Hydraulic response of the Rhine-Meuse delta to Delta21

The effect of implementing Delta21 on water level statistics in the Dutch delta region

June 26th, 2023

Wouter Zijlstra

Hydraulic response of the Rhine-Meuse delta to Delta21

The effect of implementing Delta21 on water level statistics in the Dutch delta region

By

Wouter Zijlstra

in partial fulfilment of the requirements for the degree of

Master of Science
in Civil engineering

at the Delft University of Technology,
to be defended publicly on Tuesday July 4th, 2023 at 13:00 AM.

Student number:	4562011	
Thesis committee:	Prof. dr. ir. M. Kok,	TU Delft, chair
	Dr. ing. M. Voorendt,	TU Delft
	Dr. Ir. S. van Vuren,	TU Delft
	Dr. ir. M. Rutten	TU Delft
	ir. P.T.G. van Tol,	Witteveen+Bos

Cover Image: Eeden (2021)

An electronic version of this thesis is available at http://repository.tudelft.nl/.

PREFACE

This thesis concludes my Master of Science in Hydraulic Engineering - Flood Risk at the University of Technology in Delft. The subject of Delta21 has provided a great opportunity to come into contact with an out of the box and inspirational project in the context of an ever-greater flood protection challenge in the Netherlands.

In the past I have already shown great interest in the construction (and consequent obliteration) of self-made embankments, with abundant visits to sandy shores with preferably rising tides. In the previous years this interest has only grown and intensified, evidently permeating into my personal life too after my most recent enrolment in an orchestra suitably named *Brassband **Rijnmond***. This report is the product of an arduous period in terms of my physical health, but lacks not in devotion to the research because of it.

I wish to thank the entire graduation committee for their support, patience, and positivity. My gratitude also goes towards the initiators of Delta21, Huub Lavooij and Leen Berke, and Hans Nederend for the many thorough discussions and feedback. I sincerely hope that my research has benefited and advanced the execution of Delta21. Finally, I wish to especially thank Matthijs Buijs for his regular and generous aid and advice.

Wouter Zijlstra
Delft, June 26th, 2023

SUMMARY

The Dutch Rhine-Meuse delta is expected to require many dike reinforcements on a short and long term, due to (accelerated) sea level rise. Average damage in unembanked areas will increase too, and a costly replacement of the Maeslantkering is expected after 2070. Delta21 is a project that aims to address these challenges related to flood protection, while also providing hydraulic energy storage and opportunities for valuable nature development.

Delta21 consists primarily of a large (salt)water storage lake attached to the *Tweede Maasvlakte*. It is connected to the North Sea with a pump-turbine station. On the southern side, a closable storm surge barrier spans the remaining gap to the island of *Goeree Overflakkee*. Under normal circumstances the lake functions as a hydraulic battery, using the pumps and turbines to store or generate electricity as needed. However, when water levels threaten to exceed NAP + 2.5 m at Dordrecht, the barrier closes and an upstream spillway into the lake is opened. To determine the viability of the project in the context of flood protection, the question arises: "***To what extent is Delta21 capable of providing a cost-effective alternative to the current flood protection policy in the Rhine-Meuse delta?***"

To answer this question, a one-dimensional hydraulic model is constructed with a detailed and accurate schematization of Delta21. Results are processed into exceedance frequencies for a system with and without Delta21, to obtain reductions in water levels at normative frequencies. Furthermore, a sensitivity analysis is performed to describe how various designs and configurations affect the magnitude of these reductions. Other than Delta21, no system-changing interventions are included in the scope of study.

Three strategies are formulated in which Delta21 potentially reduces costs, and evaluated using the model's results:
1 Extending the lifetime of the Europoortkering before it needs to be replaced.
2 Obviate dike reinforcements.
3 Reduce the average yearly damage of unembanked areas.

Approach 1 is shown to be ineffective. Delta21 does not achieve changes in the Europoortkering's closure frequency or failure probability per closure. Neither does Delta21 effectively mitigate a failure in the region where water level exceedance frequencies are dominated by the Europoortkering's failure probability.

Approach 2 is far more successful, accounting for 96% of the total cost reductions. Reductions in water levels at normative frequencies are translated to reduced failure probabilities of dike segments using fragility curves, which potentially yields a positive reassessment. Delta21 achieves this and obviates dike reinforcement for 41 km by 2050, and 150 km more by 2100. These lengths comprise respectively 33% and 60% of the total considered dike lengths that would need reinforcement. The net present value of obviated reinforcement costs is €752 million, with a 90% confidence interval of [€220 million, €2,821 million]. This large interval is due to large uncertainties in reinforcement cost estimations. Delta21 most effectively obviates reinforcements in trajectories with stricter norms and closer proximity to the storage dominated region. Water levels at normative frequencies are very sensitive to the operational control (i.e. closure criterion) of Delta21. An additional nominal cost reduction of ca. €278 million can be achieved when a criterion of NAP + 2.5 m at Dordrecht is maintained in the future. The sensitivity is far weaker to varying dimensions or capacities of Delta21, which are generally unnecessarily large during illustrative conditions.

Approach 3 provides the additional 4% contribution to total cost reductions. The only considered area is Dordrecht, due to its unique high economic value in low lying unembanked locations. Damage profiles are integrated with changes exceedance frequency curves to obtain the average yearly damage. This is reduced by approximately €53,000 per year now, and grows to €1.36 million per year in the future climate scenario (2100). The decrease in relation to the current system is about 42%, but the absolute value rises greatly with sea level rise. Implementation of lower closure criteria variations can yield an additional +20% now, and +10% in the future scenario.

The total net present value of cost-reductions by Delta21 is €783 million, with a 90% confidence interval of [€251 million, €2,852 million]. This covers about 20% of the total construction costs of €3.7 billion, and is insufficient to make Delta21 viable alone. However, not all costs are related to flood protection exclusively. If the components required for energy storage are viable on their own, merely the additional costs of the spillway and storm surge barrier have to be included in the cost-benefit analysis. Operational costs, which heavily depend on the operational control, must also be added. Smaller design dimensions or pump capacity of Delta21 has been shown to be just as effective, and would further cut costs. Additional savings beyond 2100 are plausible, but outside of this research's scope. Furthermore, less people displacement or flooding of unembanked areas may achieve additional societal value, but is difficult to quantify. More research will have to indicate whether attributing only specific costs, including additional value sources, and estimating reinforcement cost more accurately ultimately lead to Delta21 being feasible in the context of flood protection.

Table of contents

Preface i

Summary ii

1 Introduction 1

1.1 Motivation 1
1.2 Problem analysis 2
1.2.1 High waters in the Rhine-Meuse delta 2
1.2.2 Climate change exacerbating hydraulic conditions 3
1.2.3 Protection strategy and regulatory framework 5
1.2.4 The Delta21 project 6
1.2.1 Problem statement 9
1.3 Objective and scope 9
1.3.1 Objective and research questions 9
1.3.2 Scope of study 10
1.4 Methodology 12
1.5 Reading guide 13

2 Hydraulic analysis and schematization of the Rhine-Meuse delta 14

2.1 Hydraulic system analysis of the Rhine-Meuse area and Delta21 14
2.1.1 Current and future boundary conditions 14
2.1.2 Description of relevant controllable barriers in the current system 15
2.1.3 Detailed design and operation of Delta21 18
2.1.4 Regional classification based on dominating boundary condition 19
2.2 Schematization and model of the hydraulic system 20
2.2.1 Software and calculation method 20
2.2.2 Schematization of boundary conditions 22
2.2.3 Schematization of Delta21 components 22
2.2.4 Real-time control of barriers 23
2.2.5 Model uncertainty and database reparation 26
2.3 Concluding remarks 29

3 Opportunities for more cost-effective flood protection with Delta21 30

3.1 Inventory and description potential cost saving strategies 30
3.1.1 Lengthening the lifetime of the Maeslantkering 30
3.1.2 Obviating dike reinforcements 30
3.1.3 Reduce flooding frequencies of valuable unembanked areas 32
3.2 Contributions of Delta21 to cost saving strategies 33
3.2.1 Influence on the Europoortkering 33
3.2.2 Reduction of normative hydraulic loads at embankments 35
3.2.3 Decrease water levels exceedance frequencies unembanked areas 36
3.3 Concluding remarks 36

4 The influence of Delta21 on the Europoortkering lifetime 38

4.1 Improving Europoortkering's failure probability per closure 38
4.1.1 Simplification of the closure procedure by obviating double closures 38
4.1.2 The effect of earlier and longer closures on failure probability 39
4.2 Reducing the Europoortkering's closure frequency 40
4.3 Delta21 influence on sensitivity to changed failure probability 42
4.4 Concluding remarks 43

5 Reducing water levels at normative frequencies with Delta21 44

5.1 Reductions in the reference preliminary configuration 44
5.2 Reduction sensitivity to Delta21 design variations 46
5.2.1 Sensitivity to Delta21's lake volume and pumping capacity 47

5.2.2 Sensitivity to Delta21's spillway width and height 49
5.2.3 Synergy Delta21 and adapted Pannerdensche Kop discharge division 52
5.2.4 Synergy Delta21 and reduced Europoortkering failure probability 54
5.3 Reduction sensitivity to operational control 55
5.4 Differences in sensitivity to longer storm durations 61
5.5 Concluding remarks 64

6 Cost reductions attributable to Delta21 65
6.1 Estimated savings Maeslantkering lifetime prolongation 65
6.2 Estimated savings of dike reinforcements 65
6.2.1 Approximate the cost of dike reinforcements 65
6.2.2 Determine the amount of obviated reinforcement project kilometres 66
6.2.3 Resulting cost reduction from obviated reinforcements 69
6.3 Estimated savings less frequent flooding unembanked areas 70
6.4 Net present value of savings 71
6.5 Concluding remarks 72

7 Discussion, Conclusion, and Recommendations 73
7.1 Discussion 73
7.2 Conclusions 74
7.2.1 Influence of Delta21 on the hydraulic system 75
7.2.2 Potential cost reduction strategies with Delta21 75
7.2.3 Delta21 influence on the Europoortkering's lifetime 75
7.2.4 Delta21 reducing water level exceedance frequencies around norms 76
7.2.5 Estimated saving by Delta21 78
7.3 Recommendations 79
7.3.1 Costs and viability of Delta21 79
7.3.2 Improving and optimizing Delta21's operational control 79
7.3.3 Miscellaneous recommendations 80

Appendices 81
Appendix A Details on model schematisation 82
Appendix B Rhine-Meuse delta system overviews 90
Appendix C Exceedance frequency results validation 93
Appendix D Estimation error through exclusively statistically included sea level rise 96
Appendix E Historic determination of closure criteria 98
Appendix F Justification of simplifications and assumptions in the hydrodynamic model 99
Appendix G Spatial distribution of Delta21 peak water level reductions 102
Appendix H Determination of escalation frequencies 103
Appendix I Reinforcement cost estimation 105
Appendix J Obviated project km's within HWBP 109
Appendix K Risk calculations for unprotected areas on the island of Dordrecht 118
Appendix L Time of closure of the Europoortkering 122
Appendix M Influence of an Europoortkering failure probability decimation 123
Appendix N Water level exceedance reductions in variations of Chapter 5 for all frequencies.... 127
Appendix O Fault tree of the Europoortkering failure probability 140
Appendix P Net present value (NPV) calculations 142
Appendix Q Full hydraulic model and control 145

References 146

1 INTRODUCTION

1.1 Motivation

In the Netherlands, about 26% of the land lies below sea level, 60% is prone to flooding, and 70% of the gross national product is earned in flood prone areas (Rijksoverheid ministeries van IenW & EZK, 2015). Resulting from mean sea level rise predictions, changes in extreme weather statistics, and assessments of current failure probabilities, improved flood protection is necessary to ensure acceptable safety levels in the coming decades (Rijksoverheid, 2021). 900 kilometres of Dutch primary flood defences have to be reinforced by 2050, for which circa 5.4 billion euros has been budgeted (Ministerie van Infrastructuur en Waterstaat, 2019). Flood risk in the surrounding areas is expected to rise both due to climate change but also increased economic activity and population growth (Jonkman, Vrijling, & Kok, 2008). Looking past 2050, additional reinforcements will be needed, depending on the extent of sea level rise and intensification of river discharge statistics (IPCC, 2022). The Rhine-Meuse delta consists of a densely populated area with large economic value, and is responsible for discharging the Waal, Lek, and Meuse to the sea.

Delta21 is a solution to improve flood protection, currently as well as going into the future. An overview is presented in Figure 1.1. A detailed description of the Delta21 design is given in Section 1.2.4. The core of the enhanced flood protection lies in relocating the primary sea protection (3) and alleviate pressure on upstream embankments using large pumps (1) and storage (marked areas and number 2). Besides improvements in flood protection, the plan consists of two other cornerstone goals: energy storage through a hydraulic battery, and ecological opportunities. Together, the three cornerstones determine the viability of the plan. Furthermore, Delta21 potentially lengthens the applicability of the current flood protection strategy, and fits into various long term adaptation strategies.

Figure 1.1 Overview of the most recent Delta21 components and layout. Adapted from Eeden (2021) and Verschoor (2023)

It is not adequately understood whether Delta21 is able to significantly decrease extreme water levels in areas where this might help, and how large the resulting reductions in costs are. Not having to reinforce as many kilometres of dike saves a lot of funds, and leads to a reduced societal impact due to construction in inhabited areas. No final decisions have yet been made as to what primary design values (related to storage and discharging capacities) need to be employed. The sensitivity of the delta's response to variations of Delta21 is decisive for the design, but has yet to be researched. Preceding research into the effects of Delta21 has broached the topic, but does not employ a satisfactory hydraulic schematization to give generalizable and definitive indications to how effectively Delta21 achieves its targets. Furthermore, numerous recommendations have been made to improve such an assessment. These are treated in more detail later, but include investigating (based largely upon the works by Oerlemans (2020) and Buijs (2021)):

- The operational procedure and adjustments thereto for the Europoortkering and Delta21
- Variations in Delta21 design configurations
- Synergy between Delta21 and a changed division at the Pannerdensche kop
- Synergy between Delta21 and an improved Europoortkering failure probability
- Assessment of Delta21's influence on water levels in the entire delta area

1.2 Problem analysis

1.2.1 High waters in the Rhine-Meuse delta

The estuary consists of a complex network of rivers, estuaries, embankments, and other flood defence structures. An overview of the delta's channels and barriers is given in Figure 1.2. The hydraulic behaviour is determined by the incoming river discharge, water level at sea, and the way the delta responds to those conditions. The response is determined by physical attributes of the channels (length, flow profile, roughness, etc.) and the operation of controllable barriers. The statistical distributions of the discharge and sea water level determine the exceedance frequencies of extreme water levels. These determine for a large part the (normative) hydraulic conditions or loads for which barriers and levees need to be designed.

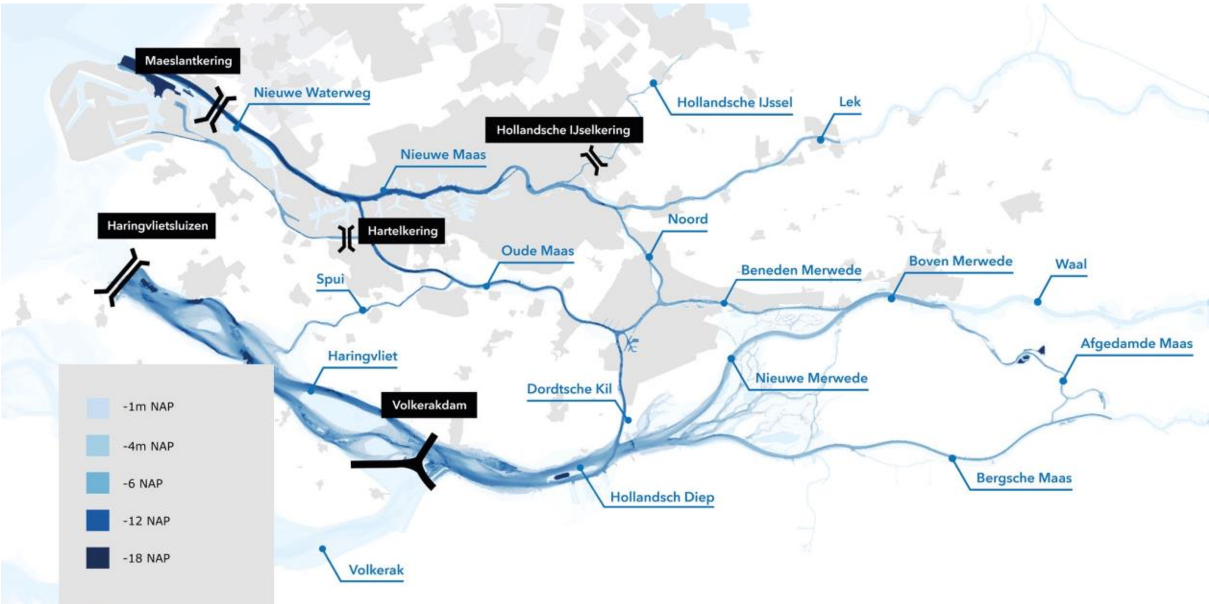


Figure 1.2 Overview of the Rhine-Meuse delta with names of channels and structures, and channel depth. (Balla, et al., 2019)

The Nieuwe Waterweg houses a key component of the Dutch delta defences: The Europoortkering. It consists of two moveable barriers connected by a levee: the Maeslantkering and Hartelkering (see Figure 1.2). The operation of the Europoortkering determines strongly how the Rhine-Meuse delta responds to storm surges (Kramer et al, 2017). It closes when predicted water levels exceed NAP +3.0 m at Rotterdam or NAP + 2.9 m at Dordrecht (Rijkswaterstaat, 2012). However, if the inner water level (temporarily) exceeds that at sea, it opens again. In fact, a mayor structural downside of the Maeslantkering is that it cannot properly resist these forces (Rijkswaterstaat, 2012), and therefore must open. The failure probability of the Maeslantkering is higher than designed for. The true probability is unknown but established at about once in 100 closures (Commissie voor Verkeer en Waterstaat, 2006). The operational software that is used is for a large part responsible for the high failure probability (Sewberath-Misser, 2022). The temporary opening and subsequent second closure are in part responsible for the complex operational control, and its high probability of failure. This has significant effects on water level exceedance frequencies of upstream branches.

1.2.2 Climate change exacerbating hydraulic conditions

The world is heating up. Consequentially, the Netherlands face a rising sea level and rising probabilities of extreme weather. The Intergovernmental Panel on Climate Change (IPCC) advises on global climate policies. It creates prediction scenarios for global warming, and corresponding changes to (among others) precipitation patterns and mean sea level. The Koninklijk Nederlands Meteorologisch Instituut (KNMI) specifies predictions locally. For the Netherlands the KNMI has created several climate change scenarios that are currently used for the design of embankments (Koninklijk Nederlands Meteorologisch Instituut, 2021). Figure 1.3 presents the four scenarios that are considered, each one containing different predictions for mean sea level rise and weather extremes. Although dikes can be designed with intermittent steps using any desired scenario, at the 'end of lifetime' they must meet the norms in the most extreme W_H (also called W+) scenario (Deltares, 2018).

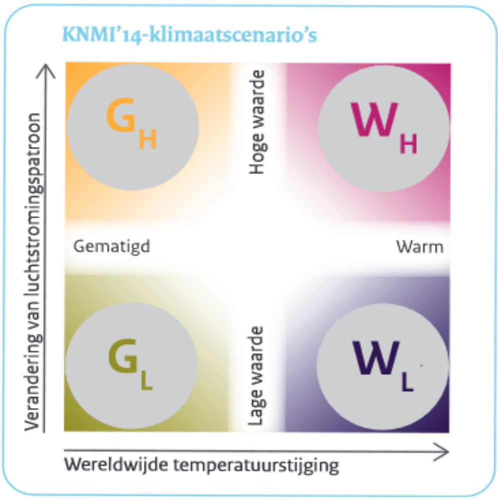


Figure 1.3 climate scenarios (KNMI 2021)

Predictions have large uncertainties, arguably even containing deep uncertainty (Bakker, Louchard, & Keller, 2017). Nevertheless, decisions on adaptations must be made now rather than later as there is plenty of common ground between predictions (Oppenheimer, et al., 2019). In every IPCC scenario, extreme sea levels (for example, today's hundred year event) become more common by 2100 (with high confidence[1]) (Oppenheimer, et al., 2019). This calls strongly for both flexible and futureproof solutions. Additionally, the gap between what solutions provide and what will be required appears to be growing, calling for multipurpose and integral solutions (IPCC, 2022).

Mean sea level rise

Relative (local) mean sea level rise impacts the Dutch delta specifically. Although this variable has been shown to 'lag behind' the global rise of mean sea level, the Koninklijk Nederlands Meteorologisch Instituut (2021) expects that this discrepancy will straighten out within several decades. Ground subsidence is currently a far stronger actor in relative sea level rise than the overall increase of water volume, but this too is expected to be overtaken by global mean sea level rise in some decennia (Koninklijk Nederlands Meteorologisch Instituut, 2021). Additionally, the acceleration of sea level rise poses an ever greater threat (Steffelbauer, et al., 2022) (Keizer, et al., 2022). It should also be noted that global mean sea level rise is a process with 'inheritance': even if emissions suddenly drop to zero, the rise still continues for some time (IPCC, 2022).

