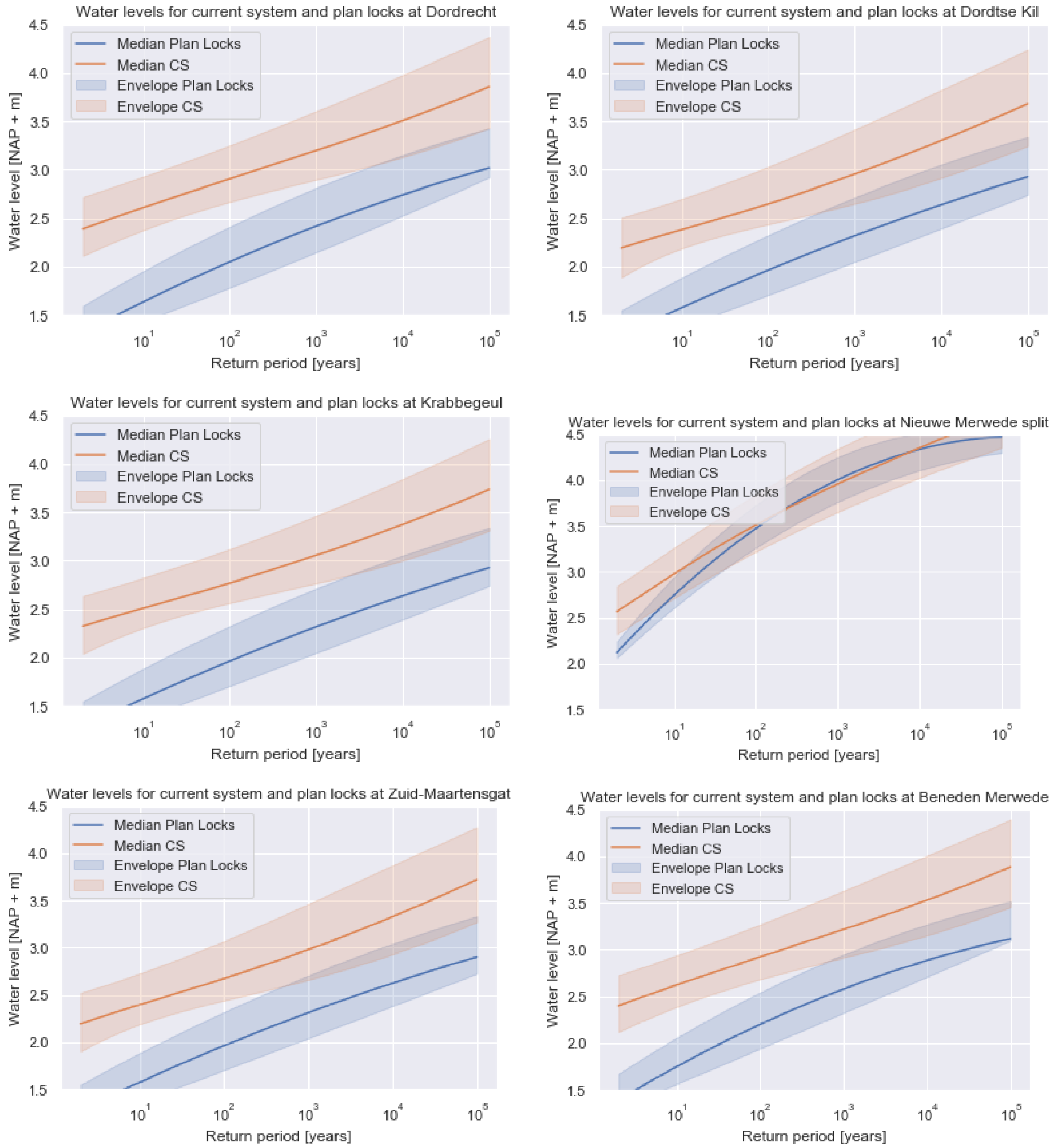


Figure C.4: Water level frequency curves for current system and Plan Locks for the year 2100.

C.2. Flood risk flood prone areas not protected by flood defenses at Island of Dordrecht

The high-water level curve envelopes derived by the method described in Appendix C.1.3 can be combined with the damage profiles derived in Appendix A. These damage profiles can be seen in Figure C.5 where the total damage profiles for all regions for the year 2020 and 2100 can be found.

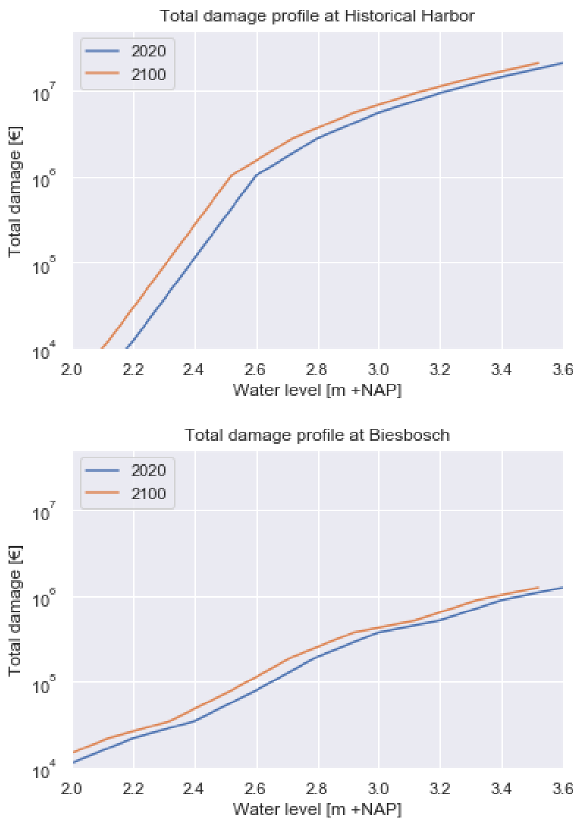


Figure C.5: Economic damage curves for all regions for 2020 and 2100.

By doing so, for the reference situation and the scenarios for the current flood protection system a set of flood risk curves are found. In Figure C.6 the flood risk curves for the reference situation and the future total flood risk curves for the current flood protection system and Plan Locks for the year 2100 can be observed. As mentioned in Section 2, the scenarios used for the current flood protection system and Plan Locks is not the same, which should be taken into account for this comparison.

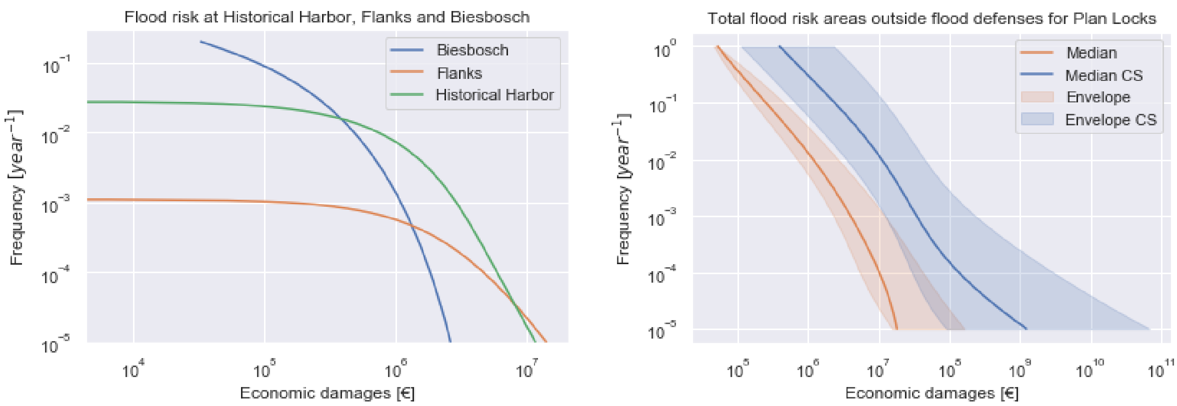


Figure C.6: Reference situation and scenarios: flood risk at flood prone areas not protected by flood defenses

D

Inclusion of Delta21 in one dimensional flow model

The components of the Delta21 plan are modeled in the SOBEK Flow-1D model that is controlled by MHWp5. As explained in Appendix B, the Singlerunner module of MHWp5 calculates water levels in the Rhine-Meuse delta for a combination of boundary conditions. Additionally, it can control the operation of the structures embedded in the SOBEK model. In the SOBEK model itself such an operational strategy is also possible, but restricted by three main factors: a structure can only have two states such as on/off or open/closed, an comprehensive closure strategy requires an elaborate and cluttered control group and it is impossible to base the operational strategy on real-time control water level, flow velocity and discharge predictions. Hence, the current flood protection system is controlled by the Singlerunner module and the new Delta21 components are too.

D.1. Implementation of Delta21 into SOBEK D-Flow1D

The SOBEK D-Flow1D model of the Rhine-Meuse delta has been adjusted to resemble a hydrodynamics of the future situation with Delta21 as well as possible. In Figure D.1 below, the original situation can be observed.

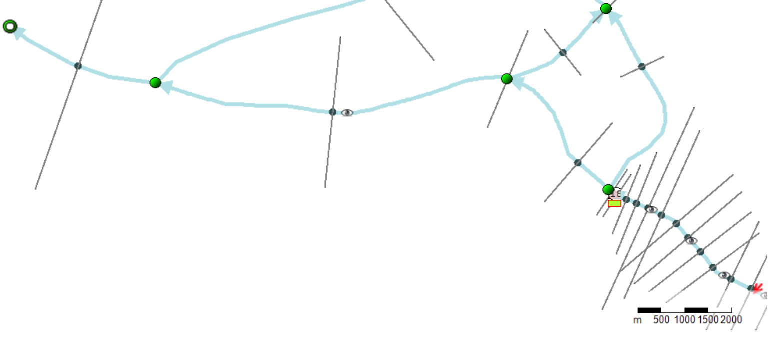


Figure D.1: SOBEK D-Flow1D Haringvliet branches

The first step to come to the new adjusted model was to remove any channels from the Haringvliet estuary (Front Delta (Dutch: 'Voordelta')) that are built over by the new Energy Storage Lake of Delta21. Next, the Delta21 lake was introduced by creating a new channel about three kilometers downstream from the Haringvliet barrier. The channel's cross-section and length were chosen as such that the total volume is large enough to store the maximum amount of pumped water during a storm event. The entrance of this channel was blocked by a weir with the same height as the channel banks. In the same structure as the weir, a pump station was placed. Additionally, the new Delta21 storm surge barrier was placed just downstream of the intersection of the original channel and the new lake. In Figure D.2 one can observe the aforementioned changes in the SOBEK model.

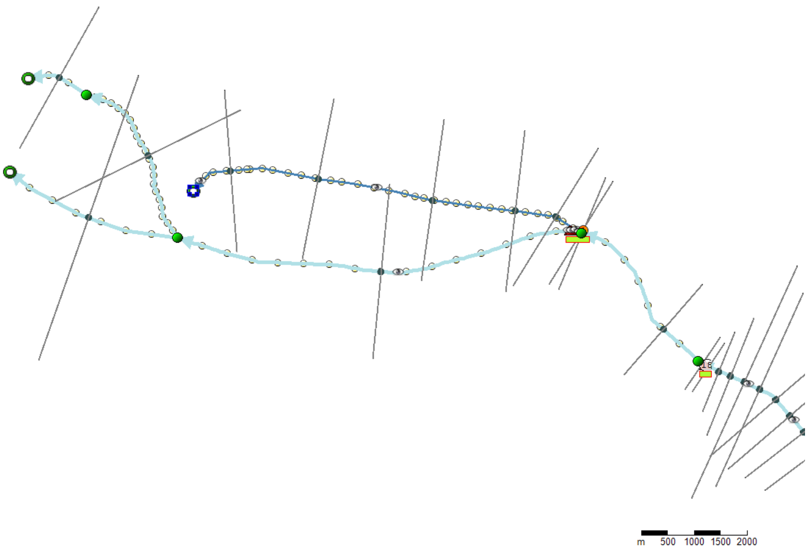


Figure D.2: SOBEK D-Flow1D Haringvliet with Delta21 implementation

In Figure D.3 the Delta21 storm surge barrier, weir, pumping station and entrance to the energy storage lake can be observed in more detail.

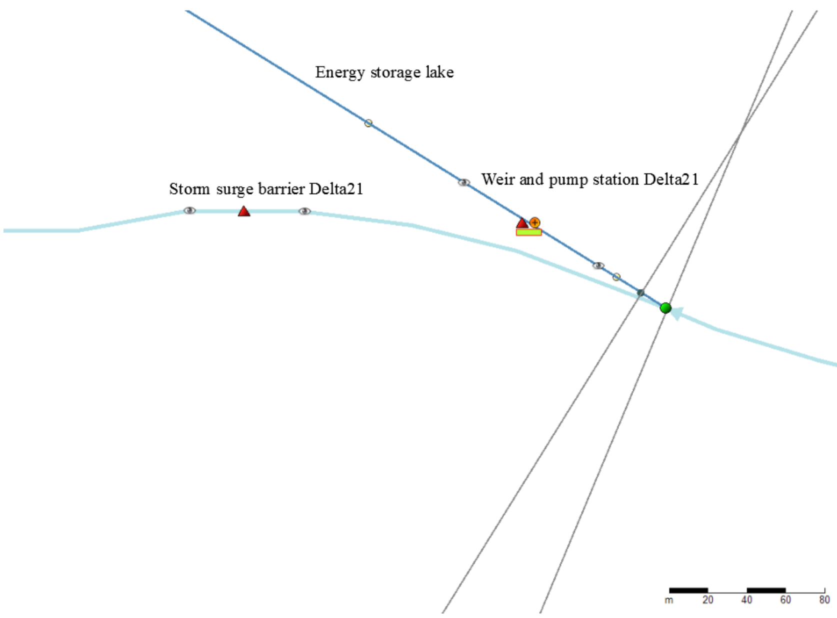


Figure D.3: Close-up of Delta21 components

The implementation of Delta21 in D-Flow1D SOBEK is somewhat different from the actual layout that is currently proposed. As is mentioned in Chapter 4, the entrance of the energy storage lake is a spillway and a pumping station discharges water from the lake into sea. The problem with the implementation of a spillway is that in SOBEK the flows over or through the spillway are dependent on the upstream water levels. In reality however, the spillway is constructed as a set of siphons in which the flow is controlled by vacuum pumps and plugs. This means that basically the flow through the spillway can be specifically adjusted and the hydrodynamic effects match that of a controllable pumping station. Moreover, there is no pumping station located at the downstream end of the modeled energy storage lake. As the hydrodynamic processes within the lake are not relevant to this study, discharge from the lake into the Haringvliet estuary might only influence water levels at these boundary conditions and negatively impact the model accuracy. This is also the reason why the energy storage lake is made larger than in reality, as it is not allowed to overflow during long storm events with high pump discharges.

D.2. Schematization and implementation of Delta21 components

The physical implementation of the Delta21 components is of large importance to the impact of Delta21 on the hydrodynamics in the region. Hence, in this section the energy storage lake, the storm surge barrier and the weir and pumping station implementations are shown in detail.

D.2.1. Energy storage lake

In Figure D.4 one can observe the cross section of the energy storage lake. As can be observed, the largest portion of the section is storage area and a smaller part is the flow profile. The flow profile is kept large enough so that water levels across the lake are almost uniform.

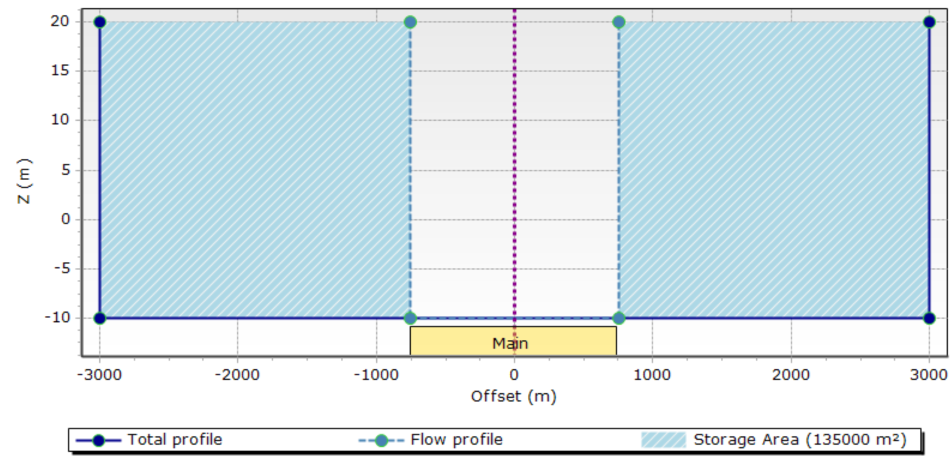


Figure D.4: Cross-section of the Energy Storage Lake.

D.2.2. Storm surge barrier

The storm surge barrier of the Delta21 project is modeled as a single gate with an open and closed state. Currently, the barrier is planned to consist of a multitude of gates to increase the redundancy and reliability of the structure in case of partial failure. The cross-sectional restriction that this causes is assumed to be negligible as the remaining cross-section is assumed to be equally large as the current Haringvliet channel. Therefore, as all gates would actually be operated simultaneously and equally, modeling the Delta21 storm surge barrier is physically acceptable and drastically reduces the operational complexity.