Table 1.1 presents data on mean sea level rise and speed thereof. The ranges represent 90% confidence bounds (as defined by the IPCC). The Dutch government even considers scenarios ranging to 5 m of sea level rise (Rijksoverheid, 2021). This does not necessarily indicate what is expected, but rather what range is within reason and could conservatively be prepared for (Rijksoverheid, 2021). Figure 1.4 shows sea level predictions graphically.

Table 1.1 Sea level prediction scenarios (Koninklijk Nederlands Meteorologisch Instituut, 2021)

Year	2050	2050	2050	2100	2100	2100
Emission scenario	SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
Sea level rise in cm	14-38	15-41	16-47	30-81	39-94	54-121
Rising speed in mm/year	2.8-8.7	5.2-10.6	5.8-12.1	2.9-9.1	4.4-10.5	7.2-16.9

[1] This corresponds to the standardized IPCC confidence levels. High confidence can be understood as 90%-100% likely to happen.

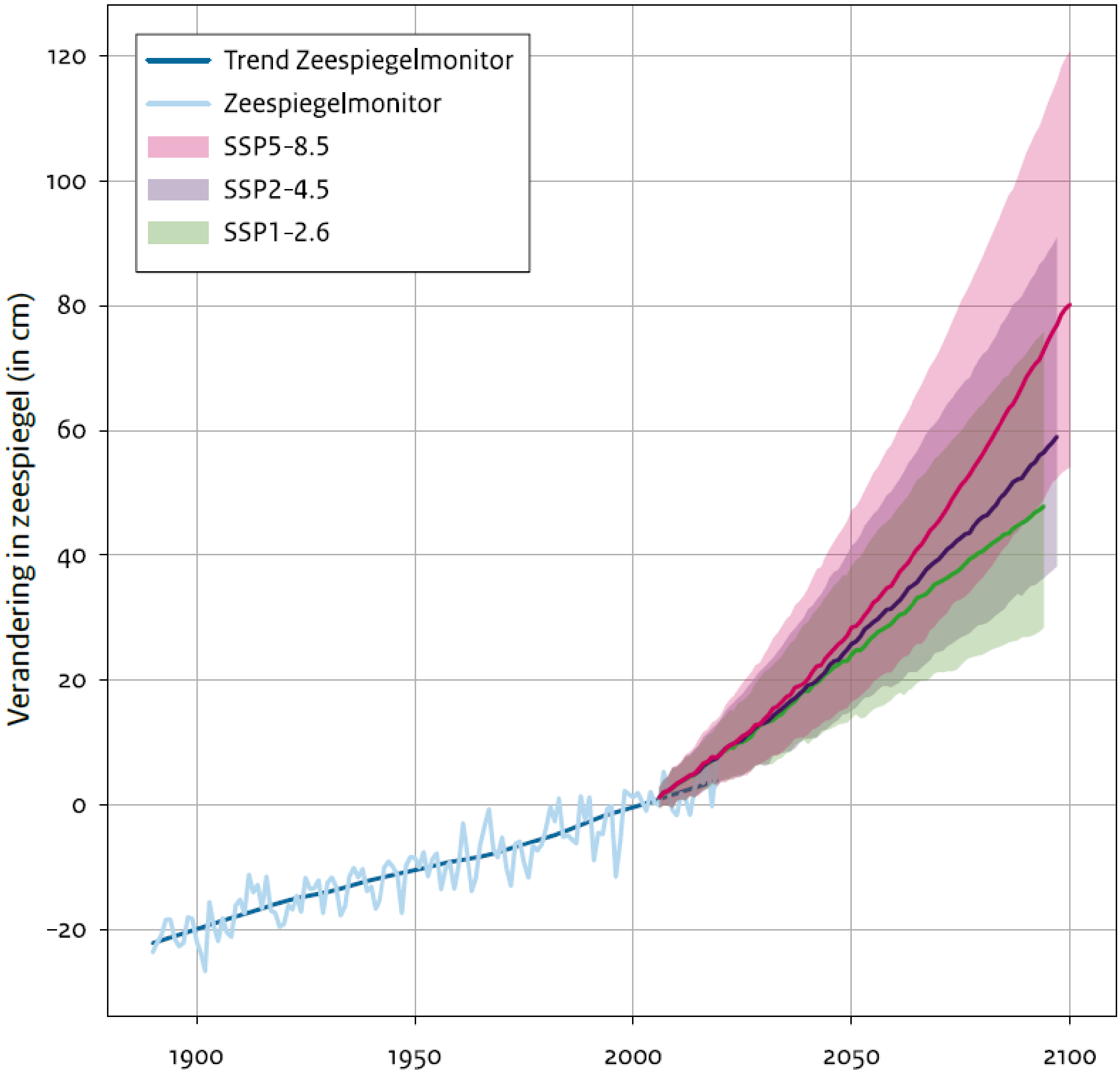


Figure 1.4 Sea level projections for the Dutch coast (Koninklijk Nederlands Meteorologisch Instituut, 2021)

Storm surge

The probability distribution of storm surge heights, being caused by wind conditions, is not expected to change much in a changing climate for the Dutch coast (Sterl, et al., 2009). Slight intensification of South-western winds might occur, but the most recent predictions indicate that this effect is insignificant until the year 2100 (90% confidence) (Koninklijk Nederlands Meteorologisch Instituut, 2021). There is also no strong evidence to suggest that the distribution of storm surge duration will change with climate change, again because wind conditions remain fairly similar.

River discharge

Preliminary estimations can be made as to what trends river discharge distributions follow, but the field is not studied as extensively as mean sea level rise. Extremes are generally expected to intensify (Oppenheimer, et al., 2019) (Koninklijk Nederlands Meteorologisch Instituut, 2021), meaning larger extreme discharges in the Dutch storm season (winter). The tendency for the Rhine shows intensified extremes for high discharge conditions. But, near future predictions show weaker trends (Görgen, et al., 2010). More specifically, at Lobith the once in 1000 years discharge is expected to change by -5% to +20% (average +5% to +10%) between 2021 and 2050, and -5% to +30% (average +10% or more) between 2071 and 2100. Shifted design distributions are available for the four scenarios of Figure 1.3, with integrated uncertainties (Smale, 2018). The W+ scenario employs a changed discharge distribution as given in Figure 1.5.

The Koninklijk Nederlands Meteorologisch Instituut (2021) concludes that in the period 1950-2018 the trend of high precipitation indicator[1] is slightly towards the less extreme, too small to be considered significant. However, it is expected high precipitation will increase in the future, see Appendix B. This ranges between about -5% to +30% in 2100 including IPCC scenarios 2.6 and 8.5. (90% confidence bound). Research suggests a maximum discharge in the Rhine at Lobith. Vriend et al. (2016) conclude that this number lies somewhere around 17,500 m^3/s. Hegnauer, Kwadijk, & Klijn (2015) go so far as too say 18,000 m^3/s can be used as an absolute upper boundary (with it more likely being between 17,000 and 18,000 m^3/s). Nevertheless, it should be noted that this maximum value is not particularly robust, because it is strongly based on upstream events and the German flood defences will not likely remain exactly as they are now when conditions get worse.

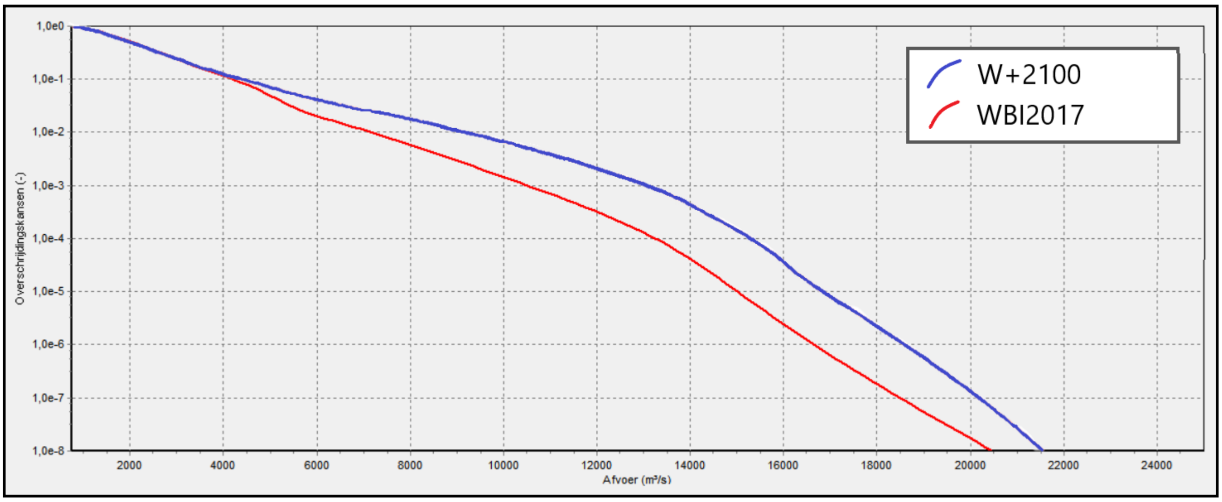


Figure 1.5 Discharge exceedance probability at Lobith in 2017 (WBI assessment) and 2100 (W+ scenario)

Summarized, hydraulic loads in the Rhine-Meuse delta system will increase, even though the precise extent thereof is shrouded in uncertainty. The resulting increase in normative conditions inevitably results in new flood protection challenges and costs.

1.2.3 Protection strategy and regulatory framework

The legal framework for flood protection in the Netherlands is comprised in the 'Waterwet', with its yearly delta program providing plans, measures, and research for water safety, spatial adaptation, and drinkable water supply (Rijksoverheid, 2021). This law dictates that all primary flood defences must be evaluated to assess if they meet the (new) norms (see Figure B.13 in Appendix B) (Waterwet, 2009). The WBI[2] comprises the guidelines and tools for assessment. Negatively assessed dikes must be reinforced, a process overseen by the High Water Protection Program (HWBP): an alliance between water boards and Rijkswaterstaat. The scope of the delta program and HWBP stretches to 2050.

The Expertise Netwerk Waterveiligheid (ENW) has concluded that the current flood protection strategy can be scaled into 2050, but when extended beyond that starts to exhibit serious negative spatial, ecological, and societal effects (Expertise Netwerk Waterveiligheid, 2019). This is regardless of the technical and financial feasibility, which is expected to remain workable towards 2100. Therefore, although the reinforcement of dikes is currently still a viable option, the ENW strongly recommends to already start thinking about different approaches, starting with the relatively 'vulnerable Oosterschelde and Rijnmond-Drechtstede (Expertise Netwerk Waterveiligheid, 2019). Depending on IPCC emission scenarios and the acceleration sea level rise, consequences for the Dutch coastal area can be severe (Deltares, 2018). The closure frequency of the Europoortkering grows to once every year at 1 m of sea level rise (Haasnoot, et al., 2019). In every scenario that includes accelerated sea level rise and a high emissions, the current preferred strategy is no longer financially viable after 2050.

In a study by Deltares (Haasnoot, et al., 2019) four general directional corners are defined into which the country's flood protection can move strategically, as sketched in Figure 1.6. The 'open protected' is most close to a

[1] maximum 10-day precipitation in a winter
[2] Wettelijk Beoordelings Instrumentarium

continuation of the current approach: open flow to the sea and raising dikes to the required level, combined with an inevitable raising of closure criteria to prevent excessive closure frequencies. This strategy is estimated to be realistic up to about 1 m of sea level rise, or up to 2 m if closure levels are allowed to rise. No national or regional preferences have however been defined yet, and what approach will be pursued in the Rhine-Meuse delta is uncertain (Jonkman & Meyer, 2022). Additionally, intermediate switches between strategic pathways also belongs to the range of possibilities (see Figure B.14 in Appendix B) (Haasnoot, et al., 2019).

To address the uncertainties of climate predictions and adaptation strategy, the delta program has started the *Knowledge Program Sea Level Rise* (KPZSS) (Rijksoverheid, 2021). It contains several research goals, two of which directly relate to flood protection in the delta:

- ***Exploration of the system****: how much can it handle and with what measures can one extend the current strategies?*
- ***Long term options****: what is possible once the current strategy is no longer viable, and how can one start examining this now?*

Summarized, as of today there is no clear and definitive long term flood protection strategy, and an urgent need for dedicated research into what (type of) projects can provide futureproof solutions.

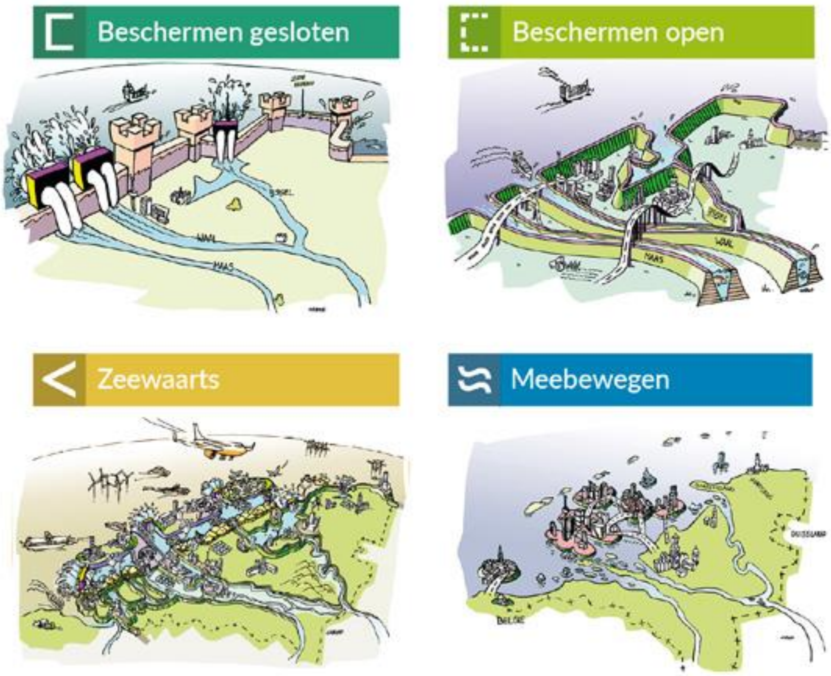


Figure 1.6 Adaptation directions for large sea level rise scenarios

1.2.4 The Delta21 project

This section introduces the Delta21 project and follows the most recent designs available, currently that of Lavooij and Berke (2019). The design is not set in stone, and still subject to updates. The design below is the preliminary or reference configuration. For a more detailed description of the components, how they function/operate, and how this is schematized, the reader is referred to Chapter 2.

The most recent layout of the Delta21 project is presented in Figure 1.7. Considerable stretches of levees and dunes have to be constructed alongside several structural elements and bathymetry changes. The essential Delta21 components that influence the hydraulic functioning of the entire Rhine-Meuse delta system are as follows:

1. Pumping and generation station
    - 226 Archimedes screws which can be used in both directions (pumps and turbines). Total capacity is approximately 10,000 m^3/s (Jacquemin, 2021).
2. Spillway

- A controllable overflow spillway with a discharge capacity ranging from 5,000 m^3/s to 20,000 m^3/s. Can be opened when the new storm surge barrier is closed.

3. New storm surge barrier
    - Is normally open, but closed during storm conditions. Closes when the water level at Dordrecht threatens to exceed a certain criterion.
4. Storage lake (also: energy lake):
    - The storage capacity of the lake is designed at approximately 400 million m^3, with a water level range between NAP -5.0 m and NAP -22.5 m.
5. Tidal lake (extended estuary):
    - The area encompassed between the new barrier, energy lake, and Haringvlietsluizen. It better resembles an estuary than a lake, but is referred to as such for consistency's sake. It introduces some additional channel length and storage area during storm conditions. The surface area is roughly around 25 km^2. The depth within this region is increased by 1 meter through dredging.

When a storm surge coincides with significant river discharges, Delta21 can *escalate:* pumping water out of the storage lake, closing the storm surge barrier, opening the spillway. The result is an enhanced storage and discharge, even though the connection to the sea is closed off. The water level in the tidal lake drops, and consequentially also in the upstream branches of the delta. This alleviates hydraulic conditions throughout the are, and Delta21 attempts to achieve various targets in the context of flood protection:

- Reduce the need for dike reinforcements
- Reduce the frequency and intensity of flooding at unembanked areas
- Alleviate conditions at the Maeslantkering and lengthen its lifetime
- Be better equipped to deal with long storm events

The project will cost an estimated €3.7 billion in total (Berke & Lavooij, 2018). The lifetime of the civil structures of Delta21 in this report is assumed at 100 years, and its pumps/turbines at 50 years. Yearly costs for maintenance and operational are estimated at approximately €15 million per year (Berke & Lavooij, 2018). If and when construction may start is uncertain, but could start as soon as possible according to the initiators (Delta21 v.o.f., 2021b). It would take about 8 to 10 years after the greenlight is given before the project is completed. For now 2030 is assumed, which is quick given the numbers above, but considered a feasible earliest moment by the initiators.

Function of Delta21 nonconcurrent with storm events

in normal conditions the spillway is closed and storm surge barrier open. The storage lake is used on a daily basis as a hydraulic battery, using the pumps during low electricity demand hours, and letting water flow back in during high demand hours. Furthermore, the area offers opportunities for generating solar/wind energy and creating additional habitats with tidal flows and large ecological value.

Interaction of Delta21 and the Europoortkering

The Europoortkering is a crucial component as a closable storm surge barrier, but has some peculiar limitations as discussed in Section 1.2.1. A failure probability reduction of the Maeslantkering will be required in due time (Botterhuis et al., 2012). Before it is reinforced or replaced however, a changed operational control can prolong its lifetime somewhat. For example, closing the barrier earlier and leaving it closed until the storm ends greatly simplifies the operation. Preventing double closures with intermittent discharging may also yield lowered failure probabilities. The main question which arises is whether it is possible to employ Delta21 to relieve the Maeslantkering during storm conditions with high discharge. It must be able to ensure the inner water level never exceeds the outer water level at the Maeslantkering during an event, or at least significantly less often. Being able to mitigate extreme high waters with Delta21 alone may also yield smaller Europoortkering closure frequencies.

The above strategy may extend the lifetime of the current Maeslantkering somewhat (Sewberath-Misser, 2022). But it is likely not enough to ensure acceptable safety levels on the long term, considering significant sea level rise. Previous research has also shown that Delta21 may not be particularly effective in lowering extreme water levels when a closure frequency limit of once per year is maintained (Buijs, 2021). Exactly how (much) the performance of Delta21 is affected when the Europoortkering failure probability is reduced and/or a high closure frequency is accepted remains to be investigated.

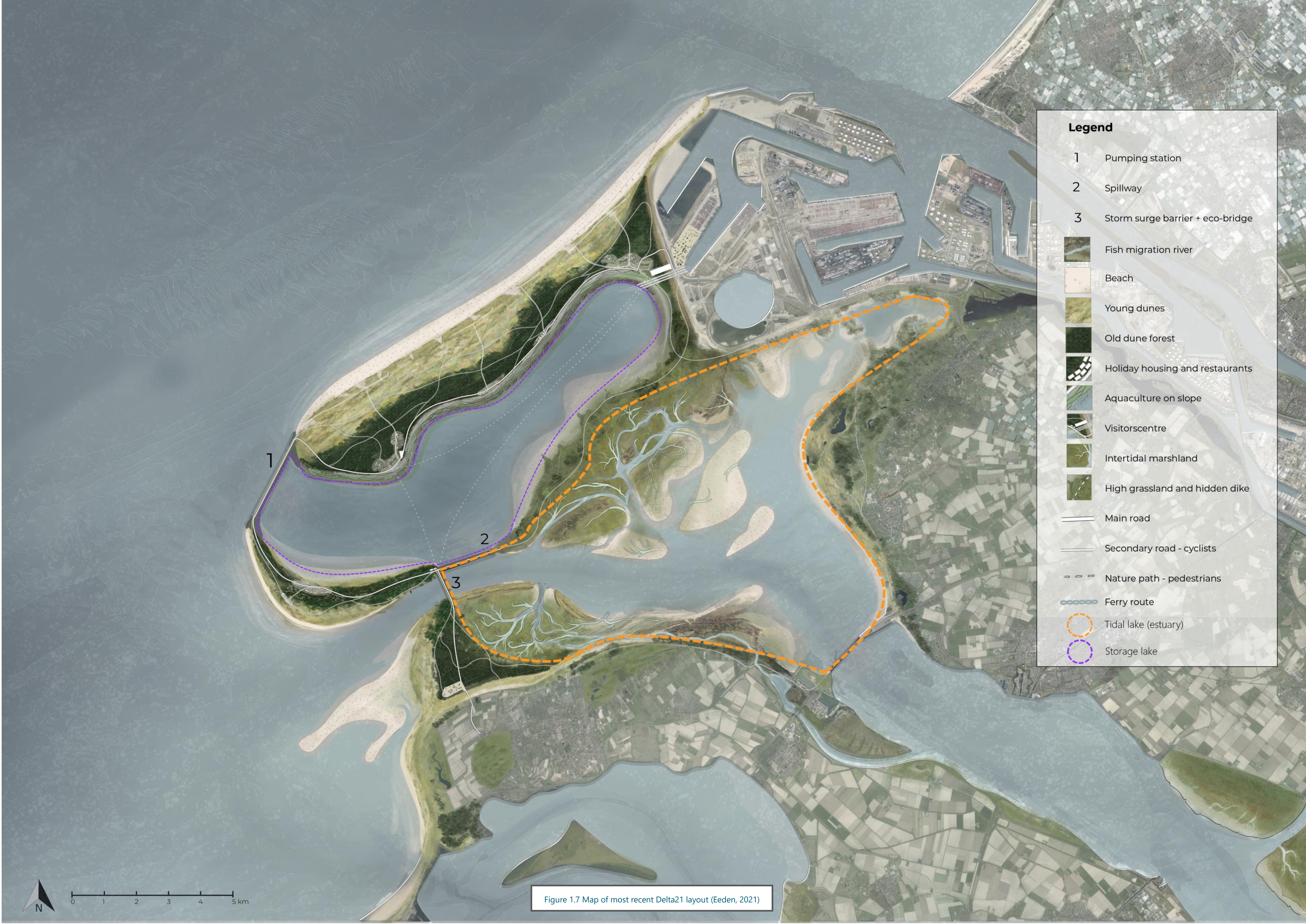


Figure 1.7 Map of most recent Delta21 layout (Eeden, 2021)

Synergy with other projects

There is not one single solution that instantly accomplishes one or the other strategic direction as defined in Figure 1.6. Delta21 can have synergies with other out of the box ideas to combat long term threats. For example, a plan by Beaufort (2022) combines nicely with Delta21. The main idea is to divert more water into the Waal at the Pannerdensche Kop and use the Haringvlietsluizen as the primary discharging branch for both Rhine and Meuse. Delta21 could accommodate one such 'water corridor' nicely due to its location and discharge capacity. A combined implementation with a changed division at Pannerden is a particularly interesting variation to investigate further.