In Figure D.5 below, the cross section of the storm surge barrier of the Delta21 project can be seen. The brown dotted line at NAP + 10 m indicated the lower edge of the gate and the upper edge of the sill is situated at NAP -5 m.

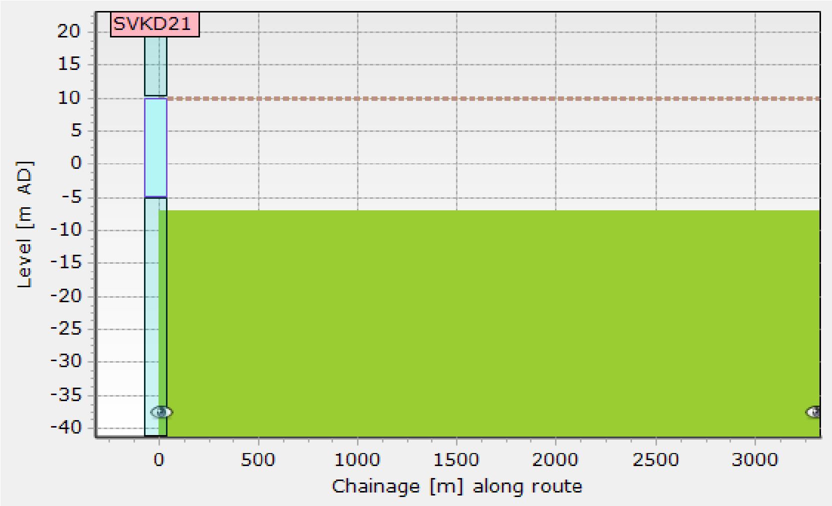


Figure D.5: Cross-section of the Delta21 storm surge barrier.

D.2.3. Weir and pumping station

As can be seen in Figure D.6, the weir and pumping station connect the Haringvliet channel to the energy storage lake. The orange circle with the arrow pointed downstream is the pumping station.

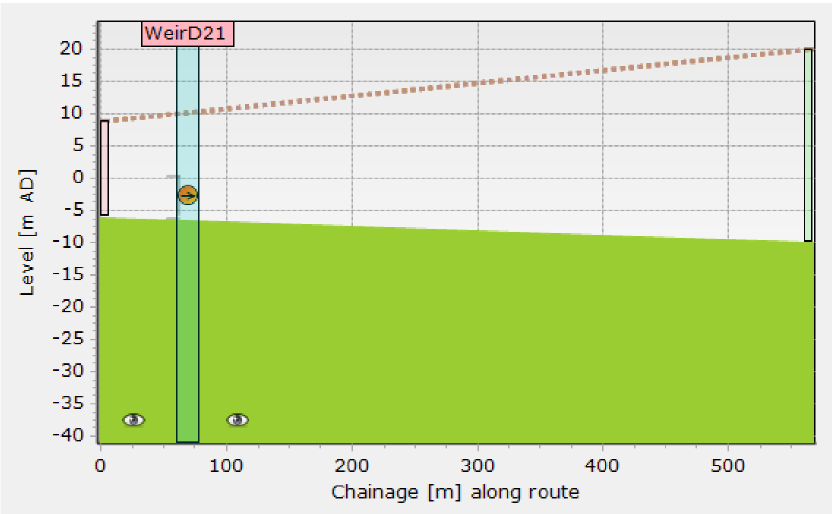


Figure D.6: Cross-section of the Delta21 weir and pumping station connected to the energy storage lake.

D.3. Inclusion of real-time control on Delta21 components

The two active components of the Delta21 model are the storm surge barrier and the pumping station. Just like the Maeslant barrier, Hartel barrier, Hollandse IJssel barrier, Haringvliet barrier and the Volkerak sluices, the Delta21 storm surge barrier and pumping station are controlled by the real-time control module of the Singlerunner. As is explained in Appendix B, the real-time control module uses water level predictions for the current system state to make a decision on any future state changes. If such a state change takes place that influences the hydrodynamic behavior of the system, new predictions need to be made as the system state has changed. For this new state all components controlled by the real-time control module determine any future state changes. Hence, this process is very iterative and computational times depend largely on the amount of state changes of all components and the resulting number of predictions or "cached runs".

Any actions undertaken by the Delta21 storm surge barrier and the pumping station are made with water level, water velocity and water discharge information from the real-time control module. Just as the Maeslant barrier, the water levels at Dordrecht and Rotterdam are taken as the main driver of any actions. If the water levels at these locations stay under a certain level, no actions are needed. Whenever the decision is made that the storm surge barrier and the pumping station need to be employed, the exact timing and intensity of this employment depends on water levels in the Haringvliet and downstream of the storm surge barrier. Additionally, the water pumped away is based on river discharges. Here the objective is to lower the water level at Dordrecht as much as possible (if needed) with an optimal use of energy required by the pumping station.

D.4. Control system set-up of Delta21 components

D.4.1. Overview of control systems within Delta21

The control systems of the Delta21 components depend largely on the specific configuration that has been chosen. The basic principle stays the same however. The new storm surge barrier and pumping station are referred to by a control group in SOBEK D-Flow1D as shown in Figure D.7. The orange block is a 'timerule' rule and the blue oval is an output location. The rule is referred to in the Singlerunner file of the storm surge barrier and pumping station, which is discussed later on. The output refers to a certain variable of the structure. For the storm surge barrier this variable is the lower edge of the gate and for the pumping station this is the pumping discharge. Hence, for every time step the rule is given a certain value (e.g. pumping discharge) and this value is directly transferred to the output at which point the variable (pumping discharge) is adjusted in the SOBEK D-Flow1D model.

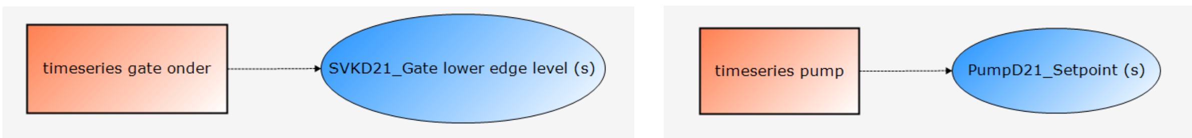


Figure D.7: SOBEK control groups of the storm surge barrier and pumping station

The signal that is given to the output location is determined by the source code of the Singlerunner software. For each structure such as the new storm surge barrier and the pumping station of Delta21, a new source code file needs to be created. This file contains the rules that allows the structure to change its state. Such a state is for example a 'rest' state or a 'pump' state when applying it to the Delta21 pumping station.

D.4.2. Control system of new storm surge barrier

The operation of the new storm surge barrier is closely related to the operation of the Maeslant barrier. The barrier starts in its 'rest' state and whenever a water level higher than the closure level is expected, the barrier calculates its moment of closure. At the moment this closure time is calculated the barrier switches to its 'mobilized' state. From this state the barrier switches to its 'closing' state at which the gate is slowly lowered and once the gate is fully closed, the 'closed' state is reached. Whenever the water level at Rotterdam and Dordrecht are going to be below the de-escalation level for an open barrier, the barrier can be opened and goes back to its 'rest' state. In Figure D.8 a schematization of the control system of the storm surge barrier can be found.

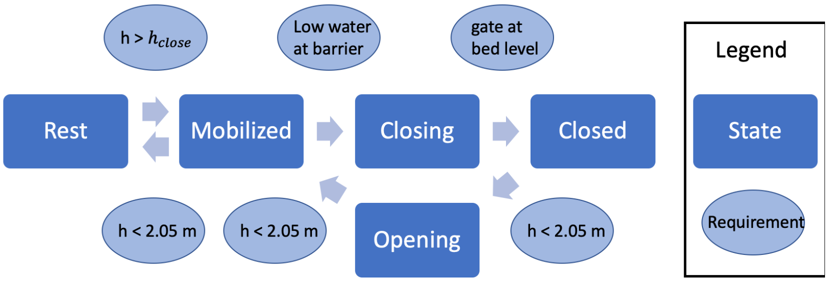


Figure D.8: Schematization control system of Delta21 storm surge barrier

D.4.3. Control system of pumping station

The control system of the pumping station is a little more elaborate than that of the storm surge barrier. However, the basic structure is similar. The pumping station also starts in its 'Rest' state and is mobilized whenever a water level higher than the closure level is expected. The station is turned to 'ToPumping' whenever the Delta21 storm surge barrier is closed. This state means that the pumping capacity of the pumping station is increased with 500 m^3/s every 10 minutes. Hence, the higher the required pumping discharge, the longer the station stays in this state. Whenever the required discharge is met, the 'Pumping' state is reached. From this state, the discharge of the pumping station can be adjusted depending on the water level in the tidal lake. If the water level in the lake gets too low, the discharge can be lowered and if the water level is still quite high, more water can be pumped out to maximize the efficiency of Delta21. The moment the projected water level at Dordrecht goes below 2.05 meters, the pumping station is slowly turned off again through the 'FromPumping' states. In the end the pumping station reaches the 'Rest' state once more. In Figure D.9 the control system is schematized.

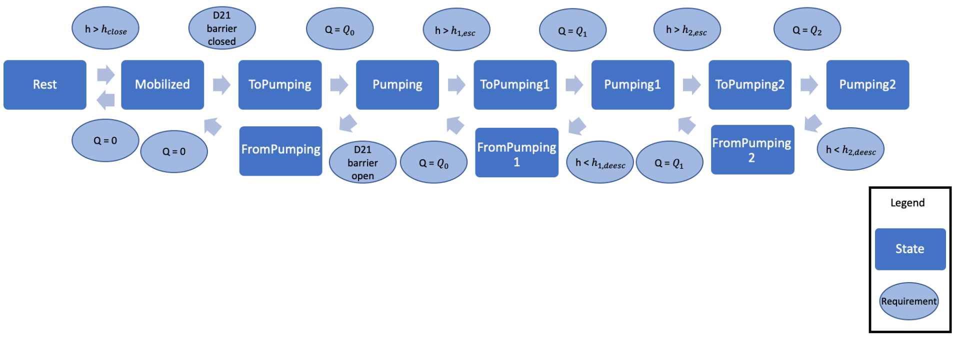


Figure D.9: Schematization control system of Delta21 pumping station

E

Influence of Delta21 on flows and water levels at the Rhine-Meuse delta

In this appendix the influence of the Delta21 project on flows and water levels in the Rhine-Meuse delta is discussed. It is relevant to investigate the change in processes in the Rhine-Meuse delta, because it may give an indication into the reasons of the high-water level reduction induced by Delta21. Additionally, this investigation of other processes might shed a light on problems or bottlenecks in the system. Firstly, the flows and water levels at the project area of Delta21 are discussed, then at the Island of Dordrecht and finally at other locations in between the project area and the Island of Dordrecht are discussed.

E.1. Flows and water levels at project area

The Delta21 project influences the water levels at many locations within the Rhine-Meuse delta, but as can be expected, the region closest to Delta21 is affected the most. The Haringvliet is considered to be in this region of the project area. Drawing large amounts of water from the Tidal Lake or the Haringvliet causes the water levels to drop significantly. In Figure E.1 the change of the water level upstream and downstream of the new Delta21 storm surge barrier can be observed. It is clear that due to the large amounts of water being pumped from the Haringvliet, the water level does decrease with a few meters.

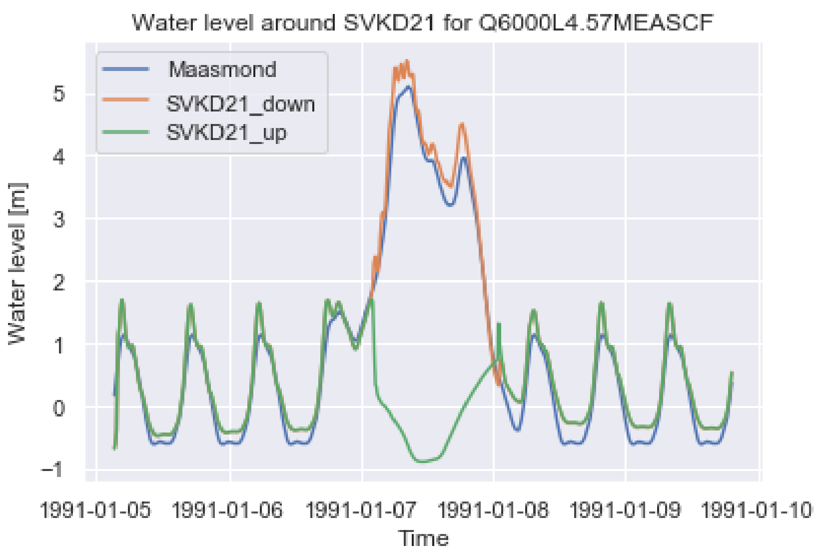


Figure E.1: Water level upstream and downstream of the Delta21 storm surge barrier for no sea level rise

The same water level drop can be observed upstream of the pumping station that has been implemented. In reality, a series of siphons would be present, but for modeling purposes it is a pumping station with a variable discharge. It can be seen on the left side of Figure E.2 that the water that is pumped away from the Haringvliet heightens the water level at the Energy Storage Lake. It should be noted that in reality this water level at the lake is relative to the bottom of the lake, not NAP + 0 m. On the right side of Figure E.2 the discharge out of the Haringvliet can be seen.

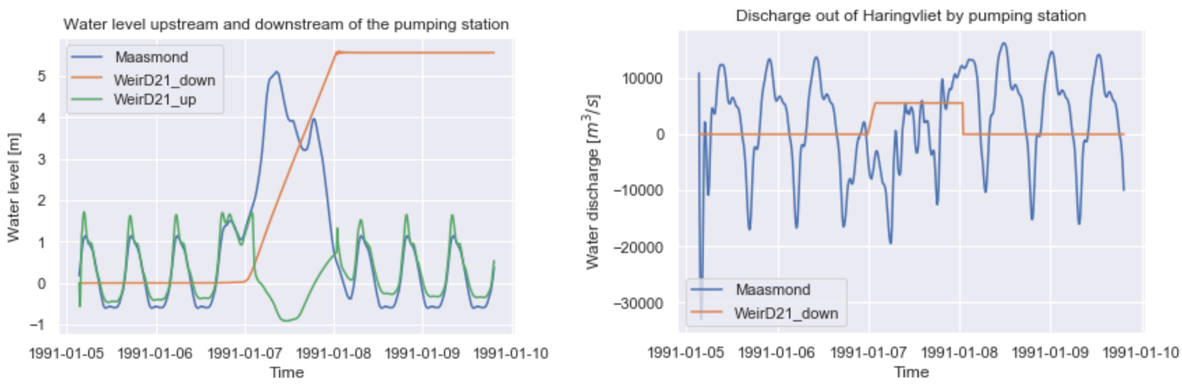


Figure E.2: Water level and discharge at Delta21 pumping station for Q6000L4.57MEASCF

E.2. Flows and water levels at Island of Dordrecht

E.2.1. Influence of Delta21 on extreme water levels

As this report focuses on the use of Delta21 for the water levels at the Island of Dordrecht, it is important to assess the physical processes that occur at that location. In Figure E.3 one can see the lowering of the extreme water level at the Island of Dordrecht for a combination of a Rhine discharge of 6,000 m^3/s, 4.57 meters storm surge and a correctly functioning Europoort barrier. On the left side the water levels are given for the reference situation and on the right side for the maximum scenario with a sea level rise equal to 1.1 meters. It is clear that the absolute water level reduction of Delta21 for this specific set of boundary conditions is larger for the scenario than for the reference situation. This can be partly explained by the fact that the minimum water level at the Haringvliet is reached earlier for the reference situation than for the scenario. This is due to the larger mean sea level for the scenario with sea level rise. Hence, the pumping station is allowed to pump at full capacity for a longer amount of time.

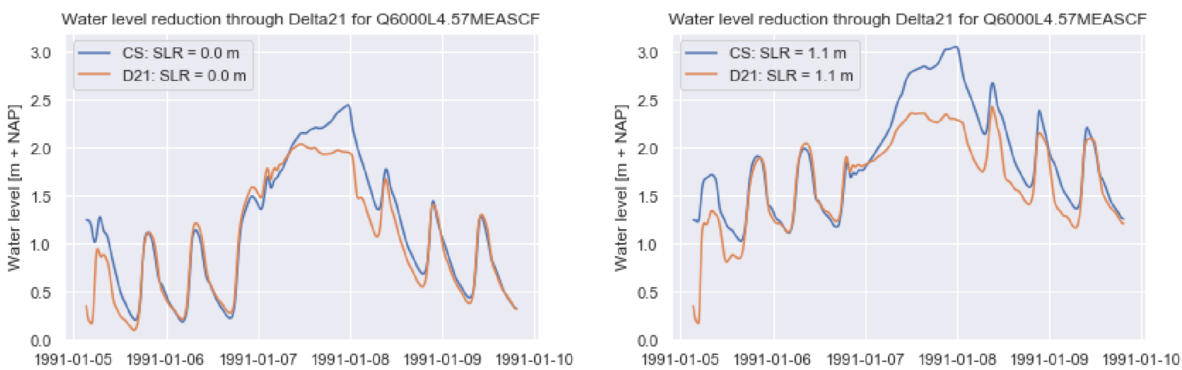


Figure E.3: Water level change due to Delta21 at Dordrecht for no and maximum sea level rise

All water level time series at Dordrecht for combinations of extreme Rhine discharges and sea water levels can be combined for both a correctly functioning and a failing to close Europoort barrier. In the charts in Figure E.4 one can observe how the influence of Delta21 increases for larger Rhine discharges for a correctly functioning Europoort barrier and shows limited impact for a failing Europoort barrier. For each Rhine discharge at Lobith, six values of storm surge are accounted for. It is also obvious that the water level reduction is very limited for smaller Rhine discharges. Hence, for locations that are dominated by the sea water level, one can imagine that the most important combinations are those for small Rhine discharges. This explains why the impact of Delta21 is very limited for these locations such as Rotterdam. The charts given in Figure E.4 are for the minimum scenario.

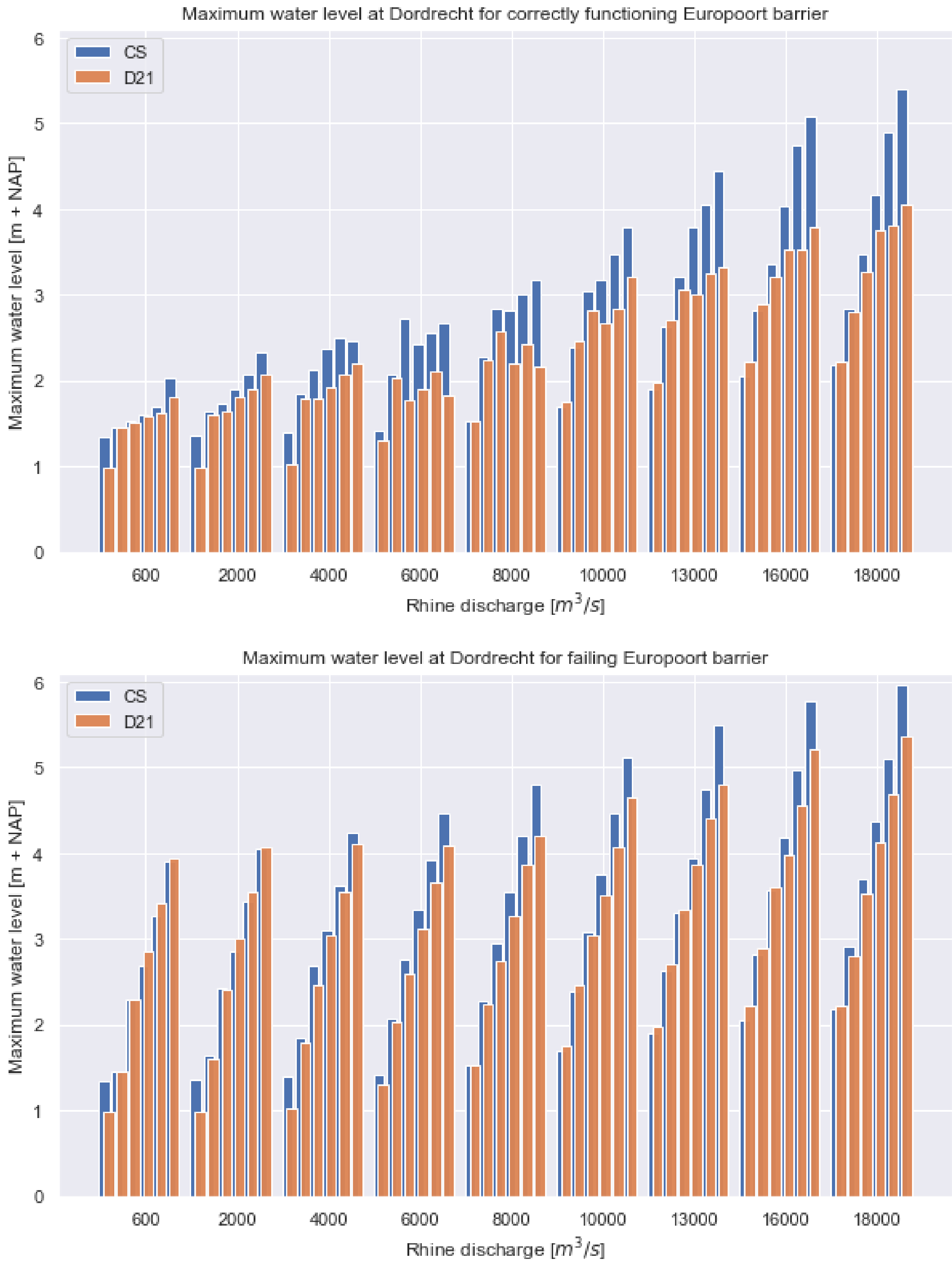


Figure E.4: Influence of Delta21 on extreme water levels for correctly functioning and failing Europoort barrier

By using the probabilities of occurrence and correlations of the combinations of storm surge and Rhine discharge, for each water level at Dordrecht a certain return period can be found and this leads to the water level frequency curves. These are the same kind of curves that have also been made for the current flood protection system in the reference situation and for the scenarios as shown in Chapter 3.

E.2.2. Influence of Delta21 on illustration points

The Delta21 project lowers the water level at Dordrecht compared to the current flood protection system for most return periods. These water levels only tell half the story, as there is a reason why the water levels are lowered. To determine what the normative processes are for a certain location around the Island of Dordrecht, one can look at the illustration points at various return periods. In Tables E.1, E.2 and E.3 the influence of the water levels for a closed Europoort barrier can be found for the observation points at Dordrecht, Dordtse Kil and Nieuwe Merwede split respectively.

The first value of each cell indicates the influence of a closed Europoort barrier for the current flood protection system and the second value for the flood protection system with Delta21. First thing that can be noticed is that for the current flood protection system the influence of a closed Europoort barrier becomes larger for larger return periods for all locations with a small exception for large return periods and sea level rise values for Dordrecht and the Dordtse Kil. The second phenomenon that may be observed is that the influence of a closed Europoort barrier increases for larger values of sea level rise for the current flood protection system. Thirdly, it can be immediately recognized that with the inclusion of Delta21 to the flood protection system, the influence of a closed Europoort barrier on the total probability of occurrence of high-water levels decreases for each location, sea level rise value and return period.

CS/D21 [%/%]	**T = 1**	**T = 10**	**T = 100**	**T = 1000**	**T = 10000**
SLR = 0.2 m	1.6/0.4	6.9/1.8	9.6/13.4	66.2/37.4	84.2/42.3
SLR = 0.6 m	11.3/4.8	11.3/4.8	52.1/26.6	90.1/26.4	86.3/18.1
SLR = 1.1 m	18.8/7.9	48.5/6.0	90.0/7.3	89.7/8.6	82.7/1.2

Table E.1: Influence of closed Europoort barrier on total probability of occurrence of water level at Dordrecht

CS/D21 [%/%]	**T = 1**	**T = 10**	**T = 100**	**T = 1000**	**T = 10000**
SLR = 0.2 m	3.0/0.9	9.3/1.4	29.0/4.4	66.4/23.1	87.7/27.8
SLR = 0.6 m	8.7/0.8	21.7/3.8	55.1/15.5	89.1/10.1	87.1/1.0
SLR = 1.1 m	22.2/1.5	61.4/0.6	90.8/1.7	90.3/0.4	86.3/0.1

Table E.2: Influence of closed Europoort barrier on total probability of occurrence of water level at Dordtse Kil

CS/D21 [%/%]	**T = 1**	**T = 10**	**T = 100**	**T = 1000**	**T = 10000**
SLR = 0.2 m	1.8/0.9	4.1/0.9	6.1/3.0	19.4/10.7	46.3/25.8
SLR = 0.6 m	5.8/2.5	7.3/3.2	18.3/9.0	49.7/19.5	80.6/31.1
SLR = 1.1 m	18.3/14.7	35.3/6.5	65.9/11.6	93.3/35.4	96.6/57.9

Table E.3: Influence of closed Europoort barrier on total probability of occurrence of water level at Nieuwe Merwede split

From the Tables E.1, E.2 and E.3 one can therefore conclude that water levels for the situation where the Europoort barrier is closed are drastically lowered due to the use of Delta21. This is true for return periods between 1 and 100 years, which are most relevant for the flood prone areas not protected by flood defenses, but also for larger return periods that are more essential to areas within the flood defenses. From this it can also be concluded that Delta21 gets almost all its water level reduction from the situation with a closed Europoort barrier. Due to this, situations in which the Europoort barrier stays open become more relevant and Delta21 is not able to reduce the water levels for these situations. There is therefore a clear limit to the water level reduction potential at the Island of Dordrecht by Delta21.

E.3. Flows and water levels at other locations in Rhine-Meuse delta

Not only at the project area and at the Island of Dordrecht the impact of Delta21 can be observed. One interesting phenomenon to see is that the flow distribution within the Rhine-Meuse delta is largely affected. In Figure E.5 the change of flow through the Spui and Hollands Diep can be observed. These river segments are the two suppliers of the Haringvliet and it is clear that for the use of Delta21, more water is drawn towards the Haringvliet than for the current flood protection system. As has been shown in E.2, the influence of Delta21 for this specific set of boundary conditions is larger for a situation with sea level rise than without. The same increased impact can be seen in the flow increase through the Hollands Diep during high water.

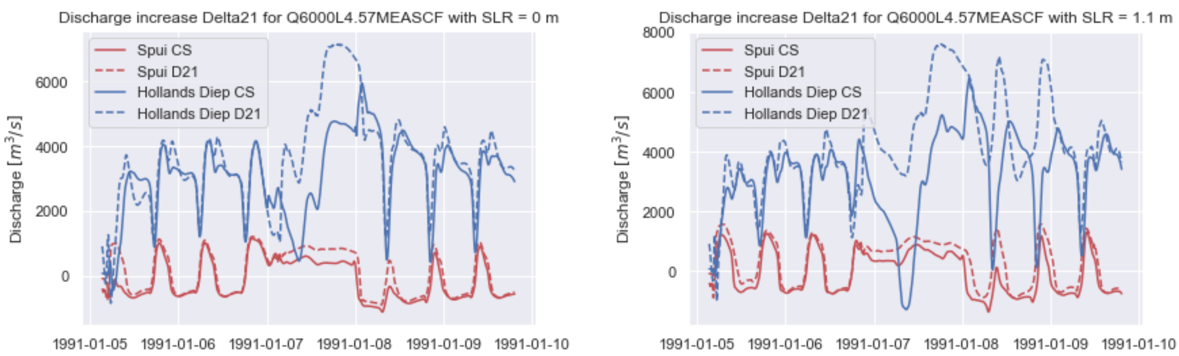


Figure E.5: Change in discharge through Spui and Hollands Diep through Delta21

This extra amount of water that is drawn towards the Haringvliet is therefore not flowing towards the Nieuwe Waterweg. More precisely, the amount of water flowing through the Spui and Hollands Diep combined during the storm is actually greater than the total amount of water coming into the system through the Rhine and Meuse. This means that more water is leaving the system than entering, hence the lowering of the water levels during high water at sea.

Water flowing into the Hollands Diep originates from either the Dordtse Kil or the Nieuwe Merwede in combination with water coming from the Biesbosch and the Amer. The Nieuwe Merwede draws its water from the Boven Merwede, which means that almost all of this discharge is river water. In comparison, the Dordtse Kil draws water from the Oude Maas, just like the Spui does. In Figure E.6 it can be observed that the discharge through both these routes increases during a storm for the flood protection system with Delta21. However, this change is much larger in relative terms in the Dordtse Kil than in the Nieuwe Merwede.

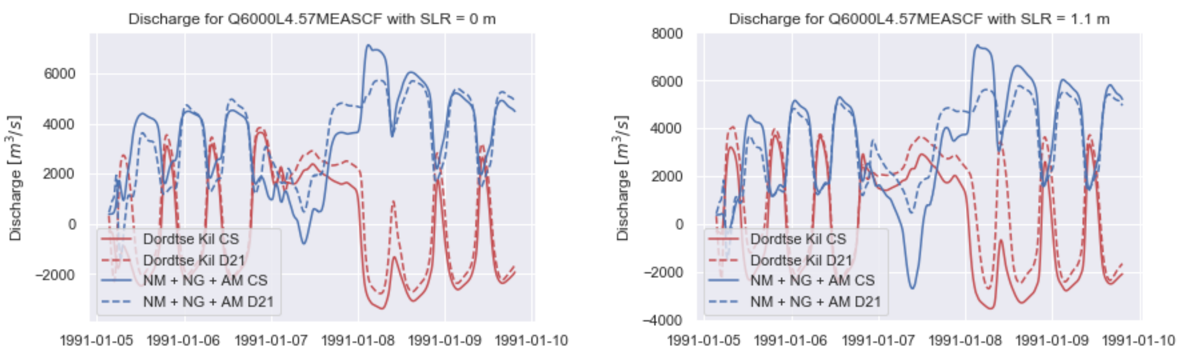


Figure E.6: Change in discharge through Dordtse Kil and Nieuwe Merwede + Biesbosch + Amer

In order to capture the findings from Figures E.5 and E.6 more generally, in Figure E.7 below the relative change in discharge through some of the river branches in the Rhine-Meuse delta can be found for the sea level rise scenarios of 0.2 m and 1.1 meters. It is clear that water is directed more towards the Haringvliet and less water goes through the Oude and Nieuwe Maas towards the Nieuwe Waterweg. The mean of these discharges are calculated as the weighted mean of the 54 combinations of boundary conditions. Though weighted, this figure in no way reflects the actual 'average' discharge change. It only represents a trend of changes in extreme discharges for the implementation of Delta21 and the influence of sea level rise on this trend.

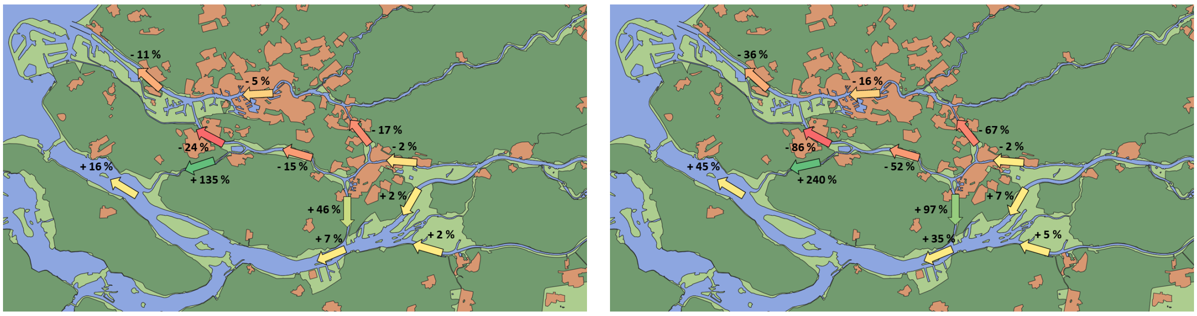


Figure E.7: Change in average discharge in the Rhine-Meuse delta compared to current system for SLR = 0.2 and 1.1 m.

From the changes in average discharge in the Rhine-Meuse delta three points can be identified where the distribution of river water is largely affected:

- Beneden Merwede / Oude Maas / Noord
- Oude Maas / Dordtse Kil
- Oude Maas / Spui

The main phenomenon that can be found from these distribution changes is that river water is directed more to the south west delta, hence the Haringvliet. This is of course logical as the placement of the Delta21 pumping station should draw water towards this location. Because the relative increase of discharges through the Spui and Dordtse Kil increase so significantly, flow velocities may increase to dangerous and unwanted heights in the future with the implementation of Delta21. These river branches can therefore be identified as bottlenecks in the new system with Delta21.

F

Computed flood risk for flood protection system with Delta21

This appendix gives a full overview of the computed water levels and flood risk at the Island of Dordrecht for the flood protection system with Delta21. Also the influence of sea-level rise and increased extreme Rhine discharges is determined.

F.1. Water level frequency curves

To acquire a comprehensive comparison between the current flood protection system, Plan Locks and the flood protection system with Delta21 is needed. This is done for the same locations are assessed as in Appendix C. Additionally to the water level frequency curves of the scenarios, also the individual influence of sea level rise and the increased extreme Rhine discharge is analyzed for the flood protection system with Delta21. For these analyses configuration 1 is chosen as this configuration has the same closure level of the Europoort as the current flood protection system and the lowest initiation level of Delta21 (and therefore the most frequent use). Hence, the sole influence of Delta21 is best observed for this configuration without any disturbance due to a change in the Europoort barrier operation.

F.1.1. Influence of sea level rise

In Figure F.1 the influence of sea level rise on the water level frequency curves for the flood protection system with Delta21 can be observed. It can be seen that the influence of sea level rise is not constant for each return period. Instead, the water level difference up until return periods of about 1,000 years are relatively small and the curves start to divert from that point onward. This is different from the behavior for the current flood protection system. It is in line with the observations made in Appendix E. There it is shown that for the current flood protection system the water level at Dordrecht is influenced more by a closed Europoort barrier for an increasing sea level rise. This means that for a rising sea level, there comes more opportunity for Delta21 to perform its water level reducing function. For larger return periods however, the influence of a closed Europoort barrier stays constant for a rising sea level. Therefore Delta21 does not change the relative rise between the sea level rise scenarios for these large return periods.