A deterministic storm surge duration of 30 hours is used in contemporary hydraulic modelling (Chbab, 2016). Research by Tijssen (2010) concludes that including storm surge duration stochastically has a neglectable influence on normative water levels. The reason for this is that deviations for shorter and longer storm surges cancel each other out sufficiently. If a measure such as Delta21 impacts longer storms differently than shorter ones, this balance might no longer uphold. It is therefore valuable to attempt longer storm duration modelling and see if Delta21 can reduce the sensitivity to this particular parameter, in order to further decrease exceedance frequencies. See Appendix A on how surge development is schematized exactly.

Preceding research

One key knowledge gap lies in the effect of combining an adapted Europoortkering with implementation of Delta21. The considered adaptations include both a reduction of the failure probability and an adapted closure operation. Using Delta21 to alleviate the Maeslantkering has the potential to reduce it's failure probability (Sewberath-Misser, 2022), and conversely an improved Maeslantkering failure probability may have a favourable effect on the effectivity of Delta21 in reducing normative water levels (Buijs, 2021). This interaction and resulting effects have not been investigated, but may very well be fortunate required reinforcement costs. Furthermore, Delta21 and a simplified closure procedure for the Europoortkering may lengthen the Maeslantkering's lifetime before it requires further reinforcement or redesign, which too is particularly cost effective.

The second key feature lies in the way Delta21 has thus far been modelled. These analyses have often disregarded essential design characteristics of Delta21, in particular how storage plays a role, which is crucial according to Donkers (2021). Besides that, the relation between design features of Delta21 and normative water levels is not known. Research into the sensitivity of the hydraulic response to design variations has mostly been foregone until now.

1.2.1 Problem statement

Delta21 has the potential to improve flood protection in the Rhine-Meuse delta in a more flexible and affordable manner than the current policy of dike reinforcement. However, the hydraulic response of the delta in future climate conditions to different configurations of Delta21 has not yet been extensively modelled. It is therefore not adequately known if and how Delta21 can achieve a cost-effective flood protection alternative.

1.3 Objective and scope

1.3.1 Objective and research questions

The objective of this thesis is to assess to what extent Delta21 is capable of providing a cost-effective alternative to the current flood protection policy in the Rhine-Meuse delta. To fulfil this, it is desired to know how well different configurations of Delta21 manage to reduce expected costs and damages. To achieve the objective, 5 research questions are formulated below:

1. How does Delta21 influence the hydraulic system?
    a. How does the Rhine-Meuse area function as a hydraulic system including Delta21?
    b. How can this system and the influence of Delta21 be schematized and quantified?
2. How can Delta21 accomplish cost reductions in the context of flood protection?
    a. What are potential strategies for reducing costs in the delta?
    b. How can Delta21 contribute to those strategies?
3. What is the influence of Delta21 on the lifetime of the Europoortkering[1]?
    a. What is Delta21's influence on the Europoortkering's failure probability per closure?
    b. What is Delta21's influence on the Europoortkering's closure frequency?

[1] Both "Europoortkering" and "Maeslantkering" are used deliberately throughout the report, and are **not** interchangeable terms. Review Section 1.2.1 on the exact definitions.

   c. What is Delta21's influence on regional sensitivity to the Europoortkering failure probability?
4. What is the effect of Delta21 on water levels at normative frequencies in the current and future climate scenario?
   a. What is the influence of the preliminary reference configuration of delta21 on water levels at normative frequencies?
   b. How sensitive is this influence to variations in the Delta21 design?
   c. How sensitive is this influence to variations in the operational control of Delta21?
   d. Does a hydraulic system with Delta21 exhibit a significantly different sensitivity to storm duration?
5. How high are the savings or cost-reductions attributable to Delta21?
   1. How much is saved by a lengthened lifetime of the Europoortkering?
   2. How much is saved by obviation of dike reinforcements?
   3. How much is saved by less frequent flooding of unembanked areas?
   4. What is the net present value of all cost reductions?

1.3.2 Scope of study

Essential modelling requirements

Central to this thesis in ensuring Delta21 is properly incorporated into the hydraulic model. This is done in close cooperation with the initiators of the plan, to ensure the schematization is consistent with the plan and any adaptations that it has been subjected to. In practise, this means adapting the existing model to represent the Delta21 design more accurately and in more detail. In particular, storage capacity of the energy lake has yet to be explicitly included. The other branches of the model, which stretch as far as Tiel/Hagestein/Lith are not altered, as they have already been implemented in detail, verified (to some extent), and used by HKV. The effects of Delta21 on water level exceedance curves (around normative frequencies) are researched in depth with the largest share of computational time. The implications of these results are translated to provide contextual information as to the performance of Delta21, but this is done in approximate fashion (e.g. estimating costs of dike reinforcements, recalculating levee failure probabilities, etc.).

Hydraulic influence of Delta21 exclusively

Exclusively the hydraulic influence of Delta21 is assessed in this research. This is but one piece of the puzzle, as Delta21 is likely to also have significant effects on e.g.: energy, morphology, hydrology, ecology, salinity, spatial planning, etc. These, while of comparable importance to the viability of Delta21, are principally not included in the assessment. On of the foremost promises that Delta21 aims to keep are those related to high water safety, thus it makes sense to lead with the investigation into extreme water levels. Morphological changes can within some decades strongly reshape cross-sectional layouts of the branches. This may in turn have a significant effect on how the system responds during a storm event. Nevertheless, for this research it's assumed that through regular maintenance any effects due to a changed bathymetry can be neglected.

An otherwise unchanged delta system with closable storm surge barriers

In this research, Delta21 is investigated as a component in an otherwise unchanged delta. Consequentially, a sea level rise of up until 1 meter is considered. Passed that, the current national protection strategy is subject to systematic change. Delta21 fits broadly into multiple adaptive strategical directions in response to climate change, as presented in Section 1.2.3. In alignment with the flood protection targets of Delta21, this research focusses on how Delta21 performs in an otherwise unchanged system: "*Protected open*". This means that although the failure probability and operation of the Maeslantkering are subject to change, it's function as a closable barrier remains. Falling precisely under the second track of the knowledge program sea level rise (Rijksoverheid, 2021), the main goal concerning the interaction of sea level rise and Delt21 is to find out how the project performs **within** the current preferred strategy, and is able to prolong its viability. Indications of how Delta21 functions in a system with a permanently closed off delta and/or a sea level rise exceeding 1 m may lead to valuable insights into the adaptability of the project. However, the performance in the first phase of its life determines for a large part the viability of the flood protection elements of the plan. Naturally, Adaptability to worse climate scenarios is a great advantage for Delta21, as one expects its lifetime to exceed the year 2100. But because of the mayor uncertainties surrounding predictions of sea level rise it is of secondary importance to investigate how Delta21 performs in a completely different system, such as e.g. *Protected closed.* Besides that, Delta21 is to be constructed within several years, and it ought to first be known how it performs on the short term. This means that no detailed quantitative account is given as to how well Delta21 fits within various long term adaptation strategies.

Research the hydraulic influence of Delta21, not an optimal design

The goal of this research is to assess to what extent Delta21 is capable of providing a cost-effective alternative flood protection approach in the Rhine-Meuse delta. It is not to design an optimal version of Delta21, or to assess different design variants. The maximum potential of Delta21 is employed during escalation, meaning that in many cases more water is discharged over the spillway then probably strictly necessary. The difference provides room for optimization, something that is not performed in this research. Note that variations are proposed in order to perform a sensitivity analysis. They are not done in context of researching design variants, or providing those. Nevertheless, the research is of course done for the purpose of advancing the Delta21 project, and design updates can definitely be formulated with the help of the results in this report.

Flow velocities

Previous research has indicated that large flow velocities may arise during Delta21 operation at bottleneck locations, such as the Dordtsche Kil, Oude Maas, Spui, and Haringvlietsluizen. Before a more detailed and optimized operation control procedure is available, and design updates as a result of this reports results, no detailed account can be given in relation to flows speeds. At this stage, effects on water levels and global cost-reductions must be investigated first, after which further research into flow speeds is able to provide useful insight into where erosion or accretion problems may arise.

Delta21 during high discharges without any storm surge

Delta21 is used during storm events in the context of this research. Attempts to use Delta21 in no-storm conditions within the model, will yield results that generally fall within one of 3 categories:

1. The Europoortkering is closed even though there is no storm. This implies a completely different hydraulic system, where the Europoortkering behaves more like a sluice than a storm surge barrier. It therefore falls outside the scope of the thesis. The system that emerges more closely resembles a closed protected delta.
2. The river discharge boundary exceeds 10,000 m^3/s. Delta21 does not achieve an increase in average discharge.
3. The river discharge boundary does not exceed 10,000 m^3/s. Delta21 can realize additional average discharge. However, there is hardly any useful impact on water level exceedance frequencies because those conditions are not illustrative around norms.

Parallel research into Delta21

A number of researchers are looking into some of the other aspects of Delta21, for example: the morphology of the new tidal lake, the design of the new storm surge barrier, or a much more technical analysis of the Maeslantkering failure probability (and its reduction possibilities). These other aspects of Delta21 might therefore occasionally be underattended to, but they are by no means of lesser importance to the project as a whole.

Priority for peak water levels

The maximum water level during an event will in many instances be a determining factor for dike failure. Some failure modes of earthen embankments also depend strongly on the water level signal before and after the peak of the storm. It is assumed that the shape of the high-water wave does not (significantly) change compared to the existing situation. Similarly, wave conditions can be decisive in some failure modes, but once again it is assumed that these conditions do not change particularly much as a result of Delta21. The 'profitability' of Delta21 in terms of flood protection must therefore originate exclusively from a reduced extreme water level.

Failure probability of Delta21

In contemporary hydrodynamic modelling, exclusively a failure of the Europoortkering is included. All other structures are assumed to have negligibly low failure probabilities, and function as expected. The same will be assumed for all Delta21 components in this research. The static components of Delta21 can generally be designed within far lower probability margins then that of the current Europoortkering (Ruiz, et al., 2022). In his research, Buijs (2021) computed high water levels at Dordrecht for several (partial) pump failures. He concludes that the reliability of Delta21 is 'non-decisive' for flood risk assessment, never leading to an increase in normative water level of more then 0.1 m. The only condition is a correlation coefficient of 0.9 or lower, which allows for single component failure probability demands which are easy to meet. Note that this research employs a far simpler schematization of Delta21, where a pump failure actually resembles a spillway failure because they are a single entity. With the improved schematization of Delta21 in this research, storage is still possible even in the event of full pump failure, meaning failure probabilities become even less influential. Verschoor (2023) argues that the failure probability requirement for Delta21 as a whole is around 1 in 30000. Currently, but also after minor improvements, the failure probability of the Europoortkering remains orders of magnitude larger. Therefore, no further analysis of the reliability of Delta21 is performed in this report.

1.4 Methodology

The research (sub-)questions are answered in order with the following procedural steps for each (sub-)chapter.

1. For this chapter, the step from the physical system to a useable model is made with a system analysis (a) and a system schematization (b). This chapter expands and elaborates on the problem analysis in order to correctly implement a hydraulic model with Delta21, and focusses on differences with respect to contemporary hydraulic modelling.

1a. Analyse the hydraulic Rhine-Meuse delta system. A description of the various branches and controllable barriers is provided with relevant characteristics. Describe the Delta21 plan in more detail, and define the boundary conditions both now and in a future scenario. Additionally, research literature in how the area is divided into certain areas where one input parameter dominates the response, and how this influences the expectations of Delta21's influence.

1b. Take the physical system and schematize it in order to enable the SOBEK calculation core to compute results. Describe how the boundary conditions are generated as usable input and how changes in climate affect these inputs. Next, formulate operational schemes for controllable barriers, and provide a detailed schematization of all Delta21 components. Finally, present how hydraulic results can be processed into probabilistic data with statistical relevance. Additionally, analyse how model uncertainty exerts itself in the computations and whether exclusion is unavoidable.

2. An inventory is made of approaches in which Delta21 potentially achieves cost reductions in the context of flood protections, along with a description of each approach.

2a. Make an inventory of saving opportunities with regards to flood protection that Delta21 can potentially accomplish. Describe how each approach leads to reduced costs, and what is required to progress these approaches.

2b. Investigate how Delta21 can contribute to these opportunities in more detail. Determine specifically in what ways Delta21 can influence the behaviour of the Europoortkering. Furthermore, specify how reductions of water level exceedance frequencies yield obviations of reinforcement projects and reduced damages in unembanked areas.

3. For this chapter, results are produced with the model to obtain data on the Europoortkering's behaviour in the range of boundary conditions. Differences between these results for a system with and without Delta21 indicate if and how effective Delta21 prolongs the lifetime of the Europoortkering.

3a. Determine how often the Europoortkering exhibits double closures in the current system, and with Delta21. Next, investigate whether there is a significant difference in the moment of closure of the Europoortkering between both systems.

3b. Present the conditions in which the Europoortkering needs to close in both systems because a predicted water level criterion is met. Then, integrate this description with marginal distributions of the boundary conditions to obtain estimates for the closure frequency. Finally, analyse the effect that Delta21 has on this frequency.

3c. Determine where, by how much, and for what frequency a decimation (factor 0.1) of the Europoortkering's failure probability per closure influences high water levels in the delta. Do this for the current and Delta21 systems, and repeat for the current and a future climate scenario. Indicate how the sensitivity of such a decimation differs in a Delta21 system compared to the current one.

4. This chapter demands the longest research and computation time. Exceedance frequencies are produced for a variety of configurations and climate scenarios with and without Delta21. The results are analysed, with a focus on effects around normative frequencies (MHW's), which serve as input for the following chapter.

4a. Determine the magnitude of the reduction in water level at normative frequencies for a preliminary configuration of Delta21. It will serve as a reference for the sensitivity analysis.

4b. Apply isolated variations to the Delta21 design and reproduce the results to estimate how sensitive they are to that particular variation. Considered design variations are the lake volume, pump capacity, spillway sill width, spillway sill height, an adapted discharge division at Pannerden, and combination with an improved Europoortkering failure probability. Investigate if and by how much a sensitivity changes in the future climate scenario.

4c. Determine bounds or candidate configurations for the operational control in a Delta21 system. This includes the operational control of the Europoortkering and interaction between the two controls. Using the same reference of 4a, determine the influence of varying closure procedures and specifically closure criteria. Repeat this for a future climate scenario.

4d. Apply a longer storm surge duration on the seaward boundary for both the current and Delta21 system. Determine the magnitude of the increase in water levels at normative frequencies for both systems to investigate whether a Delta21 system is significantly less sensitive to this parameter.

5. For the final step, reductions in water level exceedance frequencies are translated to reductions in costs. Damage profiles of unembanked areas, and cost estimations for reinforcement projects are integrated with the results of the previous chapter.

5a. The reduction in costs is estimate as a result of a prolonged Maeslantkering lifetime.

5b. Use fragility curves to approximately translate changes in extreme water level to failure probability. Then, compare the reductions by Delta21 for corresponding normative return periods per dike segment to the required reduction for a positive assessment. Repeat this procedure for the failure mechanisms piping, inner slope stability, and height. Convert to reduced costs with the results of question 2.

5b. Compute how much the water levels at normative frequencies would increase in a future climate scenario. Then, similarly to 5a, investigate where this increase in water level leads to a negative assessment of dike segments. Subsequentially, determine where Delta21 is able to fully mitigate this assessment. Convert to saved costs with the results of question 2.

5c. Compute the frequency at which areas in Dordrecht unprotected by dikes experience flooding by integrating damage profiles with changes in exceedance curves. Use the results of question 2.

5d. All flows of money are converted to their net present value. This allows an appropriate comparison of investments and reduced costs.

1.5 Reading guide

The following five chapters address each research question in order as posed above. Every subchapter provides the answer to the corresponding sub-question respectively.

- **Chapter 2 (research question 1)** gives a description, analysis, and schematization of the hydraulic delta system and Delta21's place in it.
- **Chapter 3 (research question 2)** presents the approaches which have the potential to yield cost reductions in the context of flood protection with Delta21, along with a method of how to assess this.
- **Chapter 4 (research question 3)** treats everything related to the Europoortkering and the lifetime extension of the Maeslantkering.
- **Chapter 5 (research question 4)** comprises most of the computational research done in context of this report. The effects that Delta21 has on water levels throughout the Rhine-Meuse delta are analysed here, using numerous different configurations.
- **Chapter 6 (research question 5)** combines the results of chapters 3, 4, and 5 to compute cost-reduction estimates attributable to Delta21. Finally, the time dependency of cashflows is accounted for with a net present value.
- **Chapter 7** provides a discussion of the aforementioned investigations, concluding and concise answers to all research questions, and recommendations into further research.
- **The appendices and references** succeed chapter 7 at the final pages of this document.

2 HYDRAULIC ANALYSIS AND SCHEMATIZATION OF THE RHINE-MEUSE DELTA

Question 1. How does Delta21 influence the hydraulic system*?*

In the first part of this chapter, a detailed expansion is given of hydraulic elements in the Rhine-Meuse delta in context of flood protection, including Delta21 (question 1a). A more general description of the delta has been provided in Section 1.2, and is not repeated. Attention is paid to how the system and its barriers function during extreme events, what the climate conditions are and will be in the future, and the regional classification in context of dominant influence on normative water levels. The second part of the chapter will subsequently describe how the aforementioned information is schematized into a model, specifically new and/or changed elements (question 1b). Attention is paid to the calculation method, control and design of barriers/components, and corresponding limitations, assumptions, and validations of the employed schematizations.

2.1 Hydraulic system analysis of the Rhine-Meuse area and Delta21

Ample data is available for hydraulic characteristics of the various river branches in the delta. Lengths, roughness, cross-sectional flow profiles, etc. are presented in detail in Appendix Q. This data is currently already used in contemporary research (Agtersloot & Paarlberg, 2016), and deems no further textual expansion as no changes are made upon it. The following sections provide additional information on less straight-forward aspects, and formulates some base assumptions.

2.1.1 Current and future boundary conditions

River discharge (upstream) and sea water level (downstream) provide the boundary conditions for the hydraulic system. Because extreme events are considered, they can best be described by their statistical distributions, in accordance with WBI guidelines (Chbab H. , 2016). Additional conditions (not necessarily uncorrelated) include wind speeds, waves, and storm duration. The temporal development of the boundary conditions is not fully defined by these distributions. For example, tidal signals and high discharge wave shape also influence the hydraulic response. Temporal variations of the discharge boundary are however of a much larger timescale then their seaward counterparts. The discharge in the Meuse of inferior importance then the Rhine, and is assumed fully correlated with the incoming discharge at Lobith for the lower river reaches guidelines (Chbab H. , 2016). A current and future scenario are defined below.

Current climate

The hydraulic boundary conditions are described statistically for the year 2017, with the distribution for sea water level presented in Figure 2.1, and for river discharge with red in Figure 2.2 (repeated for convenience). Note that the sea level probability is not per year, but per storm block. Generally speaking, a block lasts 30 days and each year contains 6 blocks (storm season is approximately one-half year, or one winter). Uncertainties in these extreme value fits on measurements have already been integrated in the distribution (Duits & Kuijper, 2020). 2017 is the year in which the latest assessment rounds are performed, and is therefore the reference year. These conditions are implied when the report refers to the ‘current climate’. Naturally, some climate change has since occurred, and slightly more can be expected by the time Delta21 is finalized. Nevertheless, for the sake of comparison with WBI assessments the year 2017 is retained. Sea level rise is described in reference to the average trend in 1991, and **not** 2017 or 2023. The starting point for sea level rise is therefore already 0.105 m in the ‘current climate: 2017’. Because the tidal signals used in the schematization are from 1991, the relative local mean sea level rise for 2017 is already 10.5 cm (Agtersloot & Paarlberg, 2016).