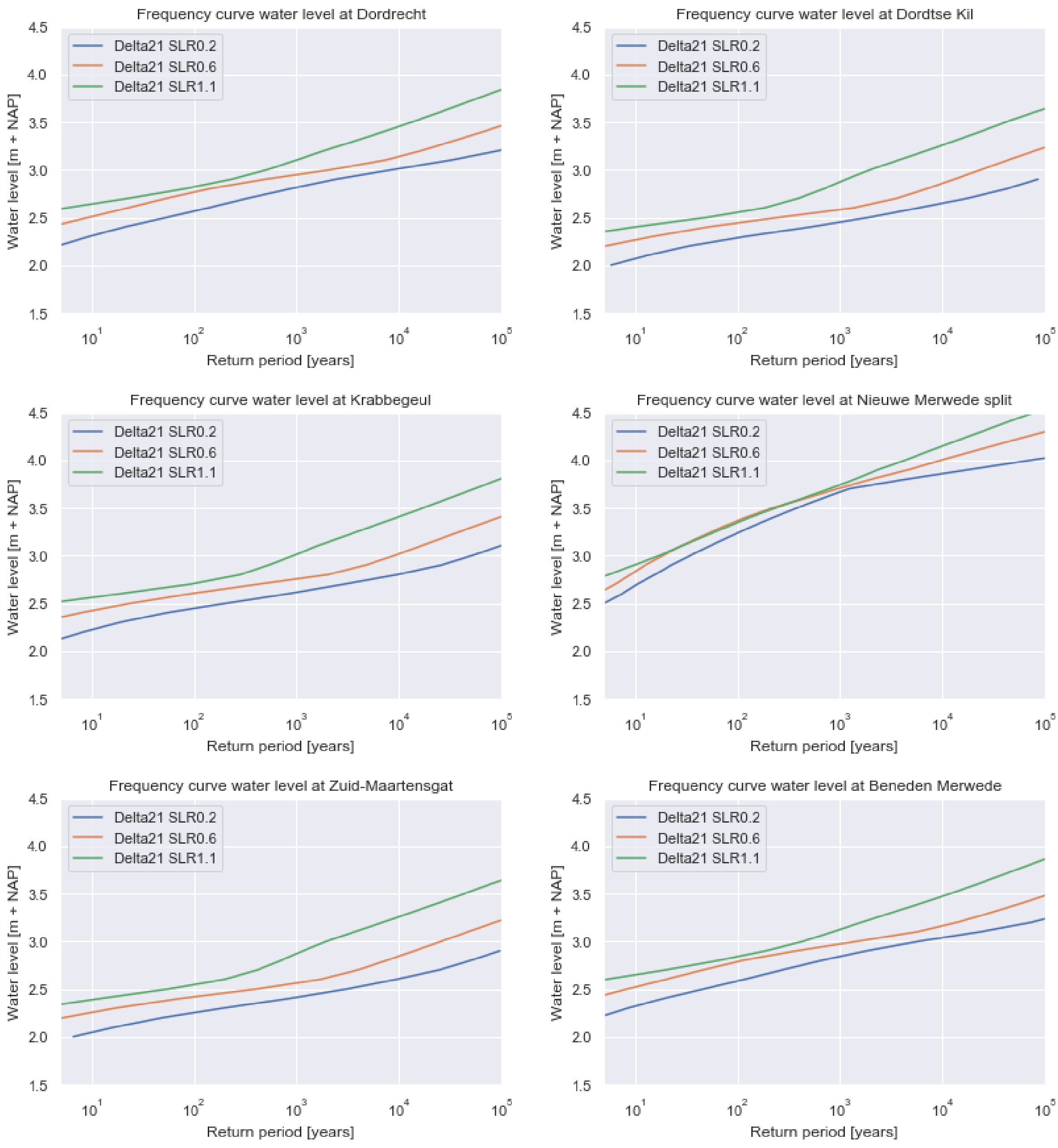


Figure F.1: Influence of sea-level rise on the water level frequency curves for various locations around the Island of Dordrecht with Delta21

F.1.2. Influence of increase maximum Rhine discharge

In Figure F.2 the influence of the increase of Q_{1000} of the Rhine on the water level frequency curves at the Island of Dordrecht can be seen. As also apparent in Appendix C, the influence of this increase of the extreme Rhine discharge is most prominently seen at the Nieuwe Merwede split location. This observation station is located all the way at the east side, and therefore river dominated, part of the Island of Dordrecht. The water level frequency curves for the Dordtse Kil, Krabbegeul and Zuid-Maartensgat are all almost identical for each of the extreme discharge values. These observation points are located at the Dordtse Kil and just upstream of the Hollands Diep, which are shown to be drained quite extensively during the operation of Delta21 as can be seen in Appendix E.

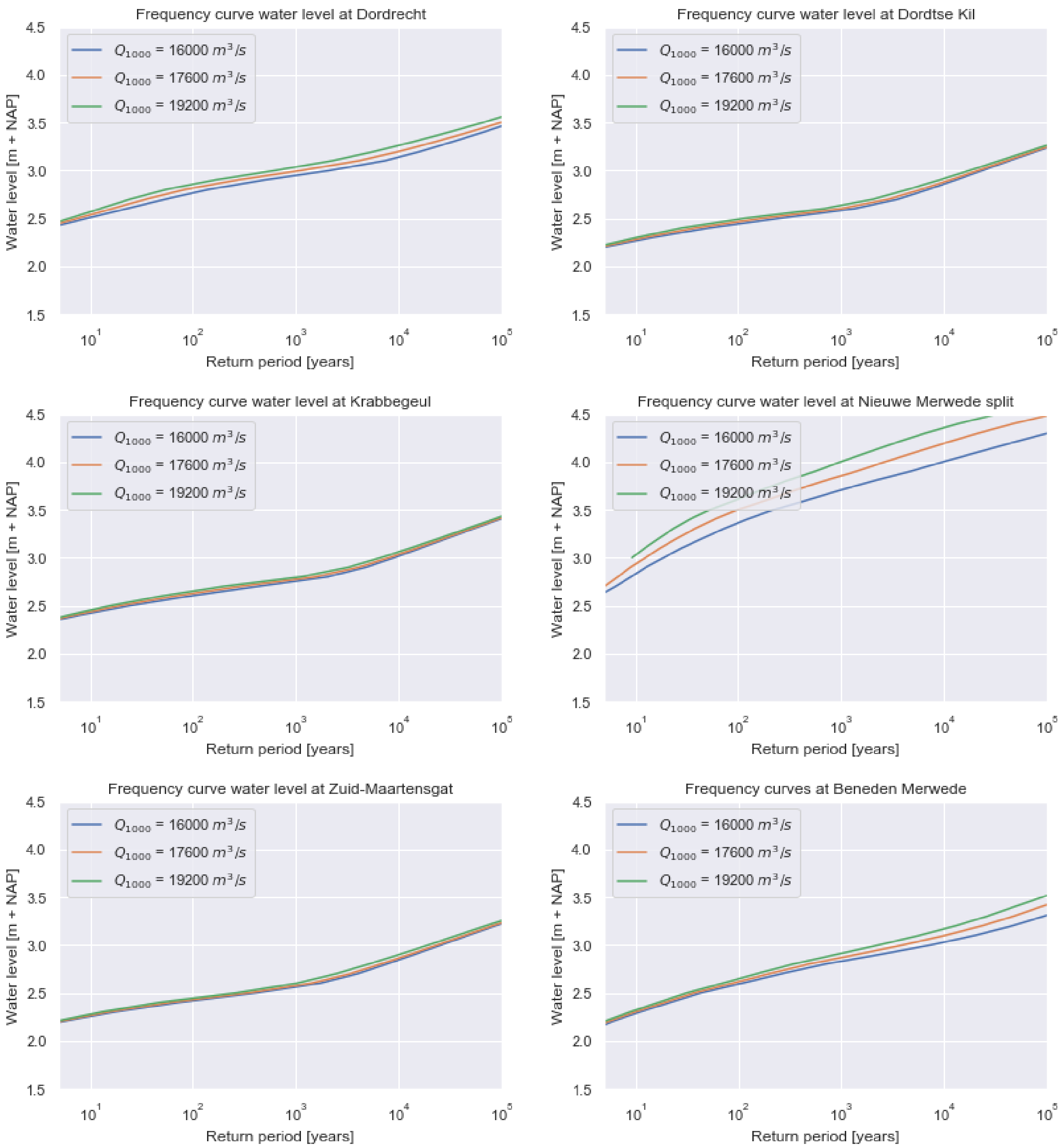


Figure F.2: Influence of increasing Rhine discharges on the water level frequency curves for various locations around the Island of Dordrecht for system with Delta21

F.1.3. Influence of configuration parameters

Influence of closure level Europoort barrier

In Figure F.3 the influence of the Europoort closure level on the water level at Dordrecht can be observed. It is clear that the closure level of the Europoort barrier has a very large influence on the water levels at Dordrecht. From Appendix E the influence of a closed Europoort barrier on the total probability of occurrence of extreme water levels at the Island of Dordrecht can be found. There are however two ways in which the Europoort barrier can stay opened. This can be due to the fact that the water level expected at Rotterdam and Dordrecht does not exceed the prescribed closure level or it does and the barrier has failed to close. The first type of opened Europoort barrier can be found for return periods from 1 to 100 years. The second type for return periods larger than about 1,000 years.

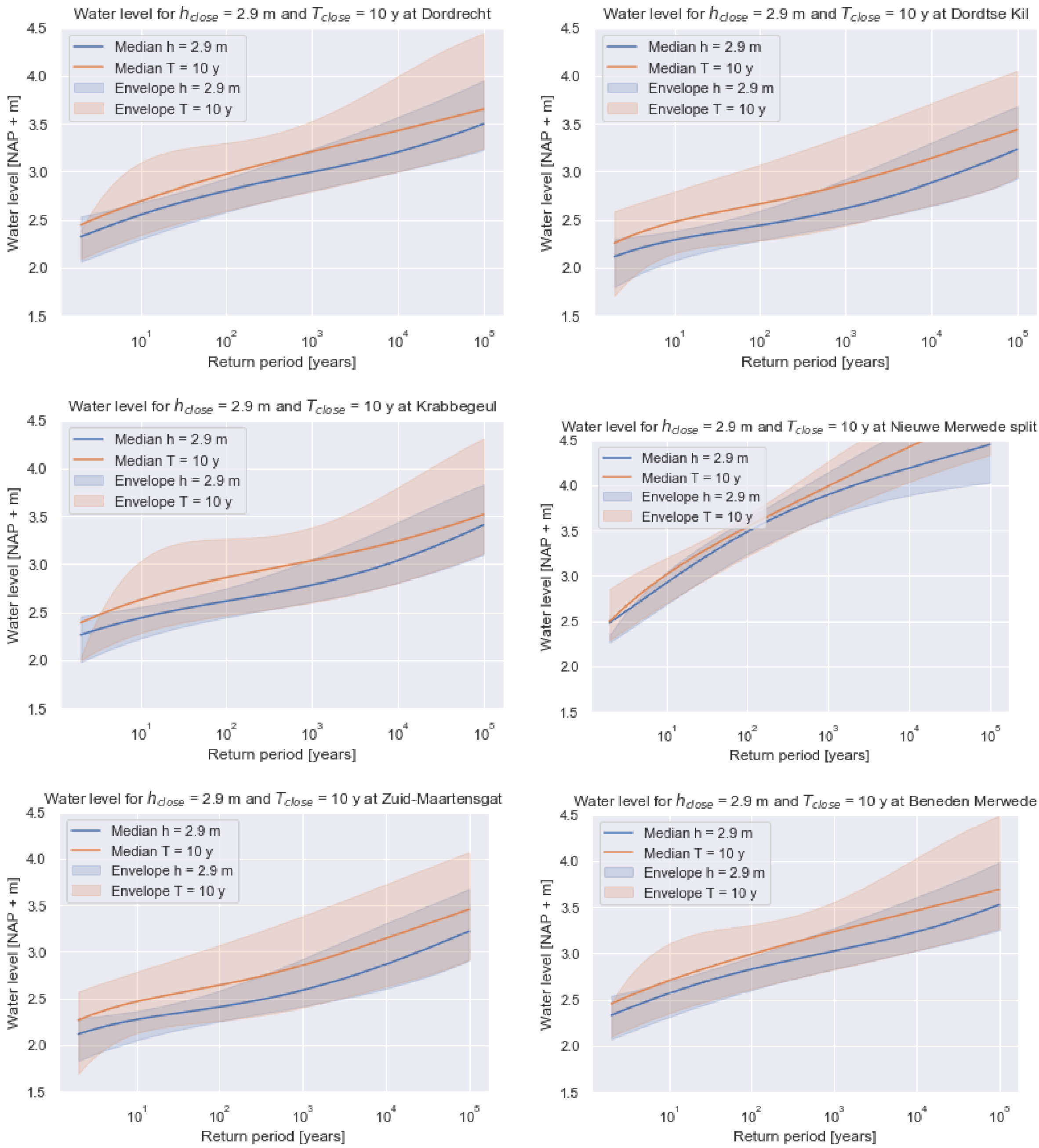


Figure F.3: Water level frequency curves for Europoort closure level and return period of 2.9 m and 10 years.

Influence of initiation level Delta21

In Figure F.4 the influence of the change of the initiation level of Delta21 can be observed. For all locations along the Island of Dordrecht, the water level frequency curves are shifted down due to a lower initiation level. This mainly counts for the locations along the Dordtse Kil and the south of the Island. As can also be seen in Appendix E the influence of Delta21 on these locations is the largest. As the initiation level of NAP + 2.9 m of Delta21 at Dordrecht is the same as the closure level of the Europoort barrier, Delta21, with this configuration setting, is only used when the Europoort barrier is closed.

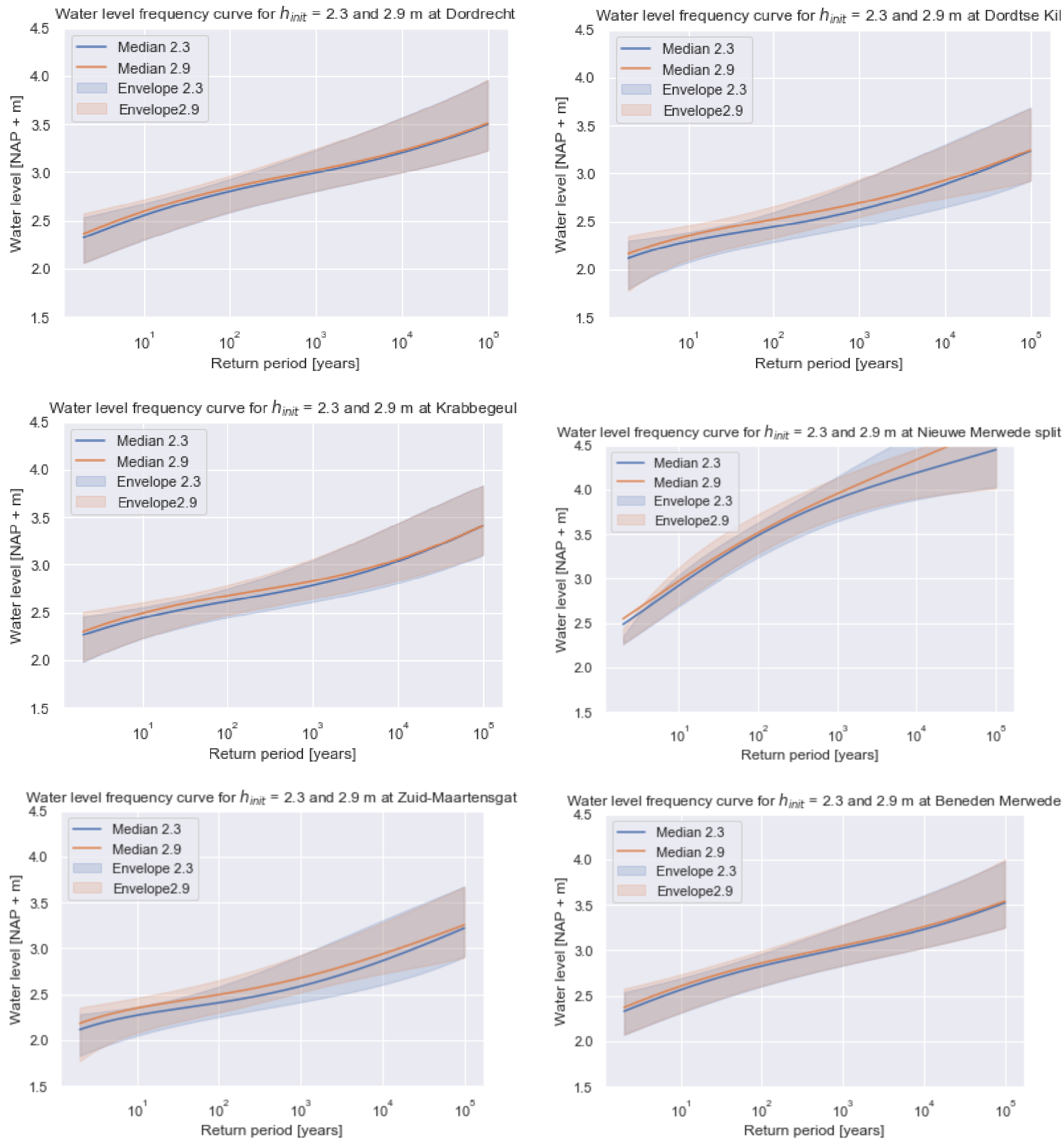


Figure F.4: Water level frequency curves for Delta21 initiation level of 2.3 and 2.9 meters

For the initiation level of NAP + 2.3 m at Dordrecht, Delta21 is also initiated when the Europoort barrier is not closed. Hence, one would expect that the influence on the frequency curve is the largest for return periods where high-water level occurrence is dominated by an opened Europoort barrier. The reason for this is that the additional situations where Delta21 is initiated is only for the situation where the Europoort barrier is opened.

To prove this point, one can look at the Dordtse Kil, where the lowering of the frequency curve is largest for a return period of about 10 years for a sea level rise of 0.6 m. Looking at the illustration point obtained from Hydra-NL found in Appendix E, one can see that the contribution of an opened Europoort barrier is about 95, 99 and 97 % for return periods of 1, 10 and 30 years respectively. Hence, at the location of the maximum contribution of an opened Europoort barrier the influence of a lower Delta21 initiation level is also largest.

F.2. Inventory of water level reduction for all Delta21 configuration

In the Figures F.5, F.6, F.7 and F.8 the water level frequency curves for all locations around the Island of Dordrecht can be found for configurations 1, 2, 3 and 4 respectively.

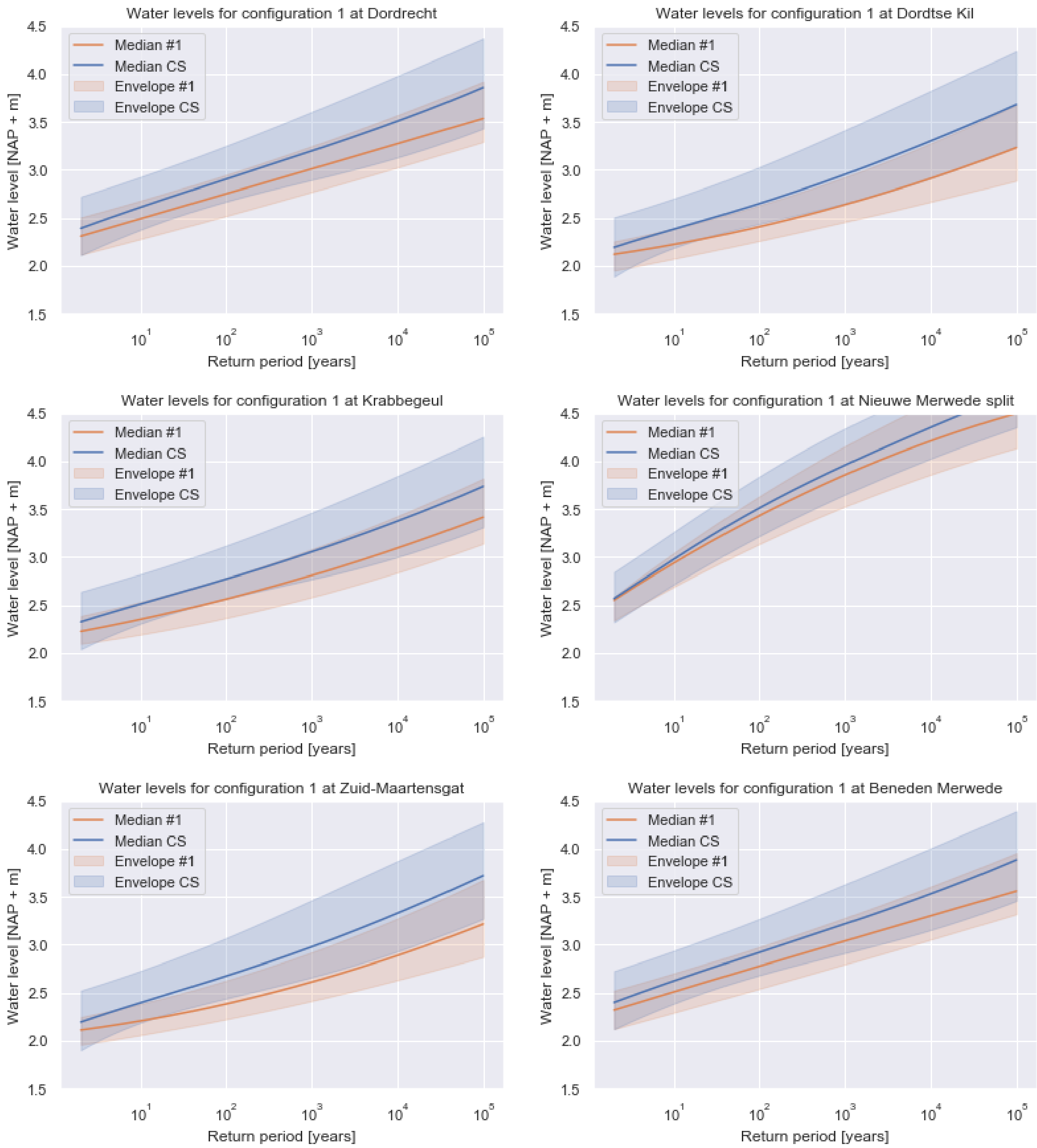


Figure F.5: Water level frequency curves for Delta21 configuration 1

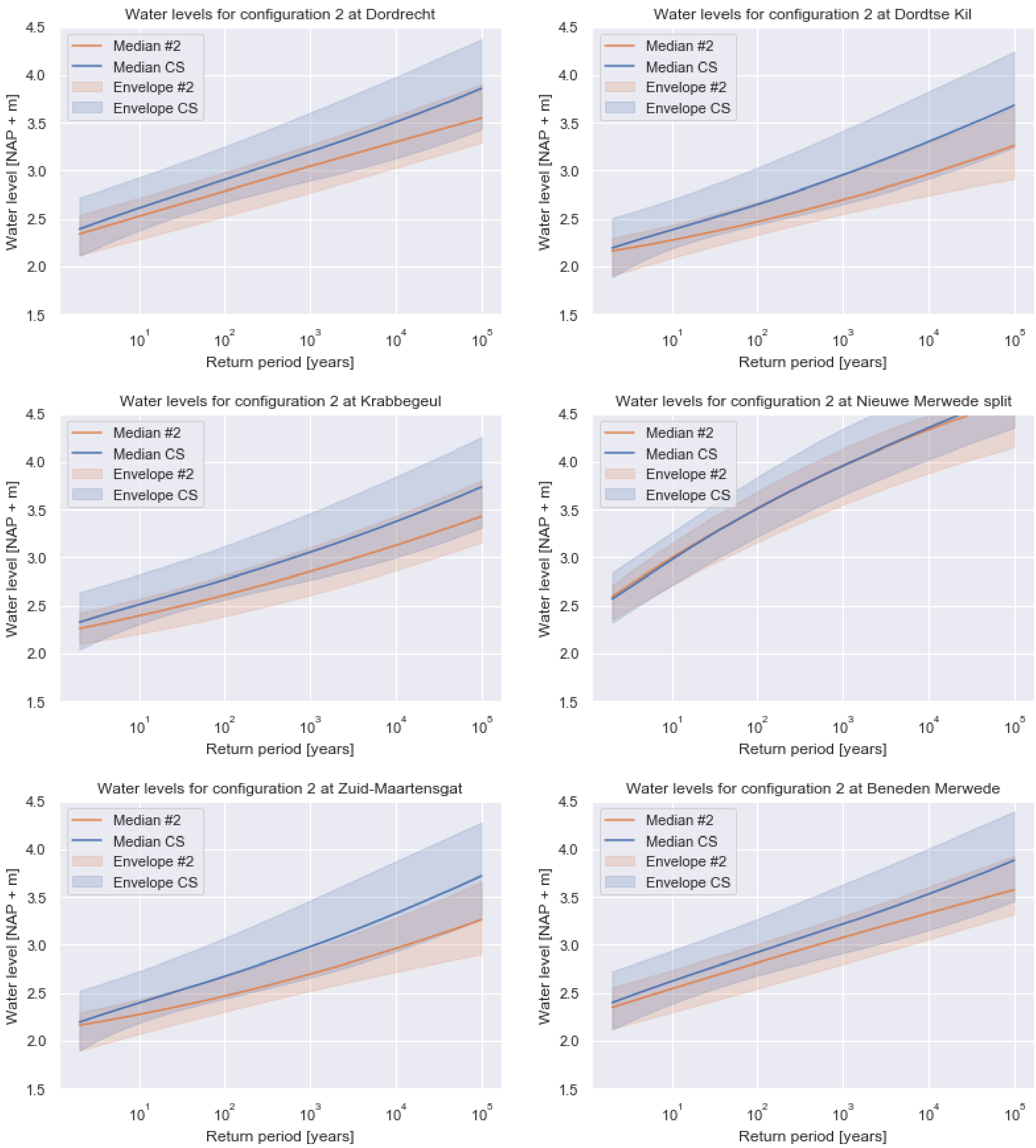


Figure F.6: Water level frequency curves for Delta21 configuration 2

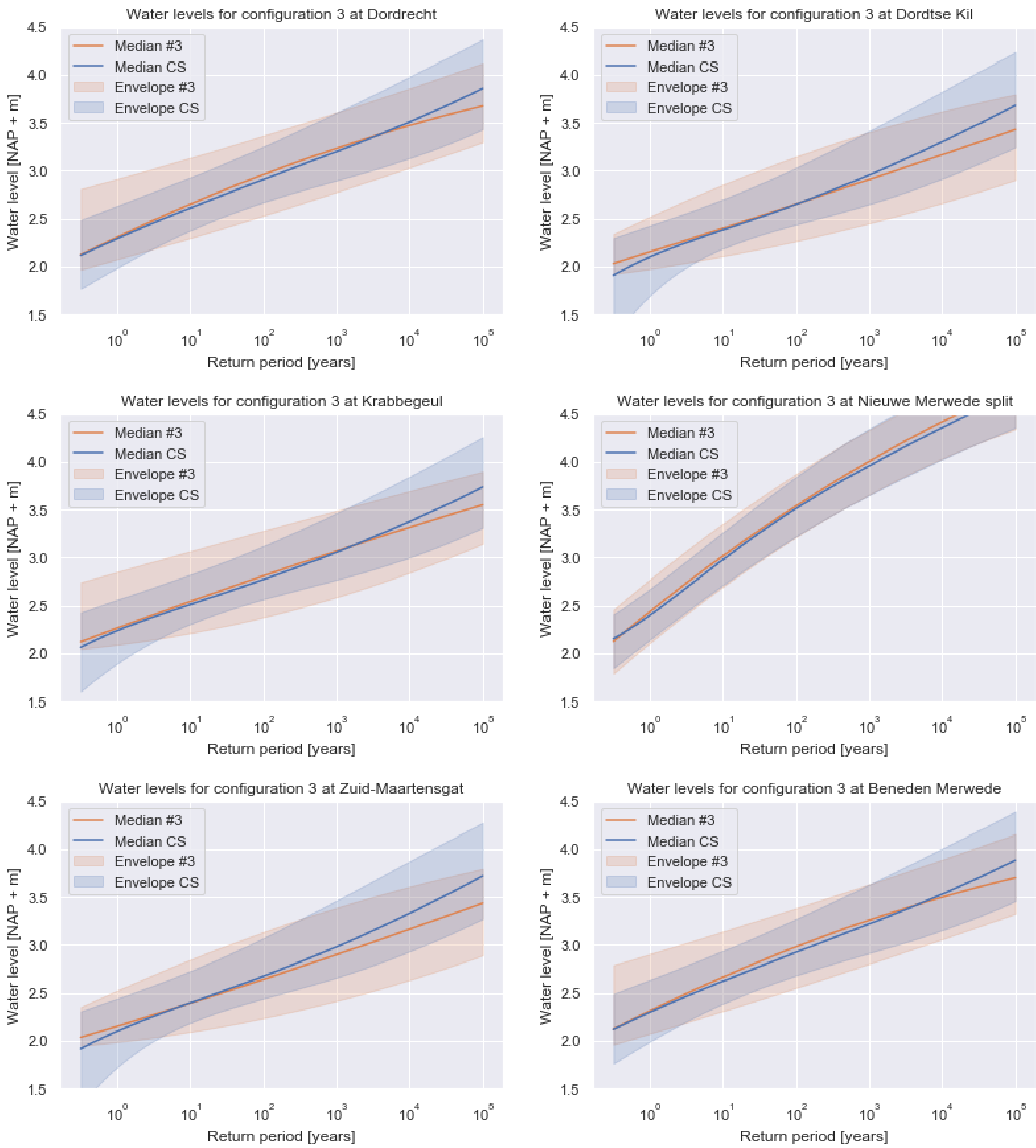


Figure F.7: Water level frequency curves for Delta21 configuration 3

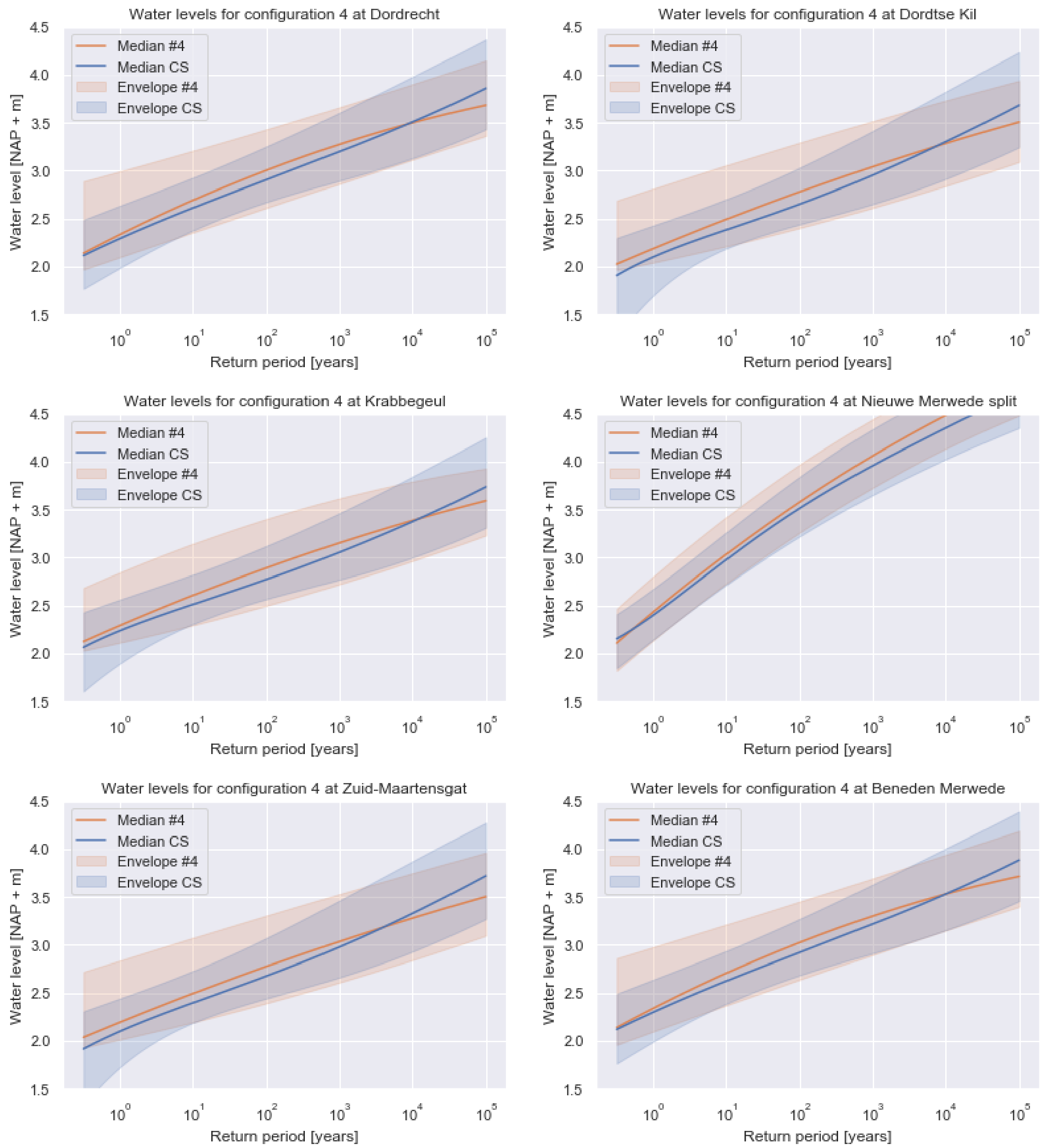


Figure F.8: Water level frequency curves for Delta21 configuration 4

F.3. Total flood risk for Delta21 configurations

The water level frequency curves from Figures F.5, F.6, F.7 and F.8 are combined with the damage profiles from Figure 3.2. This leads to the total flood risk curves as can be found in Figure F.9.