Future climate scenario

To research the long-term effects of Delta21, a single future climate scenario is formulated. It is reiterated that this research aims to assess Delta21 in the context of an otherwise unchanged hydraulic system, and conditions that exceeds about 1 m of sea level rise fall outside of the scope. The future climate scenario is based on the W+ scenario of KNMI predictions, which is also used in the new design of embankments (OI2014). The reference year is 2100, meaning a sea level rise of 0.84 m relative to 1991, and the blue curve as presented in Figure 2.2. The W+ scenario is also commonly used in other recent studies making comparisons to the current preference strategy such as by Sloff et al. (2012) or Dekker (2014). A more complete picture can be given by including the other 3 scenarios too (Slootjes & Thijssen, 2013), but previous research into Delta21 has already investigated different scenarios with different climate change and sea level rise speeds. To assess Delta21 in the scope of this report, a single scenario will suffice. Note that it is possible to shift the year (and thus speed) at which this scenario is reached can be varied somewhat to obtain a bandwidth that accounts for the uncertain climate change speed. The hydraulic calculations do not change when a different year is chosen for reference, as long as the boundary conditions stay the same. Due to the time dependency of costs and savings, this does affect the viability of Delta, which is treated in more detail in Chapter 6.

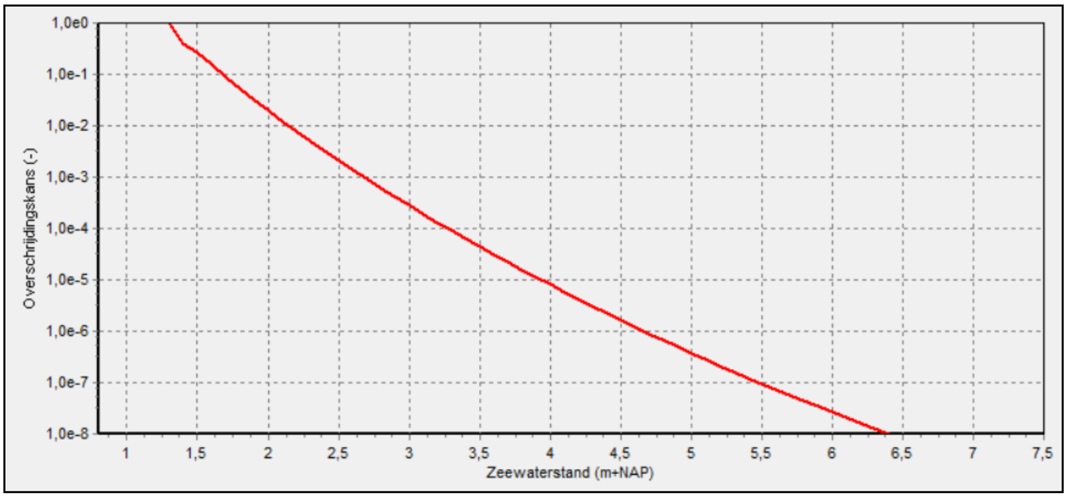


Figure 2.1 Sea water level exceedance probability per storm block at Hoek van Holland in 2017

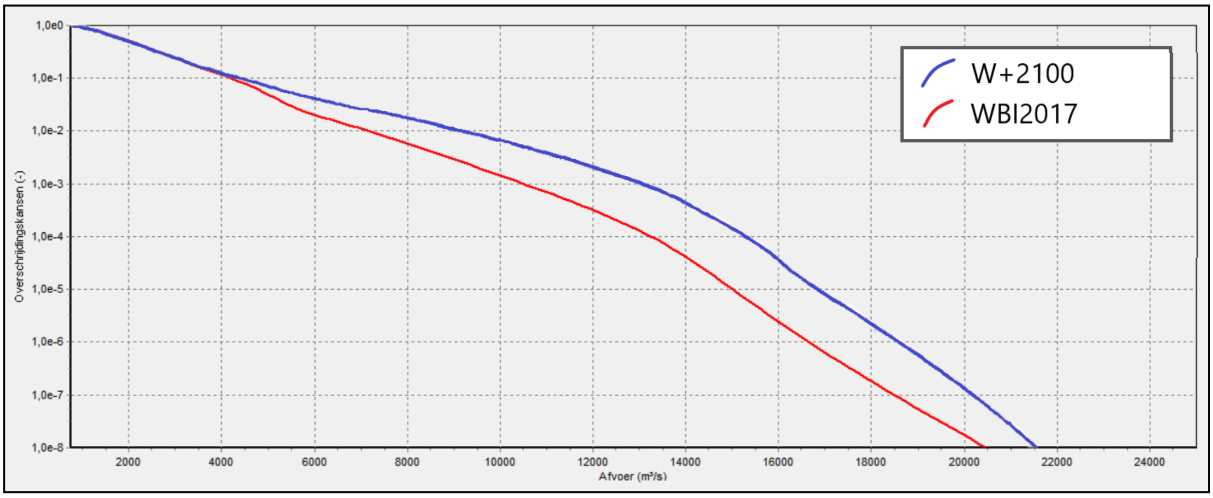


Figure 2.2 Discharge exceedance probability at Lobith in 2017 and 2100 (W+ scenario)

2.1.2 Description of relevant controllable barriers in the current system

Prediction times

All barrier controls base their decisions on water level predictions. Whereas river discharge is a fairly slow changing process and easy to see coming, sea water levels are notoriously hard to predict. Storm surge and local setups are subject to the whims of the wind. It is because of this that a decision to escalate[1] is made with predictions that look ahead in time for a maximum of 24 hours (Agtersloot & Paarlberg, 2016). Of course, it is possible to set additional lower criteria to enter higher states of alertness, which is common for a barrier with a complex and lengthy closing procedure such as the Europoortkering. But the actual closure is performed at most 24 hours before predictions exceed the closure criterion.

The Europoortkering

This barrier in the Nieuwe Waterweg was introduced in Section 1.2.1, and consists of the Maeslantkering and Hartelkering (review Figure 1.2). The closure criteria are NAP + 3.0 m at Rotterdam, or NAP + 2.9 m at Dordrecht (Ministerie van Infrastructuur en Waterstaat, 2021). The technical lifetime of the Maeslantkering is still several

[1] Usually: close. But in case of e.g. an emergency spillway, escalation implies opening.

decades, but its functional lifetime is coming to an end due to unacceptable closure frequencies and failure probabilities. Its replacement is considered by 2070 at the earliest.

Originally, the closure function of the Europoortkering was designed as presented in Figure 2.3. The decision to close depends on water levels at Rotterdam and Dordrecht, and therefore '*betrekkingslijnen*' are drawn to indicate for what conditions (Q: river discharge; H: sea water level) these levels are reached. Note that for Rotterdam, lines are drawn for a level of NAP + 3.2 m, because the decision to change the criterion to NAP + 3.0 m was not taken and executed until 1998 (Jorritsma-Lebbink, 1997). Appendix E provides more information on the historical determination of the closure criteria. The closure function in this case is the minimum of the two betrekkingslijnen, minus 25 cm to account for prediction uncertainties (which in that time was not an uncommon way to deal with said uncertainty). These margins are still included in the criteria today, because they have since not been changed. The closure function is marked black and separates the areas with and without closure. The joint yearly probability of the area that lies above this curve determines the closure frequency. The prediction uncertainty at Hoek van Holland is described with a normal distribution $N(\mu = -0.09 \text{ m}, \sigma = 0.18 \text{ m})$ (Kramer et al., 2017). This means that false (non)-closures can occasionally occur.

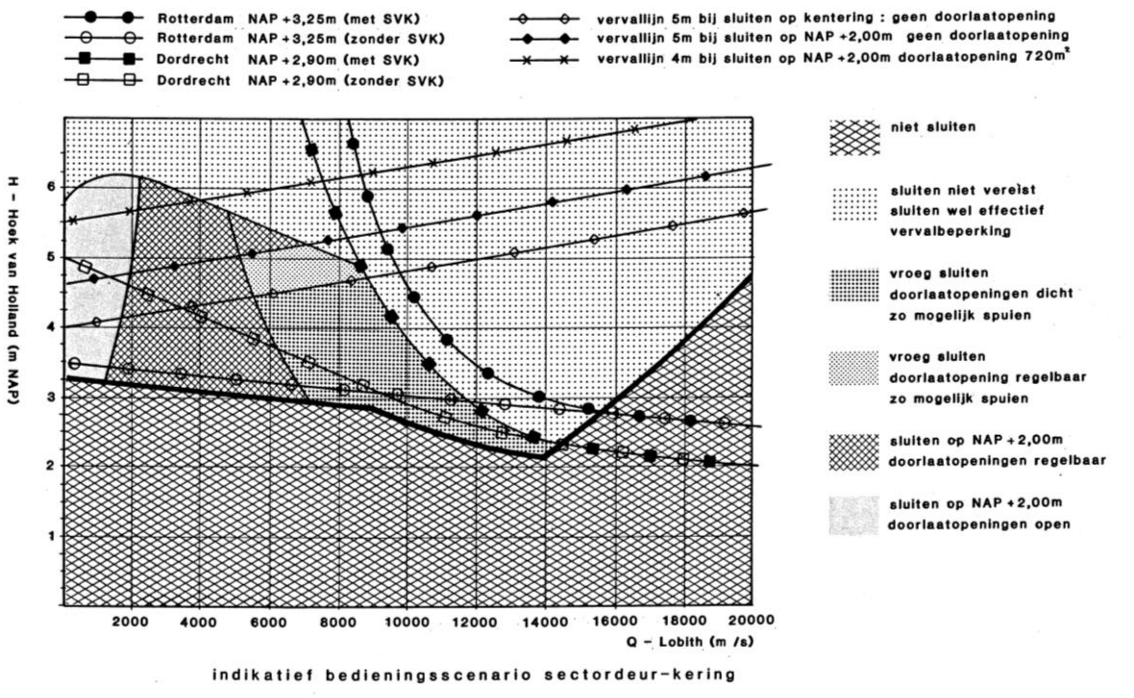


Figure 2.3 Design closure function chart for the Europoortkering (Nederend, H., personal communication)

Europoortkering - Failure probability

The Europoortkering at this time is a weak link among the primary flood protections, with a failure probability of approximately 1:1000 per year. This failure probability is the product of its probability of non-closure (≈1:100) and the closure frequency (≈1:10 years). The latter is analysed in the next subsection. The probability that the barrier fails to close consists of a failure to close plus a structural failure during closure. It is dominated by the Maeslantkering, which has a particularly high probability to not closure upon request. Research suggests that primarily the operation is responsible for a large portion of the failure probability per closure (Sewberath-Misser, 2022) (Delta21 v.o.f., 2021a) (Ministerie van Infrastructuur en Milieu, 2012). Previous attempts to implement a new system however, have failed and are accompanied with massive uncertainties as to what the new estimated failure probability would be (Pieter Jacobs, personal communication).

A second independent Maeslantkering (e.g. the Hollandkering (Rijcken & Meijman, 2022)) with similar failure probability may reduce the probability of the whole to $1{:}100^2$. A full closure by means of a lock may reduce it even further (Spaargaren, 2014). However, this research aims to assess Delta21 before such large interventions are taken. In Figure 2.4 a map is presented by Botterhuis et al. (2012) that shows the reduction of normative high water levels as a result of a failure probability improvement of the Maeslantkering. Delta21 may change the area that experiences a positive effect on normative high water levels by an improved Maeslantkering.

Figure 2.4 Spatial effect of a reduction in Maeslantkering failure probability on normative high water levels (Botterhuis et al., 2012)

Europoortkering - Number of closures

The current climate and closure criteria yield a closure frequency of about once every 10 years. With sea level rise (SLR) this number increases to once per 3 years for 0.5 m SLR, 3 times per year for 1.0 m SLR, and 30 times per year for 1.5 m SLR (Deltares, 2018). This is determined for a large part by the Rotterdam criterion, the criterion at Dordrecht is responsible for a closure far less often (statistically speaking, because a true closure has never occurred since construction). Changing closure criteria influences the closure function (see Figure 2.3) and therefore the corresponding frequency. The maximum acceptable closure frequency depends on several factors, of which most important are:

- Shipping passage: closures hinder traffic which has economic consequences.
- Maintenance: a certain uninterrupted window with no closures is required (usually during summer)
- Maximum loading: after many repetitions of extreme loading, the reliability of (esp. mechanical) components may start to decline.
- Multiple closures during one storm season: any damage to the barrier must be repaired before the next storm hits, or failure probabilities may increase drastically.

The starting point at which shipping becomes a problem is about once per year (Deltaprogramma | Rijnmond-Drechtsteden, 2011), and from a structural perspective approximately 3 times per year (Deltares, 2018). Note that without any change in closure criteria these rates are already exceeded with a mean sea level rise of respectively ~0.75 m and ~1.00 m (Deltares, 2018).

Europoortkering - Maeslantkering failure mode doors do not open.

The most commonly considered and most disastrous failure is non-closure of the Maeslantkering's doors, but there is another failure mode that affects water level developments in the delta: a failure to open the doors once the storm has passed. Several variations exist where doors do not move horizontally or even don't move up from the sill, but the effect is qualitatively similar: the discharge that would normally be resumed is now still blocked. This ultimately raises water level exceedance frequencies. Delta21 could provide some relief in such a situation by rerouting discharge southwards. However, the contribution of this failure mode to (normative) water level exceedance frequencies is very limited, as shown in Appendix F. The error by omission is therefore negligibly small, especially in the context of an approximate assessment of Delta21. Note that the situation can be particularly detrimental for the structural integrity of the Maeslantkering, but this is not being investigated in this research.

Haringvlietsluizen

The Haringvlietsluizen regulate the discharge through Haringvliet (Rijkswaterstaat, 2023), but cannot retain their operation when Delta21 is implemented. The storm surge barrier of Delta21 becomes the new first line of defence at the seaside boundary of the Haringvliet during extreme events. The influence of the Haringvlietsluizen on water level exceedance frequencies is therefore strongly reduced. It does however still provide a choke point for discharges. The new operation must simply make sure that water can always flow out into the tidal lake when Delta21 escalates. During normal daily circumstances, no operation changes are required.

Volkeraksluizen and Volkerak-Zoommeer

The Volkerak-Zoommeer is the water body South of the Volkeraksluizen (review Figure 1.2), which Rijkswaterstaat (2007b) has assigned a secondary function as an emergency storage area, effective since January 2016. When the water level on the Northern side of the sluices is predicted to exceed NAP + 2.6 m, the sluices open and allow the water level in the lake to rise up to about NAP + 2.3 m (Rijkswaterstaat, 2019). The only other condition is a closed Europoortkering. Several reinforcements to surrounding embankments, quays, etc have been completed as a result of this decision. The impact on water level exceedance frequencies has already been included in the WBI assessment rounds of 2017. With Delta21 this secondary function arguably has to be re-evaluated, because the condition of NAP + 2.6 m should principally no longer be reached when it is working properly. In any case, the frequency of the occurrence should be significantly lower.

Other controllable barriers and developments

The last controllable barrier is the Hollandsche IJsselkering, which closes when a water level of NAP + 2.25 m is predicted to be exceeded. The reliability of this first ever delta work is currently being improved (Deltaprogramma | Rijnmond-Drechtsteden, 2011), but no particular changes or significant influences on or by Delta21 are expected. A final possibly relevant development in the delta area is the optimization of the Brielse lake. Although it includes updated water retaining structures, they are mostly related to salt and sweet water management, and of no particular relevance to this research.

2.1.3 Detailed design and operation of Delta21

Chapter 1 has already introduced the Delta21 plan. The following paragraphs expand on this and provides a definition of the preliminary configuration of Delta21. How the elements are schematized and controlled within the model is presented in Section 2.2.3. The plan is not in its final design stage, and many aspects are still subject to (considerable) changes. Table 2.1 provides a summarized overview of the preliminary configuration, including a couple of other primary assumed values that are varied in the sensitivity analysis for convenience. The design is largely based on the most recent reports by Lavooij & Berke (2019), but numerous in-depth studies have since provided updated insights and suggestion.

Table 2.1 Preliminary configuration of Delta21

Delta21 design		Operational control		Other	
Spillway sill height	NAP - 4.5 m	Closure criteria D21	Dordrecht NAP + 2.5 m	Storm duration	30 hours
Spillway width	2700 m	Closure criteria Europoortkering	Dordrecht NAP + 2.9 m OR Rotterdam NAP + 3.0 m	Europoortkering failure probability	1:100
Storage lake volume	400 E10^6 m^3			Division at Pannerden	standard
Pumping capacity	10,000 m^3/s				

The pump/turbine station, most recently researched in depth by Jacquemin (2021), has a capacity of 10,000 m^3/s. The many pumps are installed at different heights, which should allow an efficient process for all possible water levels in the lake, in combination with water levels at sea.

The spillway design was originally made with the requirement to have a capacity of 20,000 m^3/s. Donkers (2021) translated this into a design that achieves this maximum capacity when the lake is completely empty, and the water level in the tidal lake is NAP + 1.5 m or more. This capacity however very quickly diminishes for a lake that is not empty, or lower upstream levels decrease. The sill height is set at approximately NAP -4.5 m, and the width equals 1278 m. This width, although sufficient to meet the original requirement, will in many conditions yield far lower discharges. More recent literature such as the landscape incorporation study by Eeden (2021) or updates by Delta21 set this number more towards 2000 m. In cooperation with the project's initiators, a larger width of 2700 m is employed to achieve the target spillway discharges in far more situations. The true width during an event is controllable by closing or opening more gates. In this research however, the full spillway is always used when possible, to calculate the full potential of Delta21, and not the optimal configuration (which falls outside the scope). The spillway opens immediately after the storm surge barrier is closed. Once the lake reaches its maximum level, the spillway capacity is reduced to equal that of the pumps, to prevent further increasing water levels in the lake.

The storm surge barrier, most recently researched by Verschoor (2023), closes when the Dordrecht criterion is met by predicted water levels, and a tidal low water is reached to ensure low flow speeds. The width in his report is approximately 1250 m, and a free flow profile that ranges from NAP - 6.0 m at the sill to NAP + 10.5 m at the top beam.

The storage lake is designed with a capacity of approximately 400 million m^3, with a water level range between NAP - 5.0 m and NAP - 22.5 m, and area of ca. 20 km^2 (Lavooij & Berke, 2019). The spatial design is most recently researched by van Eeden (2021), which reports an even larger area. This research is however not primarily based on considerations regarding energy or flood protection, so the capacity of 400 million m^3 is retained for the preliminary configuration. The lake should be emptied **within 12 hours** before the start of an extreme event where Delta21 escalates. For the preliminary configuration this is possible, but during a sensitivity analysis it is not always guaranteed. This means that the operation in daily conditions may be limited to a lower level in order to keep this promise.

The tidal lake connects Delta21 to the Haringvlietsluizen, and its bathymetry is most recently researched by Horick (2023). After the construction of the Haringvlietsluizen the mouth of the Haringvliet has experienced considerable sedimentation, a lot of which is sludge (Arcadis, 2022). This may push up water levels during escalation of Delta21, and consequently raise water levels upstream. To prevent this, the flow profiles in the tidal lake area are dredged by approximately 1 meter. Although some dredging is performed, the area provides limited additional storage during extreme events, because the water level is kept arbitrarily low by the escalated Delta21 spillway. The most crucial function is allowing water to flow easily both during extreme events to the spillway and normally towards the storm surge barrier.

2.1.4 Regional classification based on dominating boundary condition

The lower river reaches of the delta form a complex hydraulic system, with water levels influenced by discharges of both Rhine and Meuse, sea water level, wind, and Europoortkering failure. Depending on the considered location, these parameters have a larger or smaller influence on normative water levels. The combination parameters that is most likely the cause for a specific water level is called an illustration point. The illustrative conditions around normative frequencies determine strongly how a location can be characterised. Regions can be defined that indicate what dominates the normative hydraulic response. These bounds are presented for the current delta in Figure 2.5. An intervention such as Delta21 will have very different effects between these regions. In addition to that, it may change the existing borders. The areas are defined as follows, adapted from Kramer et al. (2017):

- **Discharge dominated**. There is no storm and barriers are open. Naturally, the Rhine dominates the Northern branches, and the Meuse the Southern one.
- **Sea dominated**. Fully determined by sea water level distribution. Not particularly relevant since no effects of Delta21 are noticeable there.
- **Failure dominated.** A storm at sea in combination with an Europoortkering failure dominates normative conditions.
- **Storage dominated**. A medium to high discharge (ca. 6,000 or higher) with an 'average' storm dominates this area. Usually the barriers are closed, but precise illustrative conditions differ between locations. Due to the reasonably high discharges, the area is sensitive to storm duration and phase between tidal signal and storm peak.
- **Transition areas**. No single parameter is dominant. Contributions shift when moving closer or further away from the nearest dominant area.