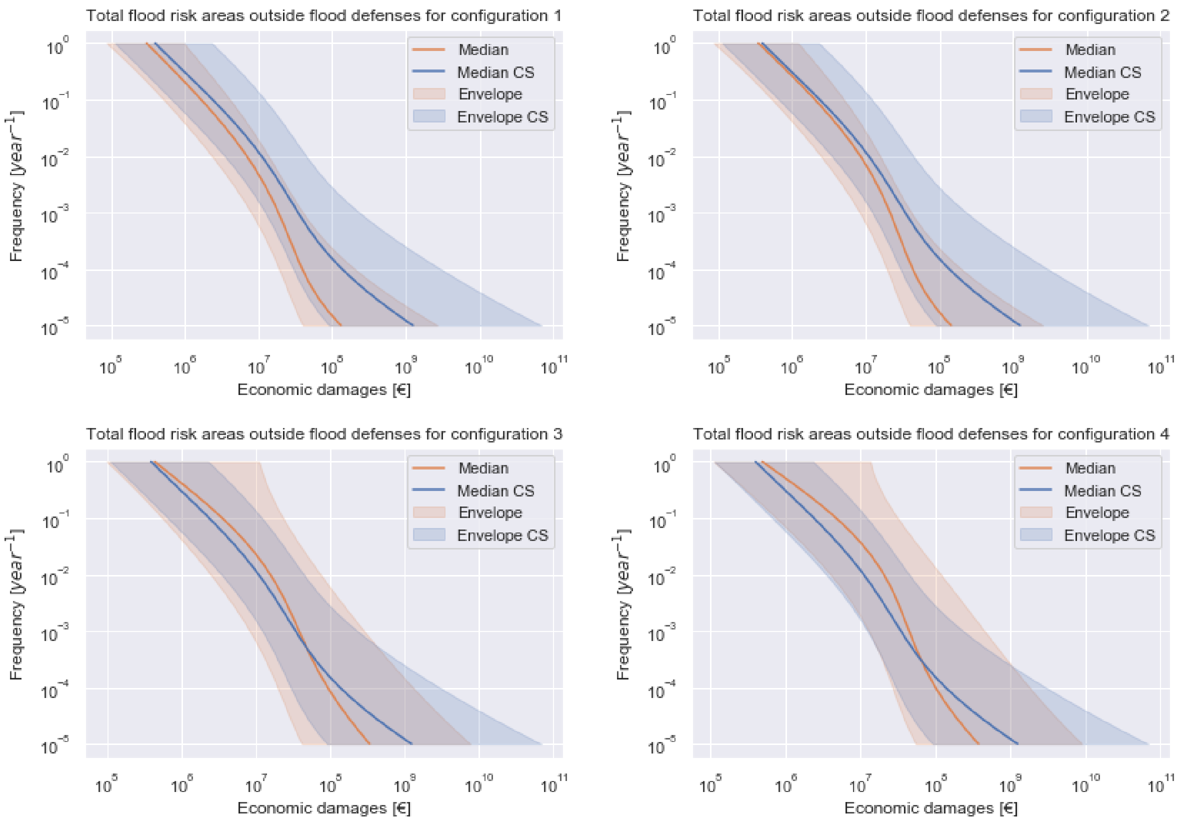


Figure F.9: Flood risk curves for the Delta21 configurations.

The flood risk curves from Figure F.9 can be translated into an annual value at risk for each of the configurations and scenarios. These annual values at risk can be found in Table F.1.

	Minimum [€/year]	Medium [€/year]	Maximum [€/year]
Configuration 1	$2.9 * 10^5$	$9.1 * 10^5$	$2.4 * 10^6$
Configuration 2	$3.0 * 10^5$	$1.1 * 10^6$	$2.9 * 10^6$
Configuration 3	$3.1 * 10^5$	$1.8 * 10^6$	$1.7 * 10^7$
Configuration 4	$4.2 * 10^5$	$2.2 * 10^6$	$2.2 * 10^7$

Table F.1: Total annual value at risk at flood prone areas not protected by flood defenses for Delta21 configurations

The difference between the total flood risk for the current system and the Delta21 configuration variants can be found in Table F.2.

	Minimum [%]	Medium [%]	Maximum [%]
Configuration 1	-25	-30	-70
Configuration 2	-23	-15	-64
Configuration 3	-21	+38	+233
Configuration 4	+28	+45	+172

Table F.2: Change in total annual value at risk at flood prone areas not protected by flood defenses for Delta21 configurations

G
Optimal operation of the flood protection system with Delta21

In this appendix the optimal operation of the flood protection system with Delta21 for the flood prone areas not protected by flood defenses is determined. This is done by assessing the computed flood frequencies and flood risk from Appendix F.

There are four main criteria that lead to the optimal operation of the flood protection system with Delta21. Those are the flood risk at the historical harbor, the flood frequency of the historical harbor, the closure frequency of the Europoort barrier and the initiation frequency of Delta21.

G.1. Flood risk at historical harbor

In Table G.1 percentages of the annual value at risk at the historical harbor compared to the annual income per household can be found. The aim is to bring down this percentage to 1%, but as can be seen, this is not possible for all scenarios and only configuration 1 can get close to this percentage for the maximum scenario. However, already just past the medium scenario, the 1 % limit is surpassed.

	Minimum [%]	**Medium [%]**	**Maximum [%]**
Current system	0.2	0.9	7.6
Configuration 1	0.2	0.7	2.3
Configuration 2	0.2	0.8	2.7
Configuration 3	0.2	1.3	16
Configuration 4	0.2	1.6	20

Table G.1: Percentage of annual value at risk compared to income per household at historical harbor for Delta21 configurations

G.2. Flood frequency at historical harbor (water at quay)

A water level of NAP + 2.5 m at the historical harbor is regarded as the level that is most significant for this region. This water level currently occurs about once every 50 years on average, as can be seen in Figure 3.4. As can be seen in the flood damage curves in Appendix C, this is equivalent with flood damages of about one million Euros. Hence, for the other flood prone regions not protected by flood defenses, the water level that accounts for flood damages of €1,000,000 is regarded as the turning point that defines a flood for this criterium. As there are three different sea level rise scenarios, a range of flood frequencies is given for each configuration of Delta21.

In Table G.2 the return periods at which the water level exceeds NAP + 2.5 m at Dordrecht are given for each of the configurations and scenarios. As one can imagine, configuration 1 reduces the water level at Dordrecht the most with its lowest Europoort closure level and Delta21 initiation level. All the other configurations show some increase of flooding frequencies with different magnitudes for varying return periods.

	Minimum [years]	**Medium [years]**	**Maximum [years]**
Current system	21	4.3	0.3
Configuration 1	55	7.6	1.4
Configuration 2	51	5.4	0.8
Configuration 3	55	2.7	0.6
Configuration 4	14	2.3	0.4

Table G.2: Return period of water level larger than NAP + 2.5 m at Dordrecht for all configurations and scenarios

G.3. Closure frequency Europoort barrier

in the different configurations of Delta21 the Europoort closure level is varied. For each closure level that was used in this report, the accompanied closure frequency can be found for the scenarios in which it was implemented. Logically, all the closure levels larger than NAP + 2.9 m were chosen as such that the closure frequency was equal to the present closure frequency, which is 0.1 $year^{-1}$. It is clear that the closure frequency of the Europoort barrier goes up to 10 $year^{-1}$ for the maximum scenario, which is larger than the limit of 3 $year^{-1}$ that is currently used.

	Minimum [$year^{-1}$]	**Medium [$year^{-1}$]**	**Maximum [$year^{-1}$]**
NAP + 2.9 m	0.2	0.9	10.4
NAP + 3.1 m	0.1	-	-
NAP + 3.4 m	-	0.1	-
NAP + 3.8 m	-	-	0.1

Table G.3: Frequency of closure of the Europoort barrier for all closure level at Dordrecht and scenarios

G.4. Initiation frequency Delta21

The components of Delta21 are initiated when the water level at Dordrecht exceeds the initiation level. This level is equal to NAP + 2.3 m for configuration 1 and goes up to NAP + 3.8 m for configuration 4 for the maximum scenario. In Table G.4 the initiation frequencies that belong to the initiation levels of Delta21 can be found. Largely the initiation frequencies are the same as the closure frequencies of the Europoort barrier, with an exception of the NAP + 2.3 m initiation level. This leads to an initiation frequency of up to 90 $year^{-1}$ for the maximum scenario.

	Minimum [$year^{-1}$]	**Medium [$year^{-1}$]**	**Maximum [$year^{-1}$]**
NAP + 2.3 m	1.2	7.8	89
NAP + 2.9 m	0.2	0.9	10.4
NAP + 3.1 m	0.1	0.5	-
NAP + 3.4 m	-	0.1	-
NAP + 3.8 m	-	-	0.1

Table G.4: Frequency of initiation of Delta21 for each initiation level and scenario

G.5. Optimal operation

By combining the information found in Sections G.1, G.2, G.3 and G.4, the optimal operation of Delta21 for the flood prone areas not protected by flood defenses can be found. Because the differences in outcomes of each of these criteria differ enormously from each of the scenarios, it is chosen to assign an operation strategy for each scenario. This means that the operation of the new flood protection system can be adjusted to the developments of sea level rise and increased extreme Rhine discharges.

When finding the optimal operation for a certain scenario, there is a order of importance of the criteria. The most important one being the flood frequency and flood risk reduction obtained by the configuration, then the closure frequency of the Europoort barrier and lastly the initiation frequency of Delta21.

G.5.1. Operation strategy for minimum scenario

From Table G.2 it can be found that all configurations except configuration 4 all have little impact on the occurrence of a water level equal to NAP + 2.5 m. Hence, it can be easily chosen to heighten the closure level of the Europoort barrier. This means that the current closure frequency of once per ten years can be retained instead of a closure frequency of once per five years. The increased flooding frequency that leads from configuration 4 is not too large for the minimum scenario. Hence, for the minimum scenario it is decided that the Europoort barrier and Delta21 work inclusively and are thus only used together and never separately. The optimum configuration is therefore configuration 4. In Table G.5 the resulting flood risk change, flood frequency and closure and initiation frequencies can be found.

- Closure level Europoort barrier = NAP + 3.1 m
- Initiation level Delta21 = NAP + 3.1 m

	Results optimal configuration
Total flood risk	$4.2 * 10^5$ €/year
Flood risk change	+ 28 %
Risk per income household HH	0.2 %
Flood frequency	1/14 $year^{-1}$
Closure frequency Europoort	1/11 $year^{-1}$
Initiation frequency Delta21	1/11 $year^{-1}$

Table G.5: Results optimal configuration minimum scenario

G.5.2. Operation strategy for medium scenario

The medium scenario poses more problems as the decrease of the flooding frequency due to the implementation of Delta21 is not as too large in absolute terms. Actually, by attempting to keep the closure frequency of the Europoort barrier constant for a flood protection system with Delta21 the flooding frequency of the historical harbor actually increases relative to the current flood protection system.

It is clear that both the situation of a constant closure level as a constant closure frequency of the Europoort barrier is undesirable and a middle road needs to be chosen. Therefore, for the medium scenario it is decided to set both the closure level of the Europoort barrier and the initiation level of Delta21 equal to NAP + 3.1 m at Dordrecht. This means that the optimal operation is not different from that of the minimum scenario.

- Closure level Europoort barrier = NAP + 3.1 m
- Initiation level Delta21 = NAP + 3.1 m

	Results optimal configuration
Total flood risk	$1.6 * 10^6$ €/year
Flood risk change	+ 25 %
Risk per income household HH	1.1 %
Flood frequency	1/4 $year^{-1}$
Closure frequency Europoort	1/2 $year^{-1}$
Initiation frequency Delta21	1/2 $year^{-1}$

Table G.6: Results optimal configuration medium scenario

G.5.3. Operation strategy for maximum scenario

For the maximum scenario it is not possible to create an optimal operation strategy that both keeps the annual value at risk at the flood prone areas not protected by flood defenses at the Island of Dordrecht within checks and helps to heighten the Europoort barrier closure level. Hence, it is chosen to create a strategy that focuses solely on keeping the value at risk at the historical harbor as close to 1 % of the income per household and the flooding frequency at this region to about 1.3 $year^{-1}$. This means that the closure frequency of the Europoort barrier rises to about 10 times per year. As this is unacceptably large, this optimal operation strategy cannot be recommended as a realistic strategy.

- Closure level Europoort barrier = NAP + 2.9 m
- Initiation level Delta21 = NAP + 2.9 m

	Results optimal configuration
Total flood risk	$2.9 * 10^6$ €/year
Flood risk change	- 64 %
Risk per income household HH	2.3 %
Flood frequency	1.3 $year^{-1}$
Closure frequency Europoort	10 $year^{-1}$
Initiation frequency Delta21	10 $year^{-1}$

Table G.7: Results optimal configuration maximum scenario

H

Method and results for including reliability in flood risk calculations

In this appendix the method and results for including the reliability of the Delta21 system in the flood risk calculations is explained.

H.1. Modeling of failure mechanisms

The three failure mechanism that have been deduced from the inventory of the relevant failure mechanisms and correlations in Section 6.3 are all modeled into the high-water model. Subsequently, each of these adjusted models were run for four different gradations of failure, namely 25, 50, 75 and 100 %.

The first failure mechanism regards the failure of opening of the siphons (spillway) of the Delta21 plan. The maximum capacity of the spillway is equal to 10,000 m^3/s and therefore the different gradations of failure could bring down the capacity to 7,500, 5,000, 2,500 and 0 m^3/s respectively. These new capacities replaced the original capacity of the pumping station in the high-water model. As mentioned in Appendix D, the spillway is modeled as a pumping station in this high-water model, which makes calculations easier and less prone to instabilities.

The second failure mechanism regards the failure of turning on the pumps of the Delta21 plan. Just as the spillway, the maximum capacity of the pumping station is equal to 10,000 m^3/s.The difference is that if the pumping station were to fail, still the available storage of the energy storage lake can be used. This was modeled by assuming that during an extreme weather event, the lake is halfway full. Reasons for assuming this are that during extreme weather events lots of wind energy is produced and part of this is stored in the energy storage lake by letting in water from sea through the turbines. However, the operator would be aware of the fact that the lake might be needed for the storage of excess river water, which means that part of the storage capacity is saved for this purpose. The halfway filled storage lake means that during 6 hours, 10,000 m^3/s of river water may be let into the lake. This means that the pumping capacity in the model remains at 100 % functioning and as soon as the volume of water equal to 6 hours times 10,000 m^3/s of water has been let in, the pumping capacity is reduced by the gradation of failure.

The third failure mechanism regards a combined failure of the storm surge barrier and the siphons to open during low water at sea. This means that after a storm water levels at sea are back to normal, but the storm surge barrier does not open anymore and water is not able to enter the energy storage lake. This is modeled by not allowing the Delta21 storm surge barrier to open after closure and by shutting off the pumps in the model (spillway in real-life) the moment they originally planned on shutting off. If the storm surge barrier fails to open, then the siphons would be opened, but for this failure mechanism this is operation fails to occur correctly. Again this is done for four gradations of failure of the siphons, but only one gradation of failure of the storm surge barrier. For the failure mechanism it is assumed that the duration of the closure of the barrier and the siphons is one day.

H.2. Impact of failure mechanisms on water levels

H.2.1. Failure mechanism 1: failing siphon system

In Figure H.1 the impact of failure mechanism 1 on the water levels at the Island of Dordrecht can be found. It is clear that the influence of a failing siphon system becomes increases for larger return periods. Furthermore, the water levels that occur for a (partially) failing siphon system are much higher than for the current flood protection system from about 50 % failure onward.

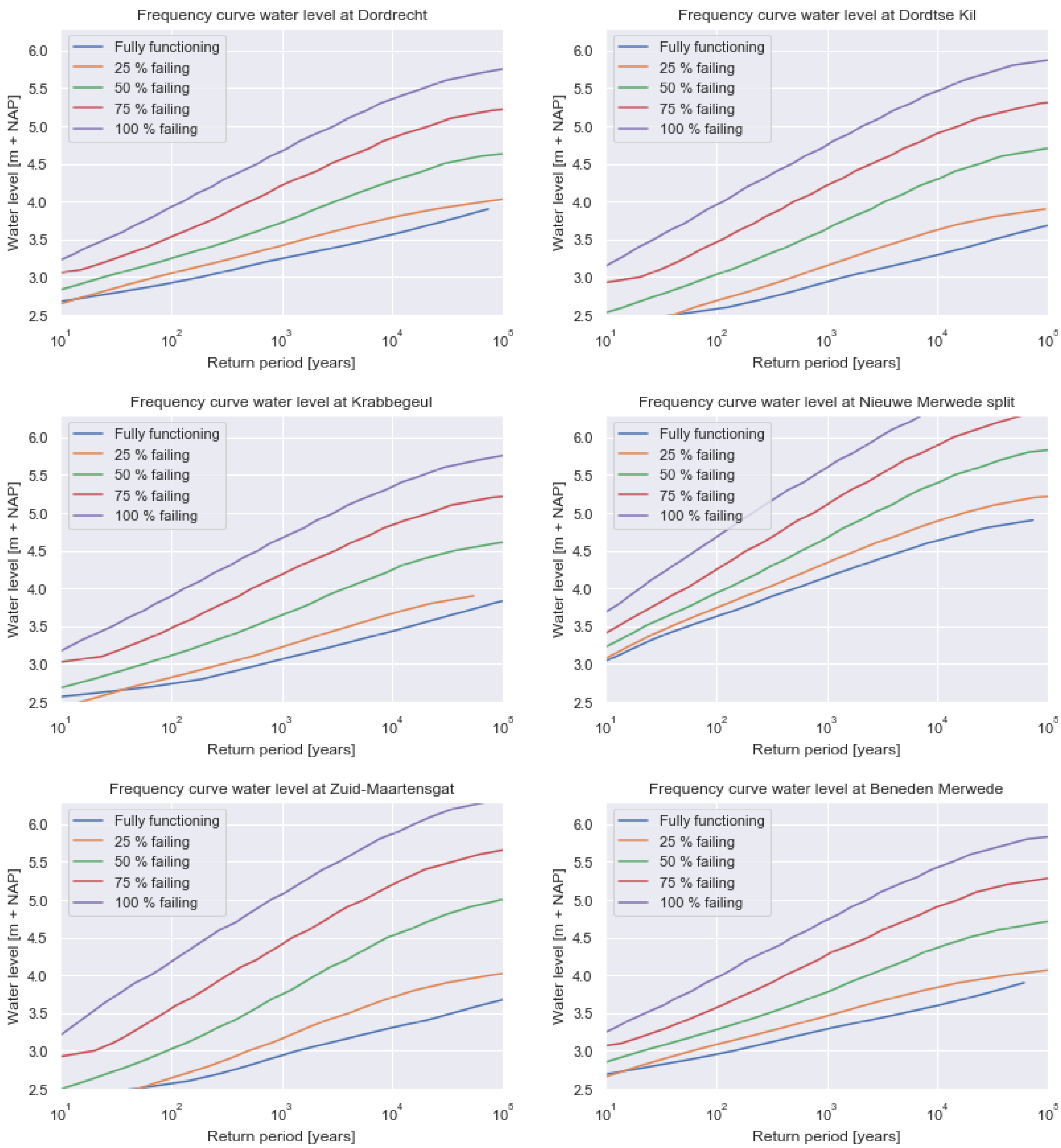


Figure H.1: Influence of (partially) failing siphons (failure mechanism 1) on water levels at Island of Dordrecht

From the graphs in Figure H.1 the maximum influence on the water level for each of the degrees of failure can be determined. In Table H.1, for each degree of failure, the maximum water level increase up until a return period of 100,000 years is given. The maximum difference is at Zuid-Maartensgat for all gradations of failure.

	Maximum water level increase [m]
25%	0.4
50%	1.3
75%	2.0
100%	2.7

Table H.1: Increase of water level due to failure mechanism 1

The water level increases from Table H.1 lead to maximum allowable probability of occurrence for a maximum impact of 0.10 m. The maximum allowed probabilities for each gradation of failure can be found in Table H.2.

	Probability of occurrence [m]
25%	0.25
50%	0.08
75%	0.05
100%	0.04

Table H.2: Maximum allowed probability of occurrence for maximum impact of 0.10 m by failure mechanism 1

The maximum allowed probabilities of occurrence for each gradation of failure can be transformed in maximum allowable probabilities of failure per component. This is done for a completely dependent and independent system and the values of this can be found in Figure H.2.

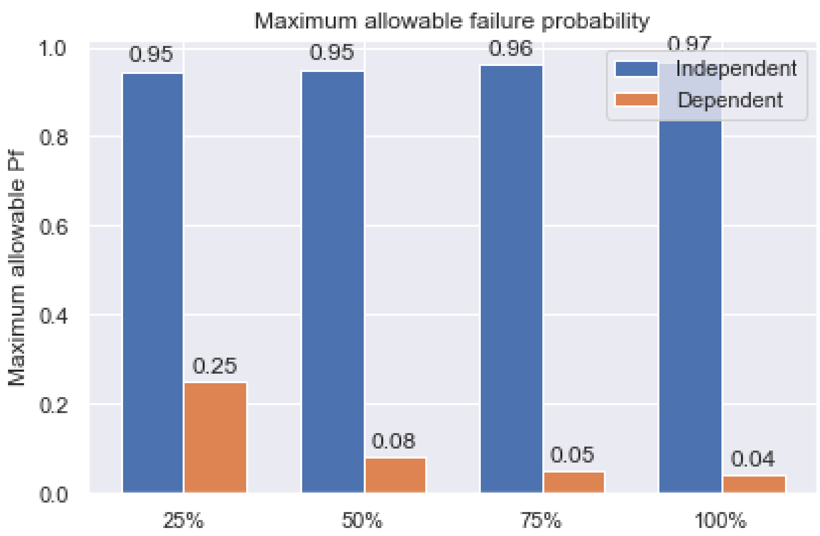


Figure H.2: Maximum allowable probability of failure for siphon system per component

H.2.2. Failure mechanism 2: failing pumping station

In Figure H.3 the impact of failure mechanism 2 on the water levels at the Island of Dordrecht can be found. It is immediately clear that the impact of failure mechanism 2 on the water levels is smaller than that of failure mechanism 1.

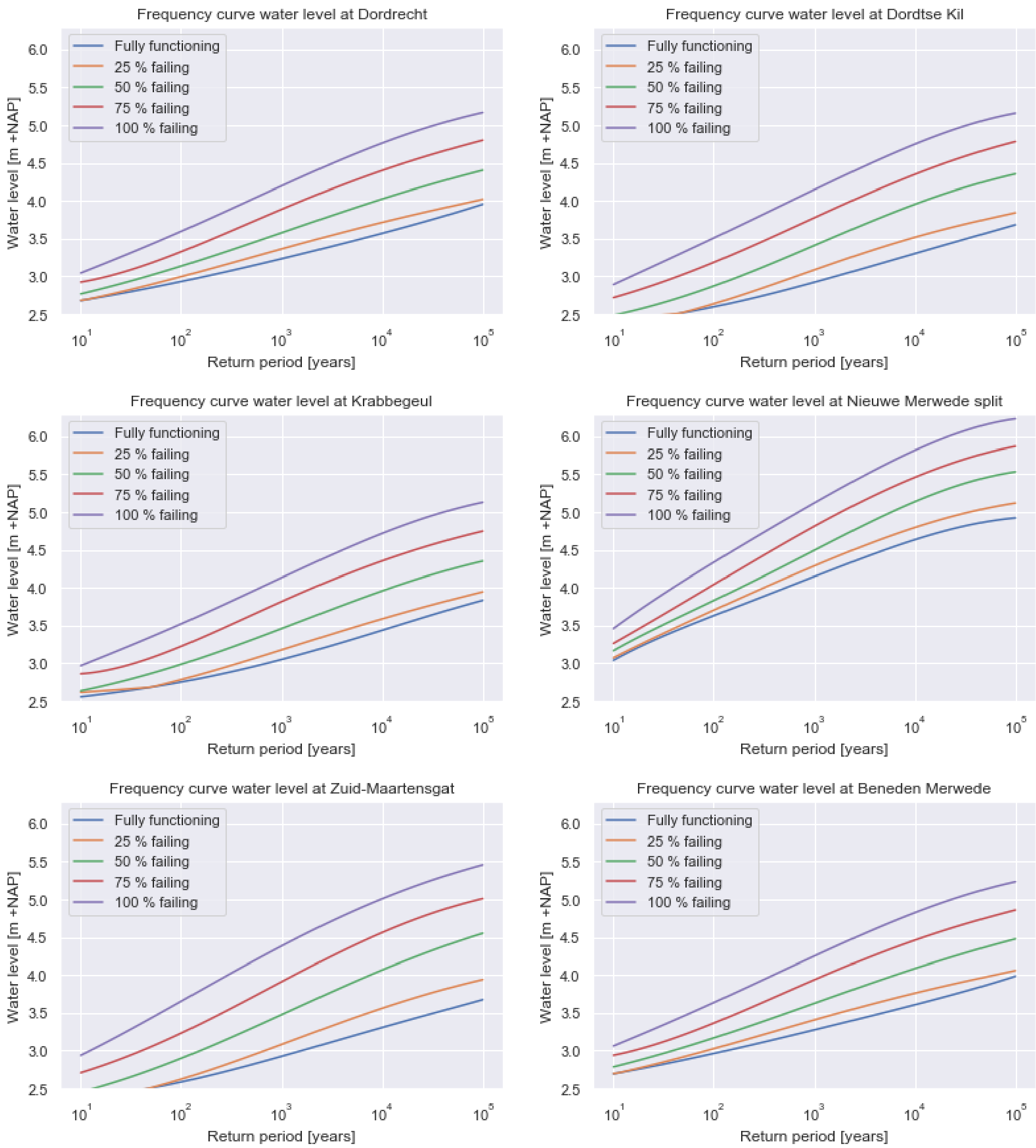


Figure H.3: Influence of (partially) failing pumping station (failure mechanism 2) on water levels at Island of Dordrecht

From the graphs in Figure H.3 the maximum influence on the water level for each of the degrees of failure can be determined. In Table H.3, for each degree of failure, the maximum water level increase up until a return period of 100,000 years is given. The maximum difference is at Zuid-Maartensgat for all gradations of failure.

	Maximum water level increase [m]
25%	0.3
50%	0.9
75%	1.3
100%	1.8

Table H.3: Increase of water level due to failure mechanism 2

The water level increases from Table H.3 lead to maximum allowable probability of occurrence for a maximum impact of 0.10 m. The maximum allowed probabilities for each gradation of failure can be found in Table H.4.

	Probability of occurrence [m]
25%	0.36
50%	0.11
75%	0.08
100%	0.06

Table H.4: Maximum allowed probability of occurrence for maximum impact of 0.10 m by failure mechanism 2

The maximum allowed probabilities of occurrence for each gradation of failure can be transformed in maximum allowable probabilities of failure per component. This is done for a completely dependent and independent system and the values of this can be found in Figure H.4.

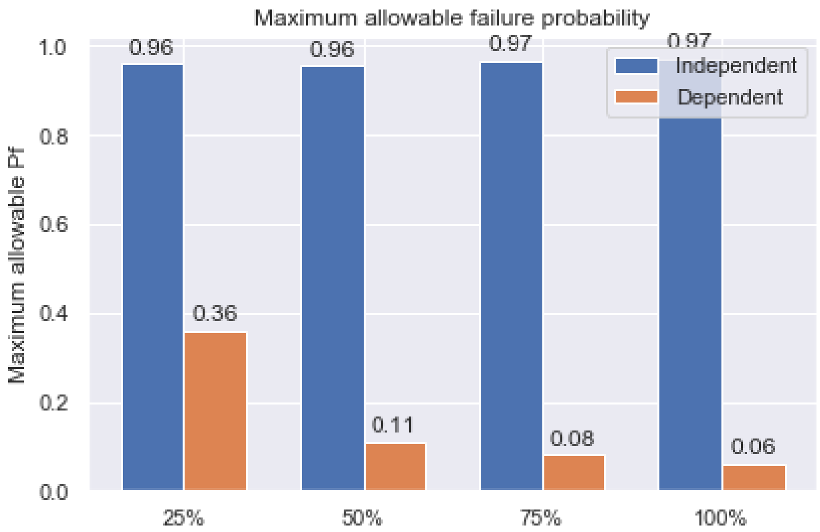


Figure H.4: Maximum allowable probability of failure for pumping station per component

H.2.3. Failure mechanism 3: failing barrier and siphon system

In Figure H.5 the impact of failure mechanism 2 on the water levels at the Island of Dordrecht can be found. It is immediately clear that the impact of failure mechanism 3 on the water levels is smaller than that of failure mechanism 1.

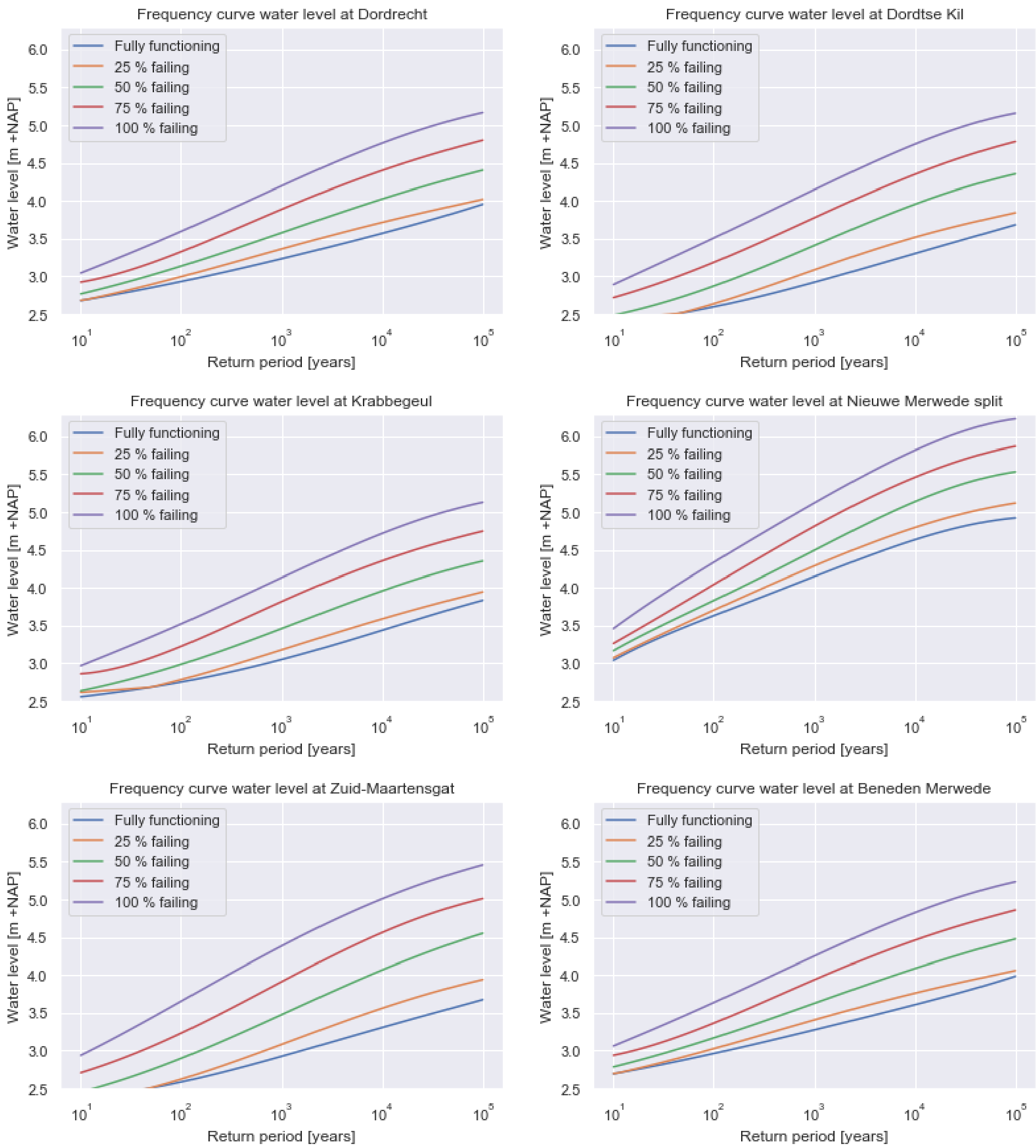


Figure H.5: Influence of closed barrier and (partially) failing siphon system during low water (failure mechanism 3) on water levels at Island of Dordrecht

From the graphs in Figure H.5 the maximum influence on the water level for each of the degrees of failure can be determined. In Table H.5, for each degree of failure, the maximum water level increase up until a return period of 100,000 years is given. The maximum difference is at Zuid-Maartensgat for all gradations of failure.

	Maximum water level increase [m]
25%	0.1
50%	0.4
75%	0.7
100%	0.9

Table H.5: Increase of water level due to failure mechanism 3

The water level increases from Table H.5 lead to maximum allowable probability of occurrence for a maximum impact of 0.10 m. The maximum allowed probabilities for each gradation of failure can be found in Table H.6.

	Probability of occurrence [m]
25%	0.73
50%	0.23
75%	0.15
100%	0.11

Table H.6: Maximum allowed probability of occurrence for maximum impact of 0.10 m by failure mechanism 3

The maximum allowed probabilities of occurrence for each gradation of failure can be transformed in maximum allowable probabilities of failure per component. This is done for a completely dependent and independent system and the values of this can be found in Figure H.6.

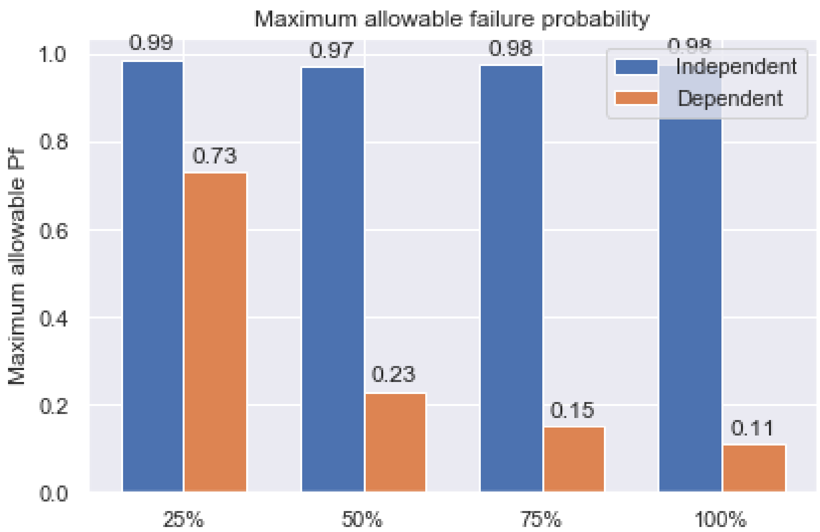


Figure H.6: Maximum allowable probability of failure for siphon system per component conditional on failing barrier

H.3. Method and results of impact correlation on allowable failure probability

H.3.1. Method of assessing correlation in parallel system

In the previous sections of this appendix, the maximum allowable failure probabilities per component for a completely dependent and independent system were given, which act as the lower and upper bounds. However, these upper and lower bound start to diverge largely for systems of many components and therefore limiting the amount of information that can actually be retrieved from this analysis. Hence, it is valuable to know how the correlation between the components actually influences the maximum allowable failure probability per component.