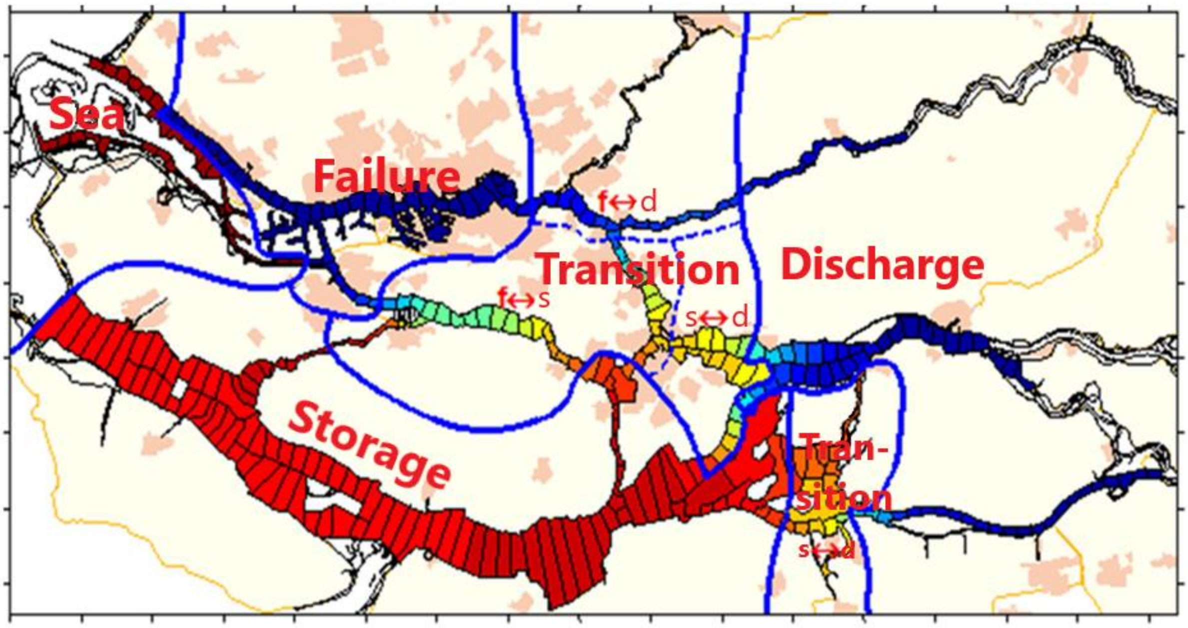


Figure 2.5 Dominant process on hydraulic response of partial areas in the lower river branches (Kramer, Smale, Bieman, & Chbab, 2017)

2.2 Schematization and model of the hydraulic system

This subchapter describes how to schematise and model the hydraulic system, including all Delta21 components. Fortunately, there is no need to start from scratch. Detailed official guidelines exist for generating water levels in the context of hydraulic loads on flood protections in the Rhine-Meuse delta (Smale, 2018), (Chbab, 2016). These are principally followed, and in-depth information is only provided on where changes, simplifications, or additions are made. Appendix A provides more details on implementation of the WBI schematization guidelines, and Appendix Q contains the final model itself.

2.2.1 Software and calculation method

The basis upon which the Delta21 hydraulic model is built consists of a fully functional one-dimensional SOBEK3-rural schematization of the current Rhine-Meuse Delta, managed by Deltares and in development at HKV (Agtersloot & Paarlberg, 2016). The schematization contains an extensive and narrowly defined one-dimensional flow grid. It has been used to generate databases with hydraulic loads used as of today, and contains a large degree of verification and validation. HKV has provided a user shell that runs this model repeatedly, for a range of boundary conditions, called the MHWp5-processor. The WAQUA report (Agtersloot & Paarlberg, 2016) states:

> *"The RMM[1] model is rather complex due to its large size, spanning over several different region types, containing numerous controllable barriers, and fairly complex boundary conditions. Instabilities still sometimes occur, increasing in number for higher sea water levels and decreasing for higher river discharges. Nevertheless, for relative databases it has been shown to perform adequately."*

As this research dives into the **relative** effects of Delta21, a description of how water level developments change in relation to the current situation - calculated with the same model - should be sufficiently accurate. A validation of the model with WBI databases is performed to confirm a correct calculation.

The computations consist of five basic steps, of which Figure 2.6 provides an overview:

1 **Generate water level signals**
For calculating the influence of Delta21 on water level development, this step is of superior importance. The remainder of this chapter elaborates on the schematization used in the SOBEK 1D program. A straightforward mass and momentum equation is solved. Details of the application of SOBEK are provided in Appendix A.

2 **Compile max. water levels for all combinations of discharge (Q) and sea water level (SWL)**
Using the MHWp5 processor, a maximum water level is compiled in a database for every location and for every combination of boundary conditions.

[1] Short fort he Rhine-Meuse delta model (Rijn-Maas-monding)

3 **Integrate with the marginal probability distributions of Q and SWL to obtain exceedance frequency curves**
using HYDRA-NL, the computed maximum water levels are assigned a probability of occurrence, to obtain statistically relevant results in the form of exceedance frequencies. Section 2.1.1 describes what distributions are employed.

4 **Compare the results from a system with and without Delta21, and map the reduction (norm frequency)**
Steps 1, 2, and 3 can be repeated for the current system, and one with (a configuration of) Delta21. The difference between the two exceedance frequency curves shows the effect of Delta21, and can be mapped for the entire delta. The most influential reduction is evaluated at the normative frequency of the considered levee, also known as normative high water (MHW). These provide the basis for answering question 4.

5 **Convert to reduced levee failure probabilities and re-assess**
The reduction in water level at normative frequency is translated to a reduction in failure probability, using fragility curves of the knowledge program sea level rise. Details on this method can be found in Section 3.1.2 and Appendix J. As a result of the WBI2017 assessments, a fairly up-to date picture of current levee failure probabilities is available. Combined with the estimated failure probability reductions, a re-assessment is performed which potentially leads to an obviation of a reinforcement.

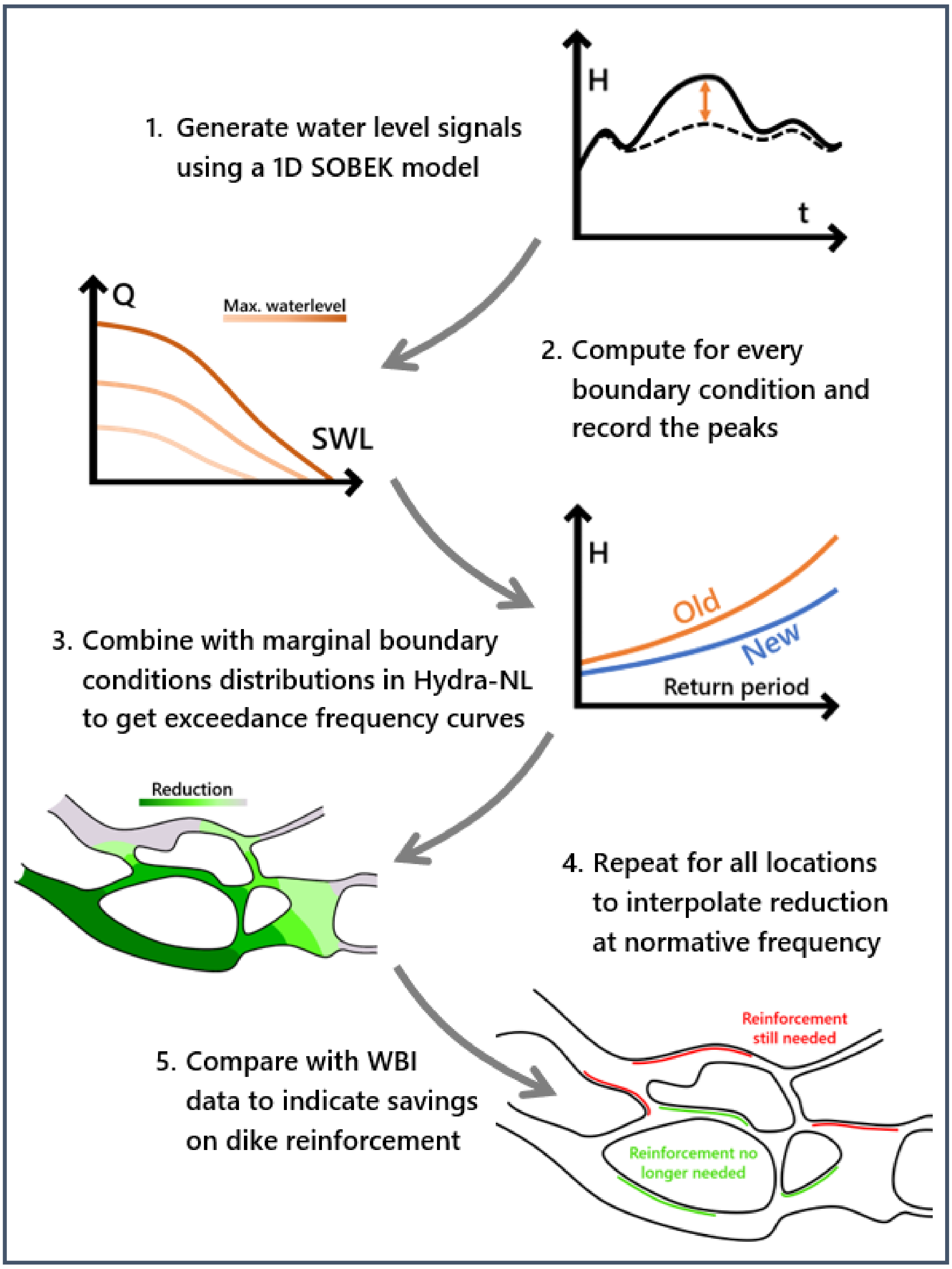


Figure 2.6 Methodological illustration of the complete model

2.2.2 Schematization of boundary conditions

The schematization of the boundary conditions also narrowly follows WBI guidelines, and is hardly different for a system with Delta21. Appendix A presents a detailed exposition on the sea water level and river discharge, based largely on the report '*WTI-2017 Basisstochasten*' (Chbab, 2016).

The seawards boundary consists of 3 components: A tidal signal, a storm surge, and an average level. Figure 2.7 provides an example, where the tidal signal oscillates around the average level and a surge is added with a standard phase shift of ϕ = -4.5 hours. A rise in sea level is schematized by raising the average level, and thus a linear addition to the tidal signal. Naturally, the distribution of extreme sea water levels is also raised uniformly by the same number. The closer to the sea, the higher average 'daily' water levels will be, which can influence the resulting peaks during a storm. Therefore, including a sea level rise statistically only (no addition to the tidal signal of the hydraulic model) will give an error in the results. Appendix D presents the magnitude of this error, which tends to be largest for the storage dominated regions (review Figure 2.5). For a W+ climate scenario with a sea level rise of 0.84 m, the accuracy becomes inadequate, and a proper hydraulic inclusion is compulsory. Relevant for question 4d is the change in storm surge duration, which is schematised by a widening of the surge signal. See also Figure 5.19 in Section 5.4.

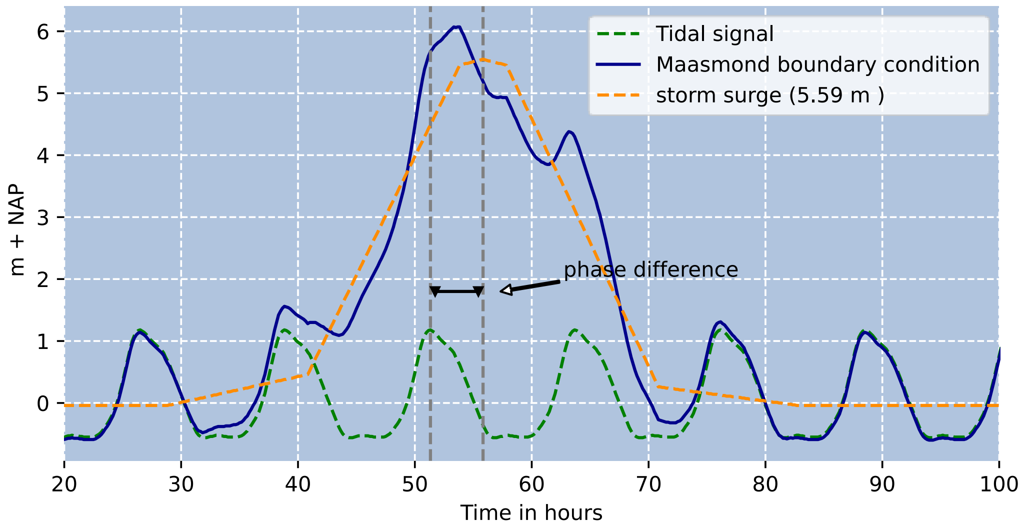


Figure 2.7 Downstream boundary condition at the Maasmond for an example storm with peak value 5.59 (SLR = 0.105 m ref. 1991)

High river discharge waves are generally of a much larger timescale once they reach the lower river reaches, and are therefore schematized as a **constant value** for the whole computational period (7 days). A predefined relation is used to distribute the various discharges at Lobith to the upstream boundaries: Tiel, Hagestijn, and Lith[1]. Climate change is represented solely by changed probabilities of discharges at Lobith (see Figure 2.2), imposed in step 3 of Figure 2.6. The distribution in the W+ scenario is used, indicating about a 10-15% increase in discharge for a given frequency above +/- 6000 m3/s (see Figure 2.2). In the sensitivity analysis of question 4b with a variation on the Pannerdensche Kop, the relation factors are changed, but the schematization is otherwise unchanged.

Note that the water level at sea and discharge in the Rhine are assumed to be independent. Various research by for example Klerk et al. (2015) points towards this not being the case, and Geerse (2013) finds that including the correlation coefficients could lead to normative water levels rising by as much as 0.1 m. Nevertheless, the WBI guidelines do not prescribe taking this into account, and therefore no such option is included in the software. The sensitivity to such a correlation may be different in a system with Delta21, which is particularly well suited to combined threats from river and sea. It is therefore recommended to re-evaluate this choice in further, more detailed assessments of Delta21.

2.2.3 Schematization of Delta21 components

The design as described in Section 2.1.3 is schematised in the one-dimensional SOBEK model. Appendix A provides details and illustrations of the implemented Delta21 components. A brief summary is provided in the paragraphs below. Many large and small improvements have been made in relation to previous Delta21 schematisations, as created by Buijs (2021) and before that by Oerlemans (2020). The most impactful adaptations are as follows:

[1] The Meuse discharge is a function of the value at Lobith too. For details see Appendix A.

1 The spillway is schematised as an actual spillway, a free overflow weir (see the sections below). The spillway design in previous schematizations is basically a pump with a maximum capacity of 10.000 m^3/s or the discharge at Tiel (whichever is lower). The advantage of this is a high controllability of the discharge; it is quite simply imposed. The disadvantages however are:

- The hydraulic behaviour of a weir is neglected, the discharge does not increase with upstream water level.
- Large fluctuations occur in the output signals due to instabilities when turning pumps on and off.
- The maximum spillway capacity of Delta21 is not the same as its maximum pumping capacity in the design.

2 The storage lake is added, and storage now plays a role. The pump and turbine station connects it to the sea. In previous schematizations, the storage lake, pumps, and spillway are implemented as one entity: a simple discharge equal to the pumping capacity at the location of the spillway.

3 The operational control (see section 2.2.4) is detached from the Europoortkering and improved. In previous schematisations, the storm surge barrier of Delta21 and the Europoortkering operate symmetrically, as if there is a single control. This does not allow a proper representation of interaction between the barriers, let alone research into dissimilar closure criteria.

Pump- and turbine station

The station is located at the 'downstream' end of the storage lake, and consists of a pump with a capacity of 10,000 m^3/s. It is always on when there is water in the lake. This does not represent daily conditions well, but given the promise of a lake that is empty at the start of a storm, it is sufficient for this research. Occasionally, the full pumping capacity was not truly needed, but optimization of Delta21 is not within the scope of this thesis.

Spillway

The spillway in the new model is schematized as a sharp crested[1] (free) overflow weir. In reality it is controlled by numerous gates, but in the model one large gate will suffice (the effective width is unchanged). Two main design characteristics determine the discharge over the spillway: it's width and the sill height, used in the spillway discharge formula of SOBEK (see Appendix A). The width is initially set at 2700 m and the sill height at NAP - 4.5 m.

Storm surge barrier

The storm surge barrier consists of a large rectangular gated orifice just downstream of the spillway. Akin to the design in Section 2.1.3 by Verschoor (2023) it is 1250 m wide, and a free flow profile heigh that ranges from NAP - 6.0 m at the sill to NAP + 10.5 m.

Storage lake

Connecting the pump/turbine station and the spillway of Delta21, the storage lake is schematized as an extremely deep, wide, and short rectangular river branch. Therefore, it can be assumed that the water level inside the lake is constant and flow speeds negligible. With a width of ca. 10,000 m, length of 2300 m, and height range of 17.5 m, the total volume results in 400,000,000 m^3. When the lake reaches its max water level of NAP -5 m, the spillway capacity will be set equal to the maximum capacity of the pumps.

Tidal lake

The existing flow profile shapes are retained but lowered by 1 m to represent the dredging included in the Delta21 project. No claim is made that this is a morphologically (semi-)stable configuration. Research on more detailed configurations has recently been published by Horick (2023).

2.2.4 Real-time control of barriers

The functioning of barriers in the hydraulic model is determined by the Real Time Control module (RTC). It decides for each barrier how to behave, according to user defined criteria. In more simple terms, it opens and closes barriers when they need to. The RTC can predict[2] future water levels with capacity of 24 hours, and makes decisions based on this. For almost all barriers, the operational control is left untouched, representing the current reality. Small exceptions are highlighted for the Europoortkering and Haringvlietsluizen. Naturally, the operational control of Delta21 is new and explained in detail below. Appendix Q provides the coded operational decision-making scripts for all controllable barriers.

[1] Because the downstream water level is fully controlled, a submerged situation in principle never occurs.
[2] A 'prediction' in a modelled situation is simply the modelled output before decisions were carried out.

The exact design parameters of Delta21 are not set in stone, so unsurprisingly neither is the operational control. When to use which component of Delta21 is a complex issue, and one that permits for much optimization. In literature on the subject one might for example find the flowchart as created by Donkers (2021), presented in Figure 2.8. Although this does not provide enough detail for the real time control of a components, it offers a starting point for the operational control. Unfortunately, the approach knows several large disadvantages, as will be explained later. Thorough discussions with the initiators of Delta21 has led to the final operational control schematization, as presented in the following sections.

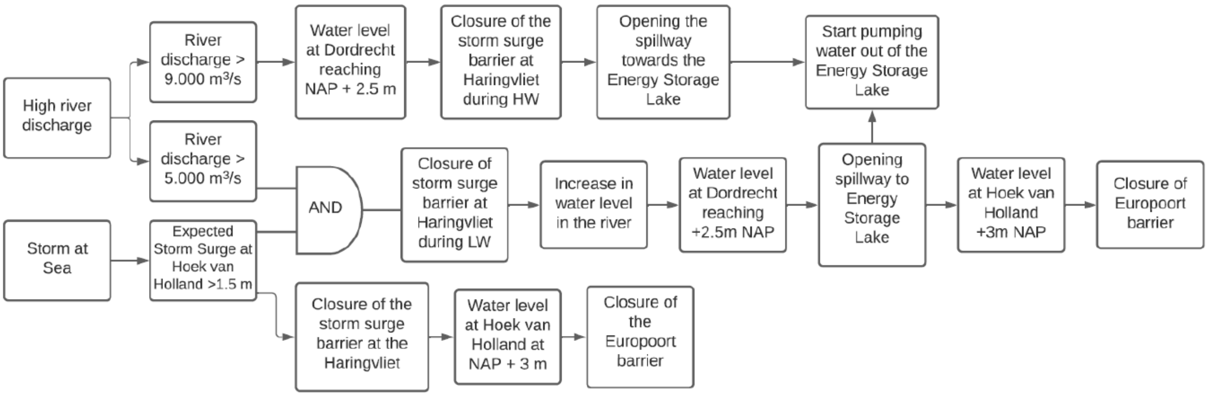


Figure 2.8 Delta21 Operation flowchart by Donkers (2021)

Operational control of the Delta21 storm surge barrier

The employed operational control of the new storm surge barrier is presented in Figure 2.9, which represents the code in Appendix Q using a decision flowchart. When the storm surge barrier escalates from rest to mobilized, the time of closure is calculated. The control attempts to find the last low water, or if that fails another suitable time. The procedure shows similarity to the one employed by the Maeslantkering. For details on how this is done see Appendix A Closing during ebb ensures that flow velocities through the storm surge barrier are reasonably low allowing for controlled closure of the gates. Also, this allows water to exit the system for the longest time, which minimizes the required total pumped discharge due to premature inflow in the storage lake. Within approximately an hour, the barrier can be closed (Verschoor, 2023).

The difference between an operation such as in Figure 2.8 and Figure 2.9 is that the former bases all decisions on boundary conditions or current measurements, whereas the latter employs (1 day) predictions of water levels at decision locations: Rotterdam and Dordrecht. Naturally, boundary conditions have a strong relation with the resulting expected water level, but escalating Delta21 early may have an undesirable effect on normative high waters. If a storm hits, the full capacity of Delta21 should be available to mitigate **peak** water levels. This prediction method far better resembles how the true system works, and Delta21 would likely profit from adhering to a similar scheme. If the spillway opens only once the level at Dordrecht reaches NAP + 2.5 m, one of three things might happen:

- The maximum water level at Dordrecht is decreased, but would never have exceeded NAP + 2.9 m.
- The maximum water level at Dordrecht is decreased to below NAP + 2.9 m.
- The maximum water level at Dordrecht is mitigated too late and (far) exceeds NAP + 2.9 m.

Using a predicted water level to decide when to open the spillway is far superior. It both completely eliminates the first option with unnecessary (and expensive) discharging, and the third option has a smaller chance of occurring because situations with steeply rising levels (from 2.5 m to 2.9 m in under 24 hours) will exhibit escalation well before this is allowed to occur. Furthermore, if the Maeslantkering fails, the predicted water levels will undoubtedly show it, whereas the boundary conditions do not provide any such information. The control request present in Figure 2.8 implies to use Delta21 with discharges exceeding approximately 9000 m^3/s, even if there is no storm at all. This operation is excluded, because it falls outside the scope of this research.