The method is basically a Monte Carlo simulation in which the performance of each component is generated and the probability of failure of the total system is known. In an iterative manner, the failure probability per component can be found.

Creating sets of uniformly distributed correlated random vectors

A set of M vectors with a length equal to N was generated. The values of in these vectors were drawn from a uniform distribution from 0 to 100. These values represent the so called 'performance' per component. Next off the correlation matrix of the system was set up, which can be found in Equation H.1. Here all values of ρ are equal to the correlation that is evaluated in this Section.

$$\begin{bmatrix} 1 & \rho_{1,2} & \rho_{1,3} & \cdots & \rho_{1,M} \\ \rho_{2,1} & 1 & \rho_{2,3} & \cdots & \rho_{2,M} \\ \rho_{3,1} & \rho_{3,2} & 1 & \cdots & \rho_{3,M} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_{M,1} & \rho_{M,2} & \rho_{M,3} & \cdots & 1 \end{bmatrix}_{M\times M} \tag{H.1}$$

The correlation matrix from Equation H.1 is then transformed by means of a Cholesky decomposition (Cholesky, 1910). This decomposition leads to a lower triangular matrix of M x M. This matrix is then multiplied by the M x N matrix of uniformly distributed random numbers. This leads to a M x N matrix of uniformly distributed numbers that are correlated in the way that is set in Equation H.1.

H.3.2. Determining acceptable failure probability per component

After the correlated vectors for each component were created, a certain performance threshold needed to be set. This means that it was assessed which parts of each vector were below the threshold and which over. If the value was below the threshold, the component is regarded as failing. This was done for each component and the boolean vectors of each component were overlapped to assess for which situation the appropriate amount of components failed. This was done for a 25, 50, 75 and 100 failure gradation. In Figure H.7 this process is visualized for a simplified case with four failing components.

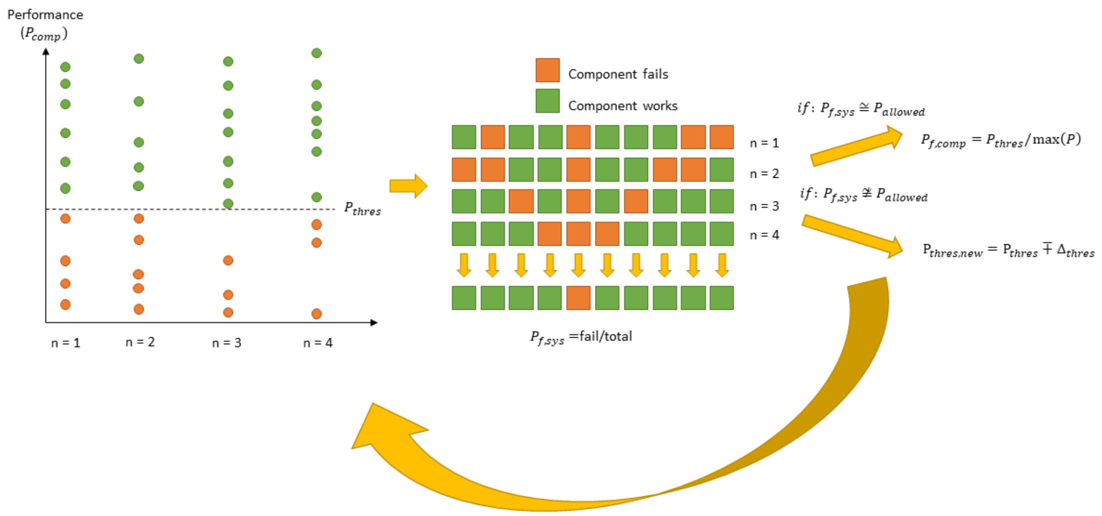


Figure H.7: Iterative process of determining failure probability per component

If the number of failures of the system divided by the amount of components was higher than the allowable failure probability of the system for the regarded failure mechanism, the threshold per component was brought down slightly and if it was smaller than the allowable failure probability, the threshold went up. If the difference between the found failure probability of the system was close enough to the allowable failure probability, the set threshold divided by the maximum of the uniformly distributed numbers was set equal to the allowable maximum failure probability per component.

H.3.3. Impact of correlation on allowable failure probability per component

For a number of correlation values, the process as described in Section H.3.2 is followed. This leads to a maximum allowable probability of failure per component for each failure mechanism for a range of correlation values. The curves that are produced as output can be seen in Figure H.8 below.

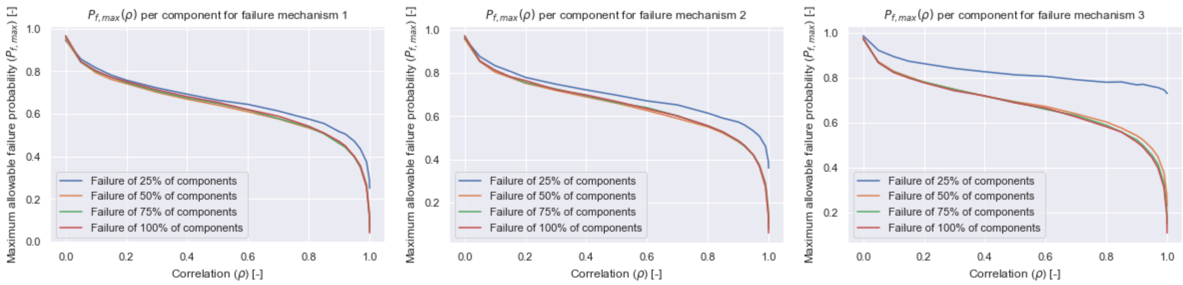


Figure H.8: Allowable probability of failure per component vs. correlation for failure mechanisms 1, 2 and 3

H.4. Sensitivity analysis

H.4.1. Sensitivity analysis: capacity of siphons

The siphon discharge capacity of 100 m^3/s is very large and it might be chosen to install siphons with a smaller capacity, e.g. 50 m^3/s. If the siphon system were to consist of 200 components with a capacity of 50 m^3/s this would only influence the allowable probability of failure for a system that is not fully dependent, but not the lower limit for the fully dependent system. This is visualized in Figure H.9. Additionally, the influence of the correlation between the components can be found and it is clear that there is, just as Figure H.9 suggests, little influence of using pumps with a capacity of 50 m^3/s or 100 m^3/s from a reliability standpoint.

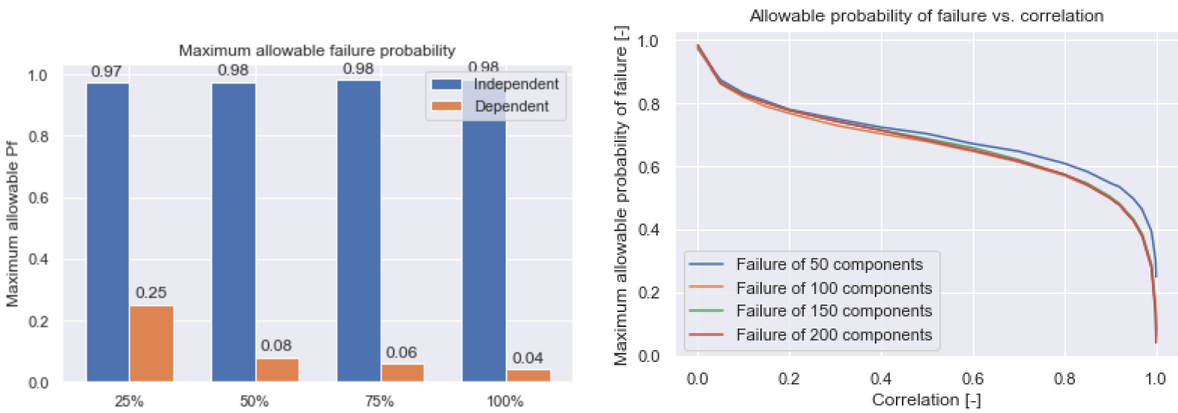


Figure H.9: Maximum allowable failure probabilities per component for failure mechanism 1 with Q_{siphon} = 50 m^3/s

H.4.2. Sensitivity analysis: capacity of pumps

Just like the siphon capacity the capacity of the pumps can also be brought down to 50 m^3/s, which is equal to the pump discharge capacity of the newest pumps at the pumping station at the locks of IJmuiden. Bringing down the capacity per pump to 50 m^3/s for 200 pumps means that the independent system of pumps is changed slightly, just as was shown for the siphon system. This can be observed in Figure H.10 below.

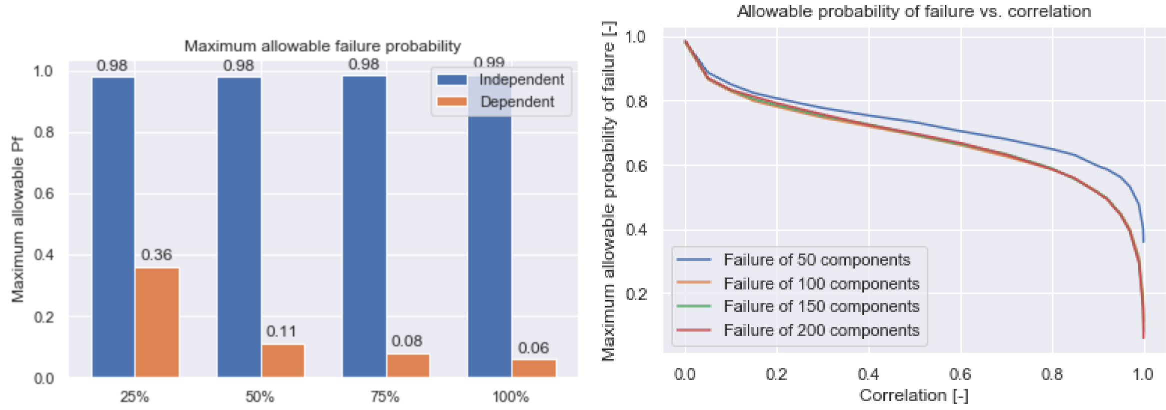


Figure H.10: Maximum allowable failure probabilities per component for failure mechanism 2 with Q_{pump} = 50 m^3/s

The pumping station at the locks of IJmuiden currently has a total capacity of 260 m^3/s. Up until 2004 this capacity was 260 m^3/s, but two more pumps of 50 m^3/s were added in that year. From Van den Bunt and Janssen (1997) it is concluded that the probability of 25, 50 and 75 % pump capacity loss is equal to 0.37, 0.19 and 0.18 %. The same reliability has been obtained for the newest pumps added in 2004 (Van Manen and Van den Horn, 2004). These values are much smaller than the 36, 11 and 8 % limits found for the pumping station of Delta21 and per pump for a completely dependent system. Though there is some discussion as to whether or not the reliability values found by Van den Bunt and Janssen (1997) and Van Manen and Van den Horn (2004) accurately depict the reality as one of the new pumps at the locks of IJmuiden failed in April of 2020 and the other one was taken out of operation (IJmuider Courant, 2020).

H.4.3. Sensitivity analysis: remaining capacity of energy storage lake

The remaining capacity of the energy storage lake influences largely the difference in the impact of failure mechanism 1 compared to failure mechanism 2. The assumption that is made is that the lake is halfway full at the moment that the pumps fail and water is let into the energy storage lake through the siphon system. To determine the sensitivity of the maximum allowable failure probability per pump, two new scenarios are analyzed: a completely empty and filled energy storage lake, i.e. room for 12 hours of 10,000 m^3/s or 0 hours. In Figure H.11 the maximum allowable failure probability per siphon for a system of 100 siphons is given for the completely empty and filled energy storage lake.

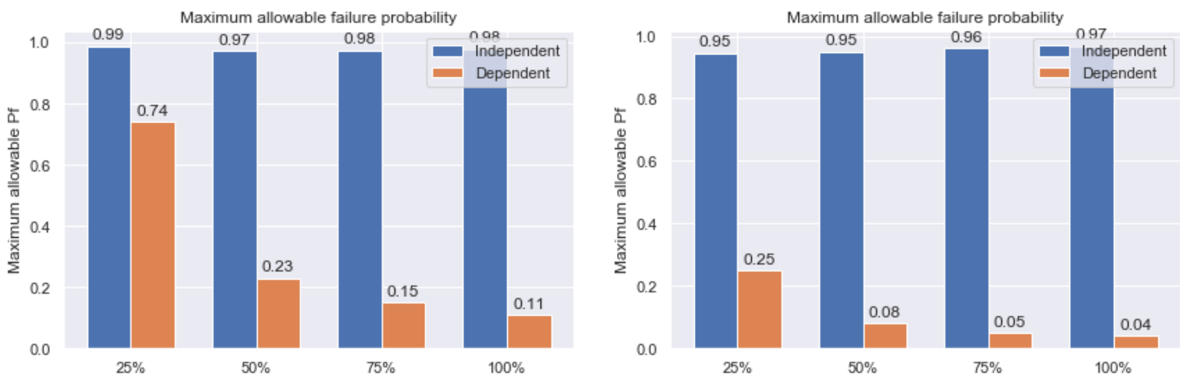


Figure H.11: Maximum allowable failure probabilities for failure mechanism 2 for empty and filled lake

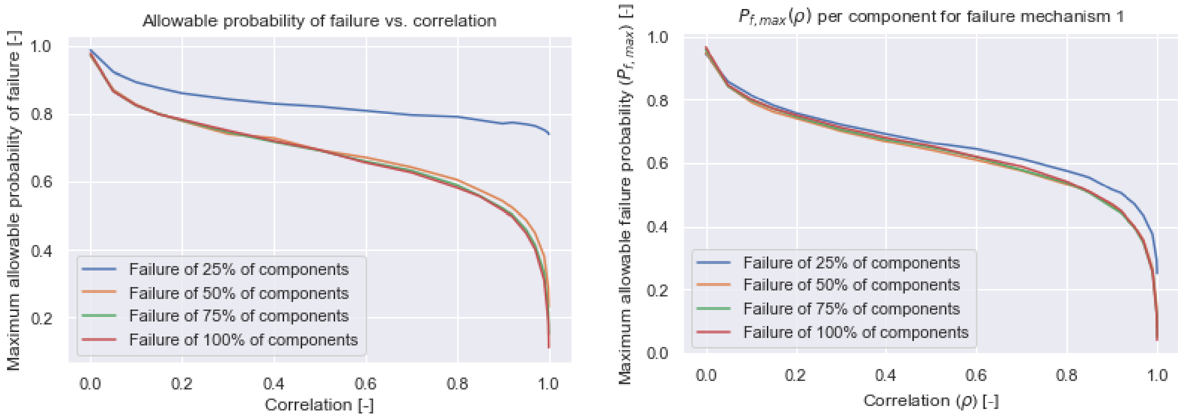


Figure H.12: Maximum allowable failure probabilities for failure mechanism 2 for empty and filled lake with correlations

This analysis shows that the influence of the remaining capacity of the energy storage lake is very large. It means that the maximum allowable failure probability for one pump given a pumping station of 100 pumps may almost triple from a filled to an empty lake.

H.4.4. Sensitivity analysis: degree of failure of storm surge barrier

In Section 6.5 a fully closed storm surge barrier is assumed for failure mechanism 3. This is the most extreme case for this mechanism, but it may be relevant to investigate the situation of a partial closure of the barrier during low water. In this sensitivity analysis, a 50 % closure of the storm surge barrier is assessed. This means that 50% of the gates of the barrier are not closed. The maximum allowable failure probabilities of the siphons for a 50 % closed storm surge barrier can be found in Figure H.13.

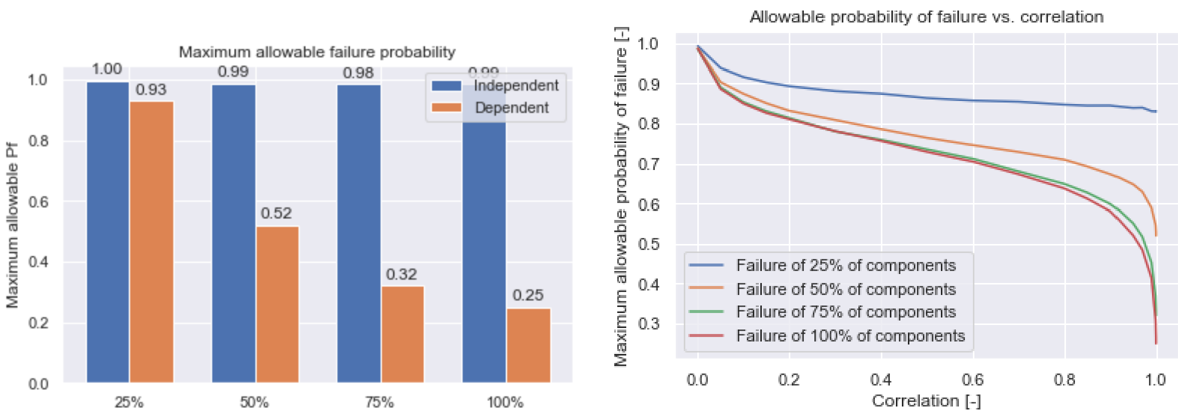


Figure H.13: Maximum allowable failure probabilities of siphons for failure mechanism 3 for partially closed storm surge barrier

This means that a partially closed storm surge barrier during low water at sea has a very small impact on the water levels at Dordrecht. For a totally dependent system, the failure probability of each siphon may be 25 % for a 0.10 meter impact at the Island of Dordrecht.

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