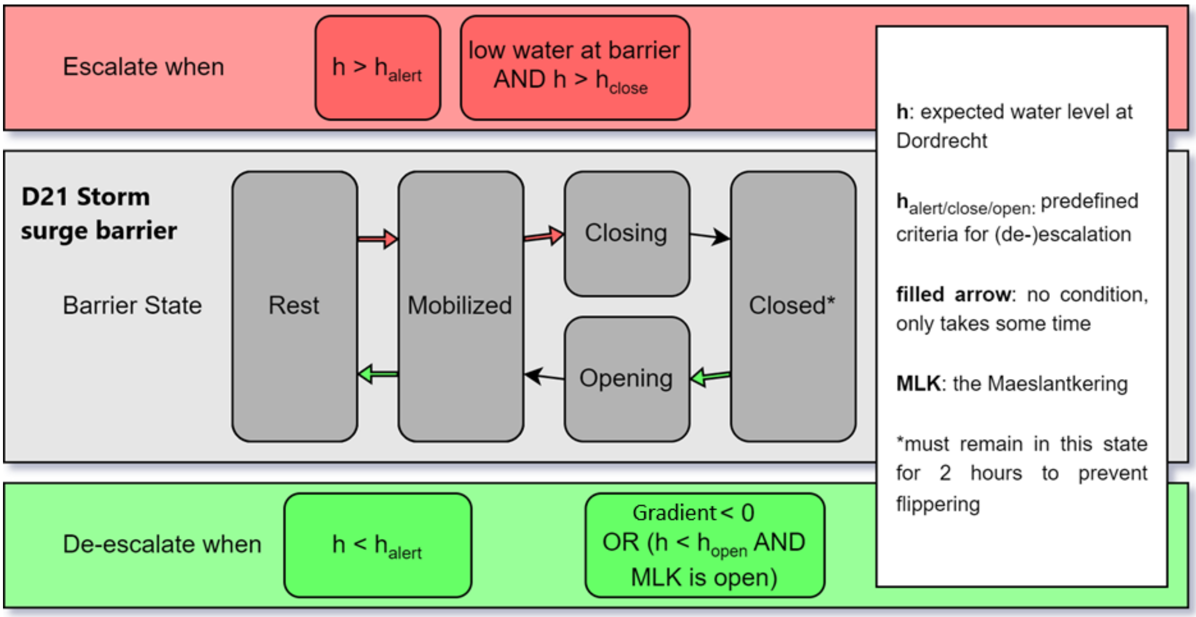


Figure 2.9 Delta21 storm surge barrier operation flowchart

Operational control of the Delta21 spillway

The operation of the spillway is exceedingly simple, as it has been coupled to the storm surge barrier of Delta21, presented with similar flowchart in Figure 2.10. The spillway's control is subservient to that of the storm surge barrier, which determines the moment of escalation (for the single reason that the barrier desirably closes before the spill-way opens up). Once the storm surge barrier is closed, the spillway gates will (start to) open. If the storage lake reaches its full volume, the discharge through the spillway is set equal to the maximum pumping capacity. Once the operational control of the barrier determines de-escalation is allowed, the spillway closes again.

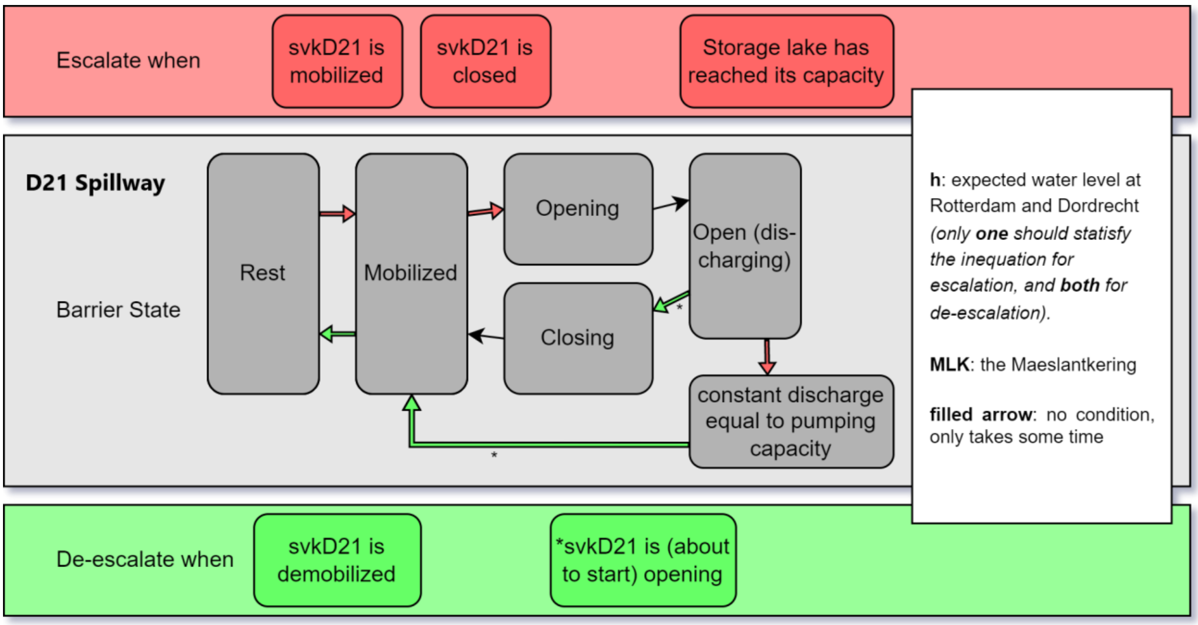


Figure 2.10 Delta21 spillway operation flowchart, taking input from the storm surge barrier (svkD21)

Note that an escalation of Delta21's spillway in this schematization means that it will be utilized to its full potential, regardless of the conditions or expected water levels. This means in practise that the spillway will always be fully open once the barrier is closed, with the exception of a completely filled storage lake. The disadvantage is that for a lot of situations this procedure will lead to a reduction far larger than what is 'required'. In other words, a large optimization opportunity lies in deciding when to open the spillway only partly. Optimization of the spillway's con-trol is however not in the scope of this thesis, and it is desirable in this stage to know what the spillway can achieve, not what it should. Furthermore, the computational time would increase massively for every time the effective width of the spillway is changed, because predictions have to be recalculated. With the number of variations in Delta21 configuration in the sensitivity analysis, such a schematization takes unacceptably long to research.

Operation changes for the Europoortkering

Even though the operation of Delta21 is configured separately from the Europoortkering, there is of course some implicit coupling between the two. When one barrier closes, the other may no longer have to and vice versa. This however does not change anything about the operational control, which still simply decides based on water level predictions. An exception to this is the Europoortkering's time of closure when Delta21 escalates. In the case of a *kentering*[1] closure, the effects of Delta21 may change the moment when flow speeds are near zero in the Nieuwe Waterweg. Therefore, a new moment is calculated as soon as Delta21 escalates, with a corresponding time shift of the entire closing procedure when required. Finally, changing the closure criteria for the Europoortkering does not change the operational procedure. Instead, it is simply initiated for different conditions and water level predictions.

Operation changes for the Haringvlietsluizen

Delta21 is the new first line of defence against the sea, and needs the Haringvlietsluizen to discharge as much as possible when it escalates. Because of this, the Haringvlietsluizen have basically lost their function during extreme high water events. It is therefore replaced with a barrier of similar dimensions but with a far simpler functionality. This new operation simply makes sure that water can always flow out into the tidal lake, but never back into the Haringvliet.

The chink (NL: 'kier') during high tide is excluded, because its function is only of importance for salinity/ecology. Another excluded functionality is a closure to prevent salination of the Nieuwe Waterweg. Normally speaking, a water level setup is generated with closed Haringvlietsluizen when saltwater intrusion threatens to reach the inlet at Schiedam. Both processes can lead to higher initial conditions when they are followed by a storm event. In particular the transitions regions (review Figure 2.5) may experience higher water level exceedance frequencies because of this, especially in the event of a failing Maeslantkering. Nevertheless, the resulting error of the simplification is shown to be acceptably small in Appendix F, even for the low return period events that typically exhibit these processes.

2.2.5 Model uncertainty and database reparation

Several sources of uncertainty are included in the entire hydrodynamic modelling process. Natural variability leads to uncertainty in the boundary statistics. Prediction uncertainty leads to incorrect decisions of the barrier controls. Uncertainties in climate change scenarios yield large bandwidths the further into the future computations go. But one source of uncertainty behaves somewhat differently than the others: model uncertainty. Model uncertainty originates from the model being a simplified version of reality and uncertainties in model parameters used in computations. Quantification of these is challenging, relying on pragmatic methods such as hindcast studies with sensitivity calculations, and expert judgement (Chbab & Groeneweg, 2017). Whereas other uncertainties are in some way integrated before the final result is calculated, model uncertainty is in a way 'added' at the last step. The computed values therefore have an uncertainty band around them, generally represented with a normal distribution $N(0, 0.25)$ for a closed Europoortkering and $N(0, 0.15)$ for an open one. Because of the nature of model uncertainty, it is itself in principle independent of return period (Chbab & Groeneweg, 2017).

This model uncertainty alone is not necessarily a problem. However, databases resulting from Delta21 calculations as well as widely used WBI2017 databases have an issue concerning the output field. Take for instance Dordrecht, which has a maximum water level for given boundary conditions and an example scenario with functioning Maeslantkering and low closure criteria as presented in Figure 2.11a. The thing that stands out immediately, is that a hill of high vales (up to NAP + 2.5 m) exists. Moving towards the top right side of the figure from this area means that boundary conditions are increasing in extremity (higher discharge, sea water level, or both). However, this does not always go together with an increase in resulting max water level. This is caused by the escalation criteria for Delta21 and the Europoortkering, which determines that a maximum water level of just under NAP + 2.5 m is still acceptable. However, just above that level the barriers close and the Delta21 spillway opens, leading to strongly decreased water levels. Only when conditions get far more extreme the system starts to turn around and once again reach water levels equal to or larger than the closure criteria. Along the drawn line one can plot an excerpt and it becomes more obvious that for 'more extreme' conditions a 'less extreme' water level is obtained, which is entirely

[1] Closure type of the Maeslantkering where Lobith discharges are above 6000 m^3/s, and the barrier closes once flow speeds reach zero.

opposite intuition. Note that there is no sudden drop after the closure criterion because many of these values are interpolated and the actual calculation grid is not fine enough to replicate such sharp changes.

The statistical computations cannot deal with this counterintuitive result very well. To work around the issue, databases are 'repaired', which basically means that the valley in the results is turned into a plateau at the height of the highest value to come before it. In Figure 2.11b this is represented as the red shaded area. Now, for increasingly extreme conditions one never finds a lower max water level, but it becomes apparent how this is likely to skew to final probabilistic results quite dramatically.

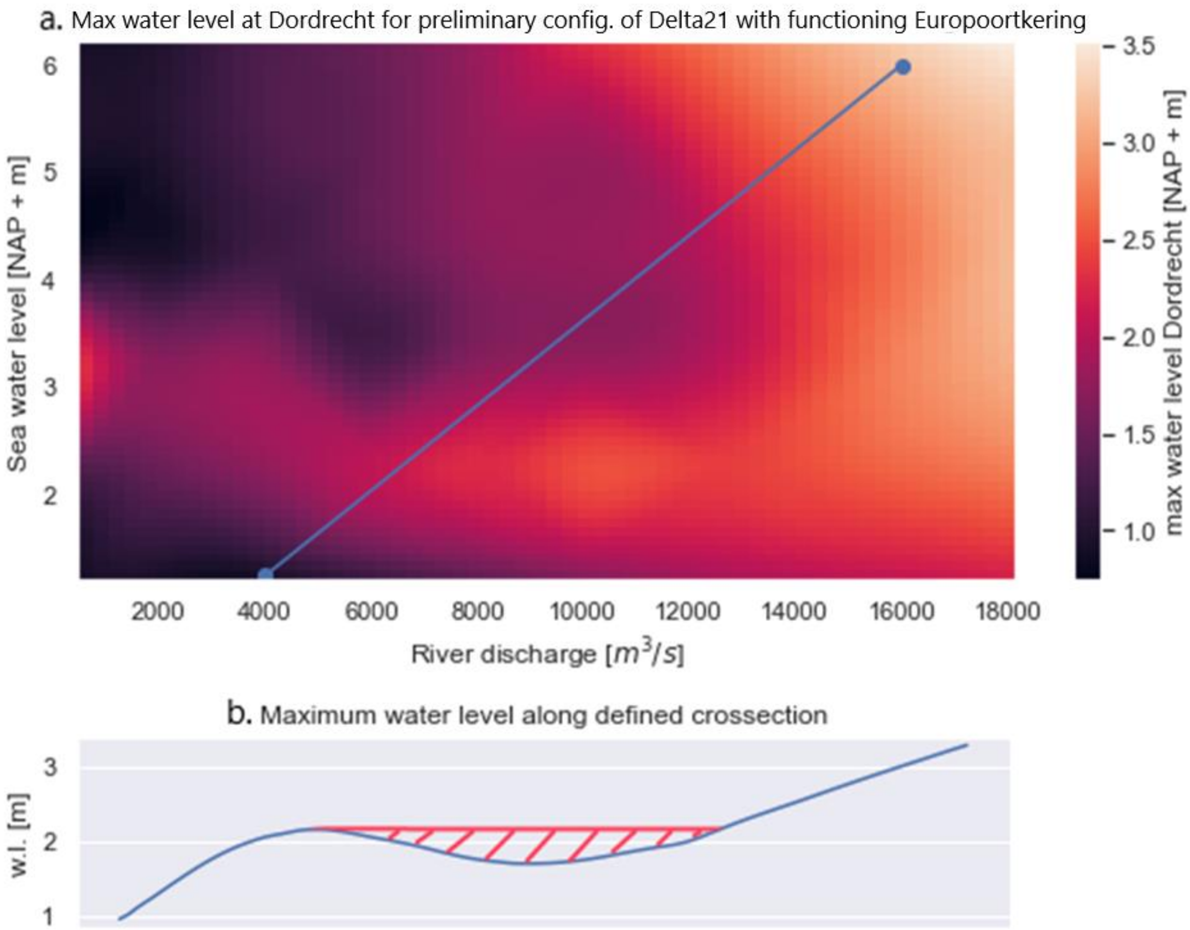


Figure 2.11 Delta21 - Output field of max. water levels at Dordrecht (a) with excerpt profile along indicated line (b)

The bigger problem however appears when the repaired output field is combined with model uncertainty. Around the plateau, a peculiar process starts to unveil. For increasing return periods, an increase in the extremity of boundary conditions does not yield a higher water level. However, increasing the extremity of the uncertainty dos, since it is modelled as a simple normal distribution. This effectively means that for increasing return periods, the boundary conditions that lead to the peak of the earlier described hill are combined with an ever larger uncertainty addition to yield a strictly increasing exceedance frequency curve. Such a line is presented in Figure 2.12. To better illustrate the process, take for example the point at return period = 10,000 years. In a probabilistic sense, this point is (by far) most likely to be caused by a discharge of 2150 m^3/s and a max. sea water level of NAP + 3.25 m. Deterministically, this would yield a maximum water level of NAP + 2.26 m, not even nearly reaching the escalation criterion of Dordrecht, but a massive 0.74 m of uncertainty is added because such small probabilities are allocated just for moving into the extremes of the uncertainty distribution. Only once water levels get so high that one has passed the plateau does this effect withdraw, but unfortunately this is far beyond normative frequencies. The exact same problem applies to WBI2017 databases too as shown in Figure 2.13, albeit with a somewhat smaller reparation as opposed to a system with pumps (such as Delta21).

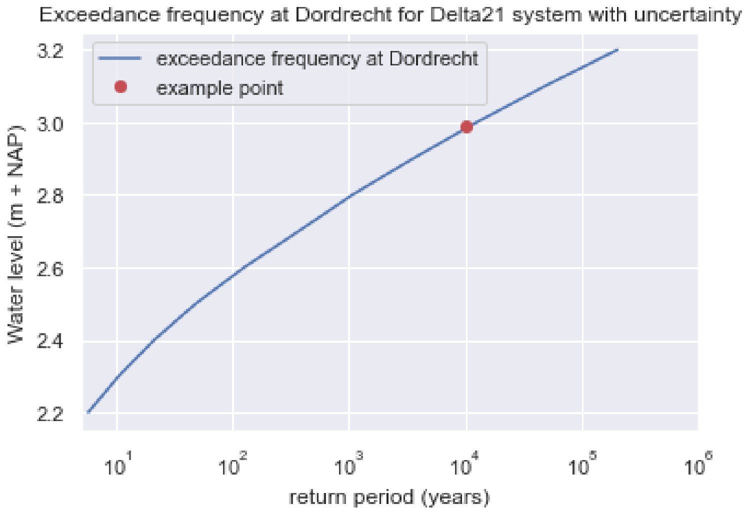


Figure 2.12 Exceedance frequency curve Dordrecht

This issue dominates the shape and position of all frequency exceedance curves, starting around the closure criterion level and going upwards from there. These curves are right now being used for determining the hydraulic boundary conditions of dike segments and designing reinforcements, but contain in them a statistical quirk that has very little to do with actual behaviour of water. If Delta21 variations are to be compared the problem is even more prominent. If a variation influences the location and height of the hills peak, such as a change in closure criterion, it yields a massive reduction. Variations that do not, e.g. the spillways capacity of Delta21, are underrepresented in the results, because normative high waters are most likely caused by a situation where the spillway is not even open (but a massive uncertainty value is added as the final step, leading all the same to a high water level).

Therefore, to properly assess the hydraulic effects of Delta21 and variations on the preliminary configuration instead of the effects of statistical eccentricities, the remainder of this research is coerced to consider only results and figures that exclude model uncertainty. Relative results between configurations give a perfectly sufficient idea of what is more, or less, effective. As discussed in Section 2.2.1, the Rhine-Meuse-delta model is only expected to perform adequately for **relative** databases anyway. It should be noted that relative reductions are expected to dampen out somewhat when model uncertainty is reintroduced, leaving about 75%. Furthermore, note that these results are in no way to be interpreted in an absolute sense, because omitting uncertainty does not only bypass the problem of a dominated curve, but also quite simply lowers (translates) it by quite a bit.

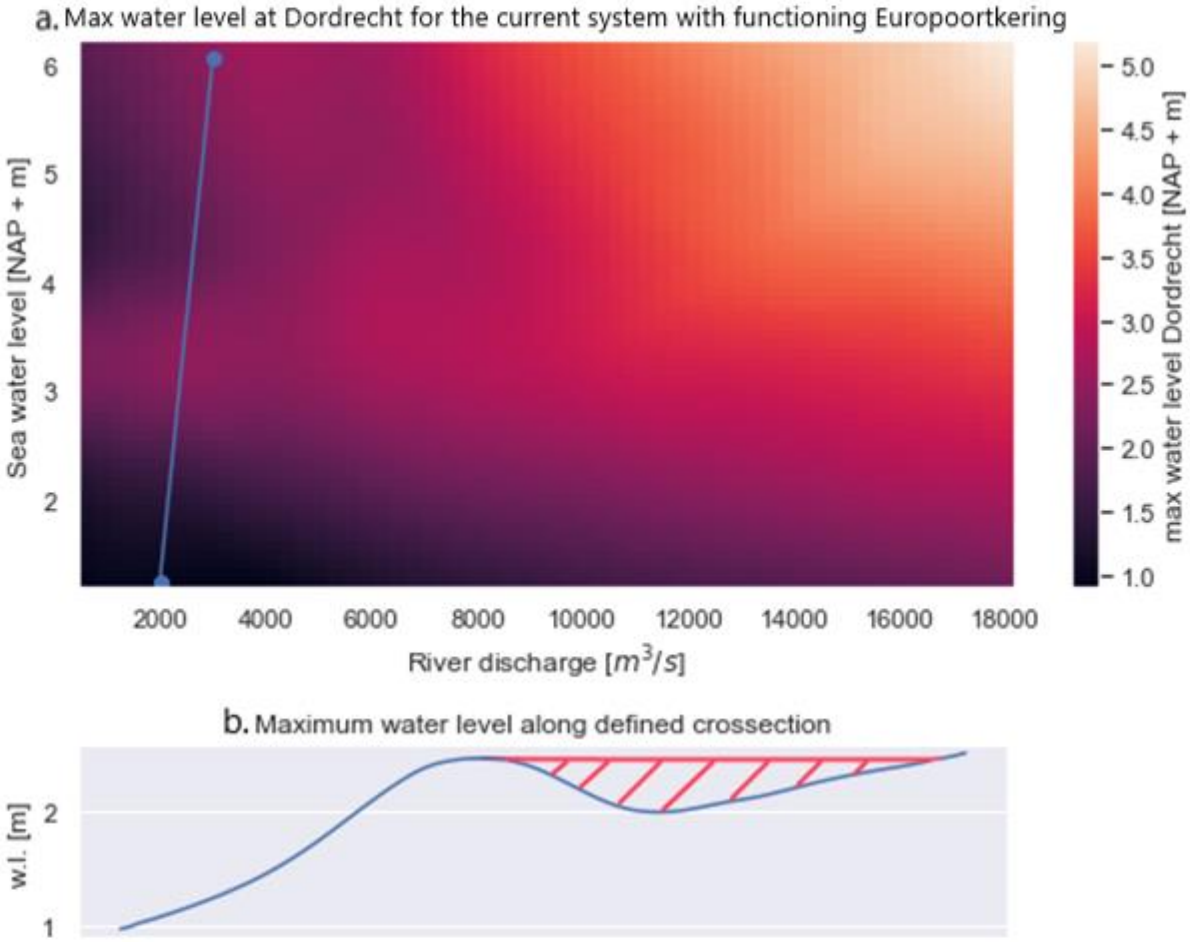


Figure 2.13 Current System - Output field of max. water levels at Dordrecht (a) with excerpt profile along indicated line (b)

2.3 Concluding remarks

Water level exceedance frequencies in the Rhine-Meuse delta are dominated in subregions by the sea water level, rivers discharge, storage characteristics, or a combination of these. Delta21 affects the hydraulic response by influencing the storage characteristics and to a lesser extent discharge capacity. The Haringvlietsluizen lose their primary seawards defence function, but otherwise the system largely is unchanged after implementation of Delta21. The model schematization of Delta21 in this research is greatly improved, accounting for all it's components. This leads to a superior representation and therefore modelling of Delta21's effects, where storage and operational control are properly incorporated.

3 OPPORTUNITIES FOR MORE COST-EFFECTIVE FLOOD PROTECTION WITH DELTA21

Question 2. How can Delta21 accomplish cost reductions in the context of flood protection?

Delta21 influences the hydraulic system by discharging and storing water, in turn alleviating upstream branches for a wide range of conditions. The following chapter takes inventory (question 2a) and describes in detail how the effects of Delta21 can lead to reduced costs (question 2b) in the Rhine-Meuse delta.

3.1 Inventory and description potential cost saving strategies

3.1.1 Lengthening the lifetime of the Maeslantkering

The Maeslantkering, being a part of the Europoortkering, has some serious limitations regarding its use as a storm surge barrier (review Section 2.1.2). In due time, it will need to be replaced because the failure probability per year is no longer acceptable, or the closure frequency exceeds approximately 3 times per year (Haasnoot, et al., 2019). When the failure probability is no longer acceptable depends on the consideration of what is more costly: raising dikes in the area where Europoortkering failure probability (partially) dominates normative conditions, or reinforcement/replacement of the Maeslantkering. Either way, any such venture will be quite expensive, and extending the time before it is required can save quite some funds.

The failure probability per year of the Europoortkering consists of two components: The product of the probability of failure per closure, and the closure frequency. Reducing any one of these will yield a smaller yearly failure probability, but a high closure frequency alone may be enough cause for interventions. Research suggests that primarily the operation is responsible for the high failure probability. In contrast, reducing the closure frequency and extending the moment when it becomes too high does definitely yield a lifetime extension.

In addition to this, the lifetime of the Maeslantkering may also be lengthened by changing the area in which normative conditions are determined by the failure probability of the Europoortkering. If for example small reinforcement measures manage to reduce the failure probability slightly, those would have greater yields if the sphere of influence of the Europoortkering failure probability is amplified. Vice versa, a smaller area of influence would mean that a rise in failure probability is less problematic (or at least lead to fewer required dike reinforcement projects). A increase in failure probability is not necessarily out of the question, as some publications do suggest that 1:100 might even be too optimistic (Tweede Kamer der Staten-Generaal, 2006) (Vreede, 2006).

3.1.2 Obviating dike reinforcements

Another promising approach to save costs is by obviating the need to reinforce stretches of dike. Although a smaller reinforcement project is less costly than a large one, the real profit comes from not needing a project at all (see Section 6.2). As a result of new norms and assessments of all embankments in the Rhine-Meuse delta, many trajectories fail to meet a minimum safety level. More specifically, numerous dike segments (*dijkvakken*) have a failure probability that exceeds a cross-sectional limit for one or more failure mechanisms (Informatiehuis Water, sd). Physical reinforcements can lower the failure probability through increased strength, but equally viable is a reduction of loads through shifting exceedance frequencies of extreme water levels. The latter is precisely the alternate and more cost-effective approach that Delta21 aims to achieve. Summarized, the approach amounts to the following, and a detailed description is given in Appendix J.

Data from the *Wettelijk Toets Instrumentarium* (WBI) is readily available at the *Nationaal Georegister* (NGR) to map all dike segments with corresponding assessments and failure probabilities per track. Three tracks are considered, in which reductions as a result of Delta21 are expected to play a role:

1 Piping (STPH)
2 Macro-stability (STBI)
3 Crest/inner slope erosion or 'height' (GEKB)

In the standard budget of allowable failure probability, room is also reserved for revetments, structures, and miscellaneous/other. These are excluded because normative conditions for revetments are dominated by wind/wave conditions, and structures + other are very case-specific which disallows a generalized method. This is despite structures and unique projects often being among the more expensive reinforcement projects.

A cross-sectional probability limit for each track is computed following WBI protocols (Ministerie van Infrastructuur en Milieu, 2019) for all dike segments. Meeting this bar will result in a categorization of III or higher, or simply put: a positive assessment. Dividing the computed failure probability by this cross-sectional limit yields a factor with which the computed failure probability has to be reduced to meet the requirement. The logarithm of this factor is called the required **decimation** (how many times the probability must be decreased by factor 10).

For a completely proper reassessment after updating hydraulic loading statistics a recalculation of every dike segment for every track would be necessary. However, this falls far outside of the scope of this research, and is not needed to get a preliminary estimate of failure probability reductions. The required decimation is therefore transformed to a required decimation height[1] through the use of fragility curves[2]. For the tracks STPH and STBI, the curves that describe this sensitivity to water level changes are compiled from the Knowledge Program Sea Level Rise (KPZSS) (see Figure J.35 in Appendix J). For GEKB, the slope of the local water level exceedance frequency curve is used. The water level change is evaluated at the normative frequency, formerly commonly known as MHW. despite current guidelines dictating the entire curve must be used for assessment, it is a good representative parameter of the hydraulic loads at an embankment. The result of multiplying the required decimation with the decimation height is a water level change needed to reassess that segment as positive, or **the required reduction of water level at normative frequency**.

When the sea level rises and extreme discharge distribution shifts, so too will exceedance frequency curves change. The same fragility curves as used in the previous section can describe for what dike segments the positive assessment turns into a negative one, given the new hydraulic loading statistics. The rise in water levels at normative frequencies is expected to be attenuated in a system with Delta21. Therefore, a system without any interventions will require more km's to be reinforced, than one with Delta21. The difference between the updated assessments indicates where Delta21 has been able to sufficiently mitigate the expected increase of hydraulic loads due to climate change.

Within the (re)assessment of how many km's of dike need reinforcement, a complex category exists that deserves some additional attention. It includes dikes that:
- Would need reinforcement as of the WBI2017
- No longer need reinforcement with Delta21 on the short term
- Do need reinforcement in the future scenario with Delta21

For these type of dike segments, two options are considered that determine if and when a cost reduction contribution should be allocated:
1 Delta21 is constructed as soon as possible. The reinforcement can be scrapped from the HWBP budget, and a cost reduction on short term is achieved. In the future scenario however, these dike segments are added to the total amount of km's that need reinforcement, which decreases the future savings.
2 Delta21 is constructed after the reinforcement has been completed in the context of the HWBP. No savings can be made on the short term anymore. In the future scenario, it is possible that a second reinforcement is needed, given a design lifetime that is generally 50 years. However, the design conditions also depend heavily on climate change, the expected chance of a later Delta21 completion, preferences of the water board, etc. A theoretical obviation of this second reinforcement project by Delta21, is therefore excluded from the estimation to retain a reliable and conservative figure.

Note that this only applies to the track on which the dike was initially disapproved. If another reinforcement is required in the future on a different failure track, cost reductions are expected. Nevertheless, if a segment is reinforced, it will likely also perform better on other tracks. This of course varies greatly depending on the specific design. Without having to go into much detail, these categories are indicated separately to account for the additional uncertainty of that saving contribution.

The resulting obviations of reinforcement projects are expressed in kilometres of dike. Cost estimations per kilometre are needed to translate those into saved funds, which will be dealt with in Chapter 6.

[1] Decimation height is the change in water level for which the failure probability is reduced by a factor 10.
[2] Fragility curves directly relate a certain water level at a dike segment to a failure probability.

3.1.3 Reduce flooding frequencies of valuable unembanked areas

To get an idea of the magnitude of savings through this approach, the two locations are considered where damages are largest in case of flooding: Rotterdam and Dordrecht (Elshof, 2014). The Rhine-Meuse delta knows many other unembanked areas, many of which are industrial, or contain ports or nature. One particularly valuable zone for example is Moerdijk. The reason for not including it in these estimates, is because this area, like many other ports, have a particularly high ground level. The water level exceedance frequencies at Rotterdam are dominated by the sea boundary statistics in combination with the Europoortkering failure probability, even in a hydraulic system containing Delta21 as will be shown in Chapter 5. Because expected savings in the Rotterdam area are negligibly small, the focus is shifted to Dordrecht exclusively. To calculate the average annual expected damage for the Island of Dordrecht Equation 3-1 is used:

$$R = \int_{f_{min}}^{f_{max}} D(f)df \qquad \text{Equation 3-1}$$

Where:

R = the average annual expected damage [€ / year]
f = the annual frequency of an event [year^{-1}]
D(f) = damage as a function of annual frequency

The bounds f_{min} and f_{max} are determined by the range of frequencies in which water level exceedance is described. Because Hydra-NL is not able to give sufficiently reliable data for frequencies lower than 10^{-5}, this is taken as the upper bound.

In his research, Buijs (2021) computes damage profiles as a function of water level for three distinct areas on the island of Dordrecht: the historical harbour, flanks, and Biesbosch (see Figure 3.1). These are able to provide an excellent estimation of the average expected annual costs, and by comparison potential for savings. The damage profiles are presented in Figure 3.2 and contain values up to approximately €5.0 * 10^7. Because of a change in among others land use and economic development, an adapted curve is included for the year 2100. The water level exceedance frequency curve for Dordrecht is computed at the marked location in Figure 3.1.

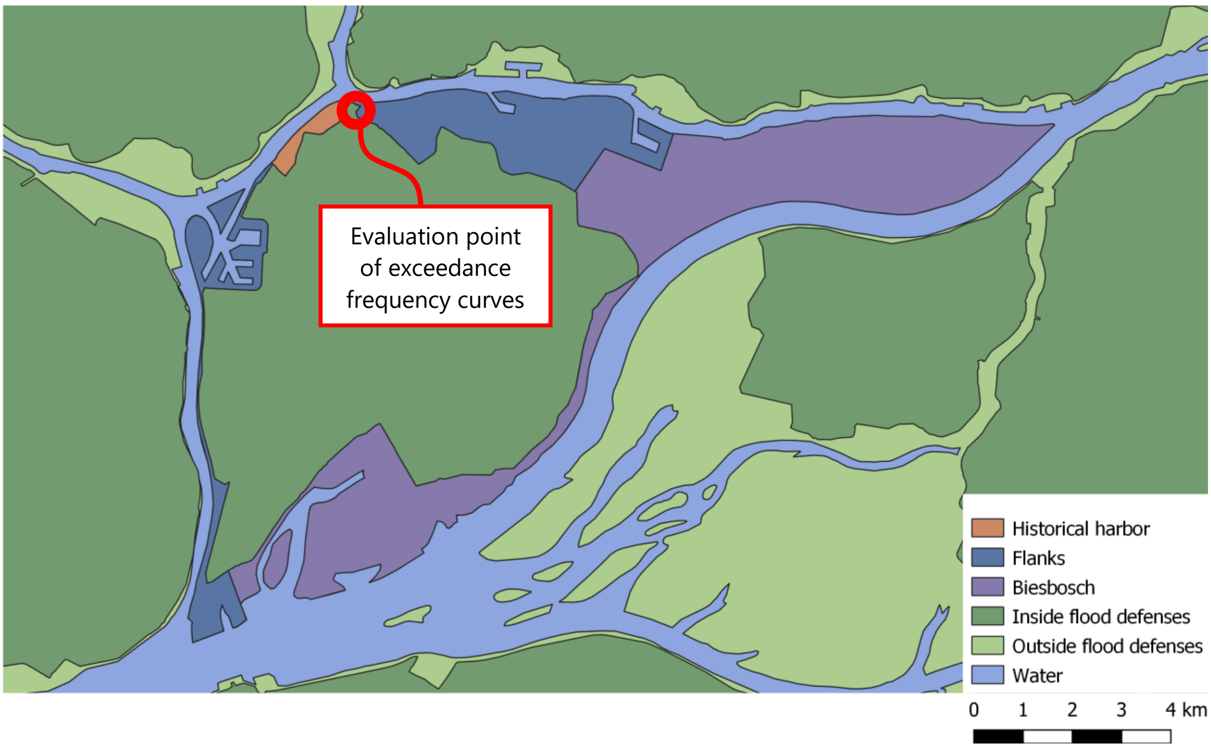


Figure 3.1 Map of unprotected areas on the island of Dordrecht with three classifications. (Buijs, 2021)

A majority of the potential damages lie around the historical harbour, with also the flanks having a concentrated value close to the harbour. Furthermore, at that location a full probabilistic evaluation of exceedance frequencies is available from model computations in various variations and scenarios. Therefore, the Biesbosch area is excluded from this basic risk estimation. The historical harbour and flanks border the Oude Maas, Beneden Merwede, and Dordtsche Kil. The exceedance frequencies at these branches are fairly well described by the marked evaluation point, assuming concentrated value around this location. Additional saving in the Biesbosch area is possible and recommended for more detailed estimates, but requires separate evaluation of exceedance frequencies, as the behaviour of the Nieuwe Merwede is significantly different.

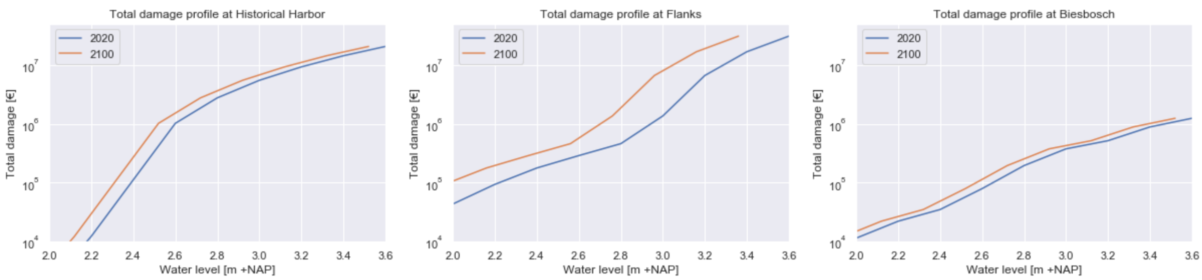


Figure 3.2 Damage profiles for every flood prone region not protected by flood defences for the year 2020 and 2100 (Buijs, 2021)

Summing the damage profiles from Figure 3.2a and b produces a total damage profile that is used in subsequent calculations. Figure 3.3 presents the profiles for the years 2020 and 2100.

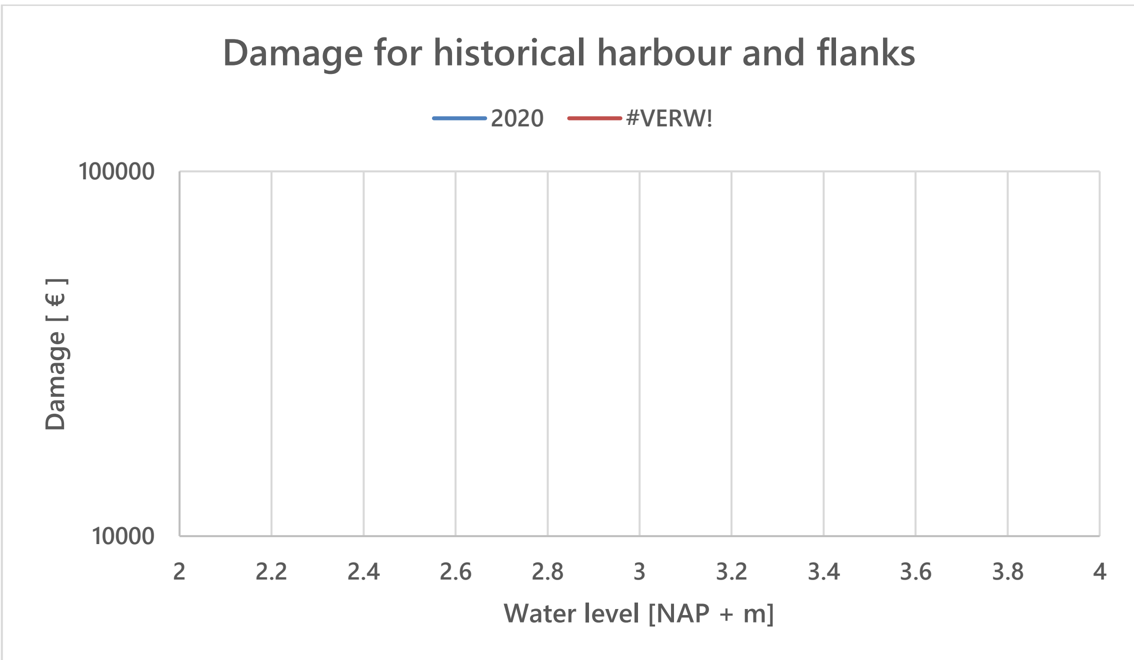


Figure 3.3 Damage estimates for Dordrecht for extreme water levels.

The damage profile is combined with a water level exceedance frequency curve for Dordrecht to produce the function D(f) in Equation 3-1 .

3.2 Contributions of Delta21 to cost saving strategies

3.2.1 Influence on the Europoortkering

Section 3.1.1 describes three distinct ways of extending the Europoortkering's lifetime that Delta21 could support. The following sections describe qualitatively how Delta21 contributes to each of these approaches. The magnitude of the defined contributes are subsequently assessed quantitatively in Chapter 4.

Reducing closure frequency per year

The closure frequency of the Europoortkering per year depends on two aspects:

1 The marginal distributions of the boundary conditions (river discharge and max sea level; see Chapter 2.1.1)

2 The closure function: a line that indicates for what combination of boundary conditions the Europoortkering needs to close. It can be plotted in a graph with boundary conditions as its dimensions, similar to Figure 2.3.

Delta21 obviously cannot change the development of the boundary condition distributions, they are merely a function of climate change. However, the closure function can be influenced. When Delta21 escalates (‘*turns on*’) before the Europoortkering does, the betrekkingslijnen might change. In other words, water levels are reduced by Delta21 alone, which may in some cases be enough to no longer need an Europoortkering closure. Because the closure criteria of the Europoortkering are defined at Rotterdam and Dordrecht, significant effects of Delta21 need to be visible at these locations to ensure a closure of the Europoortkering is not required. It should be noted that this will in some cases imply that water is being pumped out by Delta21, but flows freely back in through the Nieuwe Waterweg. Optimization however falls outside the scope of this thesis, which merely aims to investigate whether a closure frequency reduction is possible at all.

Reducing failure probability per closure request

The probability that the Maeslantkering fails upon request, which in turn determines almost fully the failure probability of the Europoortkering, consists of three primary contributors (Ministerie van Infrastructuur en Milieu, 2012) (Sewberath-Misser, 2022):

1 Failure to close upon request. This includes all the moving subsystems (e.g. the locomotive) and operational control software.
2 Structural failure.
3 Ball joint failure.

Sewberath-Misser (2022) provides detailed fault tree analysis of the Maeslantkering, of which a copy is provided in Appendix O. Among the three, the first has by far the largest contribution to the overall probability. Both the software and movable systems are responsible for this in comparable orders of magnitude. Second is the ball joint, which fails when a negative water level gradient occurs. Structural failure is almost negligible. The ball joint failure is not synonymous with a failure to close immediately. It only does when a second storm peak hits after the sudden withdrawal of the first peak, or another storm entirely hits before the joints can be repaired. Because of this, the current flooding probability of Rotterdam for example is determined almost completely by the failure to close upon request (1).

The systems that control the closure operation do however contain catches to prevent this ball joint to fail during a single event, and simultaneously discharge some additional water. The operation is called *spuien*. When spuien is followed by a second full closure, it can be referred to as intermittent spuien. It performs this operation whenever the water level on the river side of the Maeslantkering exceeds that on the seaward side. This however does add a layer of complexity to the software. With Delta21, it may be possible to prevent the inner water level to rise above the outer one before the end of the storm. Sewberath-Misser (2022) estimates that a complete omission of these catches in the operational control software could yield a 7% reduction of the partial failure probability. It would be necessary to demonstrate that the probability of needing intermittent spuien is particularly small or near-zero though.

Delta21 also has another effect on the probability of failing to close, because it affects the timing of the closure procedure. Currently, the Maeslantkering closes during near-zero flow speeds during ebb, a ‘*kentering*’. For higher river discharges, the sea water level must rise higher to reach this condition, and therefore occurs later in time. Delta21 is capable of rerouting a part of the river discharge, therefore bringing the moment of closure ahead in time. In addition to this, when Delta21 is able to pump or store the full river discharge, a closure during a previous ebb might even be possible, because the water level in the delta is not expected to rise once the storm surge barriers are closed. Earlier closure may imply a more controlled situation (for example, wind speeds and waves are not yet exceedingly high) and in the case of small subsystem failures, more time is available to improvise quick solutions.

Quantifications of how strongly an earlier closure moment affects partial failure probabilities is not readily available in literature. Detailed assessments of weak points within these systems are confidential, and no dedicated research has been done to indicate how sensitive their respective failure probabilities are to weather conditions. Therefore, this research will first attempt to demonstrate how large the potential difference in timing is, and provide further recommendations in the context of Delta21.

Influencing the borders of the region dominated by the Europoortkering failure probability

The failure probability of the Europoortkering dominates the height of the exceedance frequency curve inside the area of Figure 2.5 indicated with '*Failure*'. Research by Botterhuis et al. (2012) indicates that in the current system a failure probability reduction has a quickly diminishing impact outside the failure-dominated area (also see Figure 2.4). Several aspects of the hydraulic system can change the location of this area. The first is of course, the distribution changes of boundary conditions themselves as a result of climate change. This is however not so much a design option, but rather a scenario imposed on the delta. There remain two ways in which Delta21 can influence the illustrative conditions in the delta, and thereby change the size of the failure-dominated area.

The first is a mitigation of the effect of a Europoortkering failure. Failure probabilities of all other barriers are assumed negligible in comparison to the Europoortkering. Therefore, Delta21 keeps on discharging as long as the closure criteria as still met by predicted water levels. In other words, when the Europoortkering fails, Delta21 will attempt to mitigate the rising water levels as the storm intensifies. How effective this is depends of course on the boundary conditions and location where it is evaluated, and is further investigated quantitatively in Section 4.3. When the result of a failure is sufficiently mitigated, illustrative conditions will depend more on the other parameters, such as storage and river discharge.

The second effect is similar to the first, but enlarges the sphere of influence of the Europoortkering failure probability. Delta21 directly influences the storage characteristics of the system, as well as the discharge capacity. This means that the 'strength' of their influence is decreased. Storage and river discharge are less problematic in a range of conditions, in the way that they no longer contribute as heavily to illustrative conditions. What takes over, is the third parameter: Europoortkering failure probability with sea level statistics. Once again, the effect's magnitude depends on the configuration of Delta21 and differs per location and climate scenario. Section 4.3 investigates which of these effects outweighs the other in the current and future climate scenario.

3.2.2 Reduction of normative hydraulic loads at embankments

During storm events, Delta21 can be utilized to block the storm surge while discharging and storing river water. This in turn keeps the water level in the tidal lake low, preventing a backwater effect in the upstream branches of the delta. This reduces the peak water level during the event relative to the current system for a range of locations and conditions. The result is a shift in the water level exceedance frequencies, which implies attenuated hydraulic loading statistics and more specifically: a reduction in the water level at normative frequencies. As explained in Section 3.1.2, the reduction in water level can be translated into a reduction in failure probability. The consequence is an obviated requirement to reinforce (for a specific failure mechanism), and therefore saving on costs. Naturally, the dimensions and capacities of Delta21, as well as the criterion and timing of its employment, influence how large the reductions at each location are. Different structural design and operational variations of Delta21 are modelled and analysed in Chapter 5. Several separate contributions to the obviation of reinforcements are considered, and briefly described in the following paragraphs.

Current HWBP (2023-2050)

Resulting from the latest round of dike assessments - the WBI2017 - about 1500 km of dike has been disapproved and requires reinforcement (HWBP, 2023). The High Water Protection Program (HWBP) aims to have completed these by 2050. Currently, merely 13% of these projects have been completed, and 11% are in progress of physical reinforcement. 43% is budgeted and possibly in design stages, with the remaining 33% yet to appear on the planning at all. The majority of these disapproved dike segments therefore still offers the potential of obviated costs by Delta21. If no longer disapproved in context of the WBI2017 (see also Section 3.1.2), savings are attributed to Delta21 on a short term: up to 2050.

Future (2050-2100)

In a future climate scenario, water level exceedance frequency curves will increase again. Comparing a system to itself in the current climate, new reinforcements will be necessary due to increased failure probabilities. However, a system with Delta21 will expectedly require many less kilometres of additional reinforcement than the current system. The difference between those two figures can be attributed to cost reductions by Delta21 on the long term (2050-2100). Note that if a dike is not reinforced within the HWBP because of Delta21, it may still need reinforcement in the future scenario, whereas the current system does not include double reinforcements. For details review Section 3.1.2.

Synergy with an improved Europoortkering

Similarly to how Delta21 may positively influence the failure probability of the Europoortkering, a failure probability reduction of the Europoortkering may positively influence the reductions due to Delta21 (Delta21 v.o.f., 2021a)

(Buijs, 2021). Delta21 is expected to expand the region where a failure probability reduction has significant impact on the water level at normative frequency, and Buijs (2021) finds that for at least Dordrecht a larger dependency on Europoortkering failure is found in a Delta21 system. Therefore, additional reinforcements obviations may be attributed to Delta21 both on a short and long term. This should of course be corrected for, because a part of these obviations must be directly attributed to the failure probability reduction of the Europoortkering itself.

Volkerak-Zoommeer

An extraordinary reduction in reinforcement costs can be found in the area of the Volkerak-Zoommeer, due to its secondary water storage function. Due to this development, surrounding embankments are burdened with increased water level exceedance frequencies and an additional (often stricter) norm. With Delta21 however, the additional storage is arguably no longer needed. Corresponding embankment reinforcement costs were initially expected to be around 31.3-71.1 million (Nieuwenhuijzen & Bos, 2004b) (Nieuwenhuijzen & Bos, 2004a), but reports from Rijkswaterstaat (2011) later designated far fewer necessary adaptations. Currently, dikes on the eastern side of the Volkerak-Zoommeer have completed the required reinforcements (Montfoort, et al., 2022a&b), whereas the western dikes have been assessed positively with large margins regardless of the additional storage functionality (Bossenbroek J. , 2020) (Smorenburg, Kampman, & Broek, 2022). The stability assessment of the three dams is either positive with large margin (Albers, 2022a&b), or not dependant on conditions at the Volkerak-Zoommeer side (Pleijter, 2022).

Summarized, the current situation does not provide any potential for saving on costs with Delta21. In the future however, the usage frequency may triple in 2050 (Rijkswaterstaat, 2011), and increase even further towards 2100 in the W+ scenario. Rijkswaterstaat will already evaluate a change in upstream usage criterion by 2030. This implies no further increased loads on the dikes surrounding the Volkerak-Zoommeer. It however also means a rise in water level exceedance frequencies in the Haringvliet and Hollandsch Diep, leading to additional reinforcements regardless. With Delta21, the frequency by which the lake is used in this fashion may drop substantially, preventing the need to reinforce.

3.2.3 Decrease water levels exceedance frequencies unembanked areas

Delta21 reduces peak water levels for a range of conditions, including those that are not normative for dike segments. This means that the entire exceedance frequency curve exhibits a downward shift. Because the average risk is determined by integrating this curve with a damage profile, reductions at all frequencies contribute towards savings. The largest contribution may be found far from the nearest dike trajectory norm. Nevertheless, the sensitivity analysis of Chapter 5 is based on reductions at normative frequencies. This is because the obviations of dike reinforcements are expected to generate a (far) larger share of the total savings by Delta21.

Because the preliminary configuration of Delta21 is set to be employed at a criterion of NAP + 2.5 m at Dordrecht, limited damage reductions are expected for the higher frequency events. Similarly, for extremely small frequencies, the reduction may be limited by the end of the damage profiles. This indicates a state where in theory 'everything is broken', so an increase in water level no longer corresponds to an increase in damage.

In determining the closure criterion for Delta21, some attention is paid to the effect at unprotected areas in Dordrecht. The variations of Chapter 5.3, which deal with the operational control of barriers, indicate significant changes on the exceedance frequencies at Dordrecht. Therefore, various damage calculations are performed to also include this effect, and estimate the sensitivity. The reduction of water level exceedance frequencies works effectively the same in the current and future climate, although its magnitude may of course be dissimilar.

3.3 Concluding remarks

Delta21 has three primary strategies to reduce costs related to flood protection. It contributes to all with its enhanced discharge and storage in order to attenuate peak water levels. Per strategy, reductions in specific conditions weigh towards a saving most heavily. The most sizable contributions to a strategy originate from water level reductions in specific conditions:

1 Extending the Maeslantkering's lifetime - reduced water levels decrease the (double) closure frequency, and hence the failure probability. Additionally, synergetic effects between Delta21 and the Europoortkering may prolong its lifetime
2 Fewer dike reinforcement km's - reduced water levels at a normative exceedance frequency leads to lower failure probabilities through fragility curves, obviating the need for reinforcement.

3 Reduced expected damage - reduced water levels at all frequencies give a smaller integrated result for the expected damages at the unembanked areas of Dordrecht.

4 THE INFLUENCE OF DELTA21 ON THE EUROPOORTKERING LIFETIME

3. What is the influence of Delta21 on the lifetime of the Europoortkering?

This chapter analyses if and to what extent Delta21 accomplishes three distinct ways of extending the Europoortkering's lifetime (see Section 3.2.1). The hydraulic model is used to produce data on the Europoortkering's behaviour in the range of boundary conditions. Differences between these results for a system with and without Delta21 indicate if and how effective Delta21 prolongs the lifetime of the Europoortkering.

- For question 3a, Section 4.1 dives into possible strategies to reduce the failure probability per closure due to a simplified operational control and calmer closing conditions.
- For question 3b, Section 4.2 analyses the change in closure frequency of the Europoortkering.
- For question 3c, Section 4.3 reproduces water level exceedance frequencies with a decimated Europoortkering failure probability, to assess how the impact of such a measure changes with Delta21.

4.1 Improving Europoortkering's failure probability per closure

Section 3.2.1 describes how a reduction of failure probability per closure can be achieved with Delta21, and boils down to two distinct methods assessed in the following sections:

1. Simplify the closure procedure to reduce the failure probability of the operational control
2. Closing earlier during more manageable circumstances

4.1.1 Simplification of the closure procedure by obviating double closures

If Delta21 can manage to remove the chance for situations where a negative water level gradient is temporarily present over a closed Maeslantkering, the operational control can omit the checks and corresponding procedures to deal with this. A double closure is found by searching the MHWp5 model results for instances of '*intermittent spuien*[1]'. A double closure means that the Maeslantkering has two (or more) instances where the barrier rests on its sill. Intermittent spuien means that the barrier may have attempted to close, only to soon after open again. While the latter may be caused by computational oddities, the requirement is always a negative head difference, which is exactly the situation that should no longer occur for a simplified control.

Figure 4.1 presents the boundary condition combinations for which intermittent spuien due to a negative water level gradient occur in the current system (I.), and a system with Delta21[2] (II.). The corresponding frequencies per year and number of calculation points are given in Table 4.1. The calculated frequencies are particularly low (smaller than once in 10,000 years) and therefore cannot be accurately estimated in Hydra-NL. The number of calculations that exhibit the behaviour is also very low, further reducing the reliability of these estimates.

Table 4.1 Double closure and intermittent spuien frequencies of the Maeslantkering in the current system and preliminary configuration

Configuration	Intermittent spuien calculation points [total: 54]	Intermittent spuien frequency [per year]
Current system - I.	5	[$<10^{-4}$]
Delta21 - II.	4	[$<10^{-4}$]

Due to the limited accuracy of these values one should only attribute meaning to significant relative differences. It can be concluded that for events as extreme as these, the MHWp5 model can simply not provide meaningful and significant insights into changed frequencies, let alone improved failure probabilities as a result of them. There is no clear disappearance of the situation where the inner water level at the Maeslantkering temporarily exceeds that on the outside, so obviating this from the operational control is not possible.

In the future climate scenario no change is expected to this conclusion. Average water levels in an open delta system are allowed to rise along with sea level rise, and there is no strong reason to change the schematization of the storm

[1] Dutch term for lifting the barrier doors to allow seawards directed underflow of water.
[2] The preliminary configuration, see Section 2.1.3

shape and phase. Moreover, the closure criteria of the Europoortkering are met far more often due to sea level rise, and the frequency of double closures only appears to grow, not shrink. (See also Appendix H).

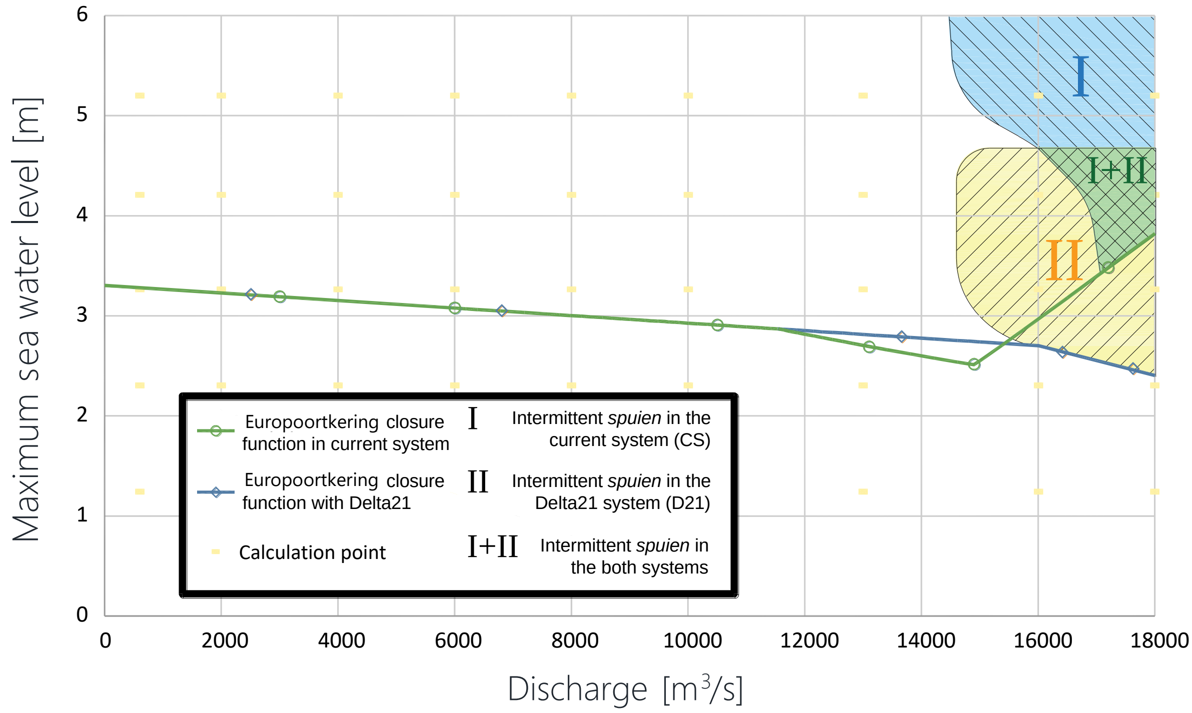


Figure 4.1 Domain where the Maeslantkering exhibits intermittent spuien

4.1.2 The effect of earlier and longer closures on failure probability

The Maeslantkering closes during near-zero flow speeds during ebb, a '*kentering*'. For higher river discharges, the sea water level must rise higher to reach this condition, and therefore occurs later in time. Delta21 is capable of rerouting a part of the river discharge, therefore bringing the moment of closure ahead in time. In addition to this, when Delta21 is able to pump or store the full river discharge, a closure during a previous ebb might even be possible, because the water level in the delta is not expected to rise once the storm surge barriers are closed. Earlier closure may imply a more controlled situation (for example, wind speeds and waves are not yet exceedingly high) and in case of small partial failures, more time is available to improvise quick solutions.

Quantification of how strongly an earlier closure moment affects the failure probability of closing is not readily available in literature. Principally, the probability that the Maeslantkering fails to close on request consists of failure probabilities of moving subsystems (e.g. the locomotive) and operational software systems (labelled BOS and BESW in Appendix O). Detailed assessments of weak points within these systems are confidential, and no dedicated research has been done to indicate how sensitive their respective failure probabilities are to weather conditions. Nevertheless, some estimates of changed closure times are calculated to see whether said research might be recommended in the context of Delta21.

First of all, Figure 4.2 presents the boundary condition combinations for which the moment of closure for the Maeslantkering is recalculated, and corresponding time in hours that it is preponed. The preliminary configuration is used for this (see Section 2.1.3), which has dissimilar closure criteria for Delta21 and the Europoortkering, allowing for the longest time changes. For a significant number of boundary conditions the moment of closing is preponed by 0.5 to 3 hours due to Delta21 changing the moment of low water at the Europoortkering. This time tends to be largest for smaller storm surges, but of course disappears for surges so small the barrier does not close at all. One or two extra hours for closing the Maeslantkering is not assumed to make a significant difference in the probability that it fails to close. A more detailed exposition of the calculation is presented in Appendix L.

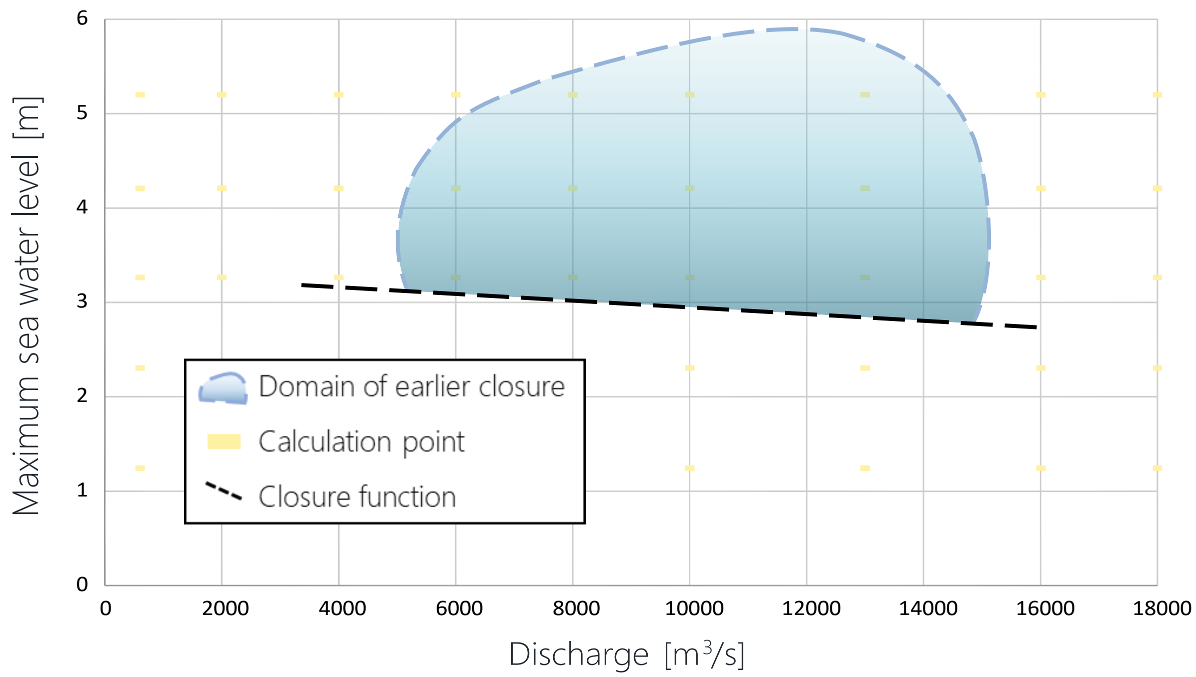


Figure 4.2 Boundary condition domain for which earlier closure of the Europoortkering is achieved with Delta21 (preliminary config)

The second option regards closing the Maeslantkering a previous tidal low water. Note that flow speeds are also near-zero during tidal high water, but closing in such a condition would yield a far high starting water level and require far more discharging during the event. There are however some critical concerns with this adaptation and therefore not considered further:

- The prediction timescale of the MHWp5 generator is 24 hours. This accurately represents the real operational software systems, which do not have predictions that go further into the future than 24 hours too. The **second**-to-last tidal low water before water levels exceed closure criteria is +/- 12 hours earlier, which means that in many calculations the decision to close is not yet made. The Maeslantkering will hence default back to closing during the last tidal low water.
- Closing earlier and using Delta21 to pump[1] away the full river discharge for 12 hours is a particularly costly procedure. The profits of this adapted closure control are difficult to quantify, and there is no strong reason to expect that they will be equally or more significant. For further research, it should be sufficient to assume the procedure is possible for conditions where river discharge is lower than the pumping capacity. Optimization of the control falls outside this research's scope.

On a final note, lower closure criteria for the Europoortkering will effectively lead to earlier closure as well in numerous cases. This however is not considered an effective approach to prolong the Maeslantkering's lifetime, because the increase in closure frequency is far greater than the reduction in failure probability per closure. Section 5.3 deals with variations in operational control, which not only effect the Europoortkering itself, but also water level exceedance frequencies.

4.2 Reducing the Europoortkering's closure frequency

As Section 2 briefly describes, determining the frequency of a certain event (for example, the closing of a storm surge barrier) can be computed easily within Hydra-NL. It is merely required to know the marginal distribution of boundary conditions and the set of boundary conditions for which a certain event occurs. The border that delineates this set is hence called a *closure function*; or more generally an *escalation* function (when the concerned event is not a barrier closing). For more detailed stepwise computations the reader is referred to Appendix H.

For the Europoortkering, the closure function is determined by its closure criteria: NAP + 3 m for Rotterdam or NAP + 2.9 m for Dordrecht. The *betrekkingslijnen* (water level equal to a certain criterion when the Europoortkering stays open) for these criteria form the basis for the closure function. They are presented in Figure 4.3. The closure function

[1] Note that every single litre of water that is allowed to flow over the spillway has to be pumped into sea sooner or later, regardless of whether this is during a storm event or long after.

of the Europoortkering is the border delineating the striped area in the figure. Above this border, the Europoortkering closes. The function is defined by the minimum of the DORD_2.9 and RDAM_3.0 lines, because either event is enough cause to close the barrier. In the current system (without Delta21) this curve is determined largely by Rotterdam, and only by Dordrecht for discharges exceeding 12.000 m^3/s (this is where the *betrekkingslijnen* intersect). Additionally, the black line represents the function where discharges are so high that a moment of *kentering* never occurs[1]. To the right of this line the Europoortkering never closes because it would not lead to lowered water levels in the delta.[2]

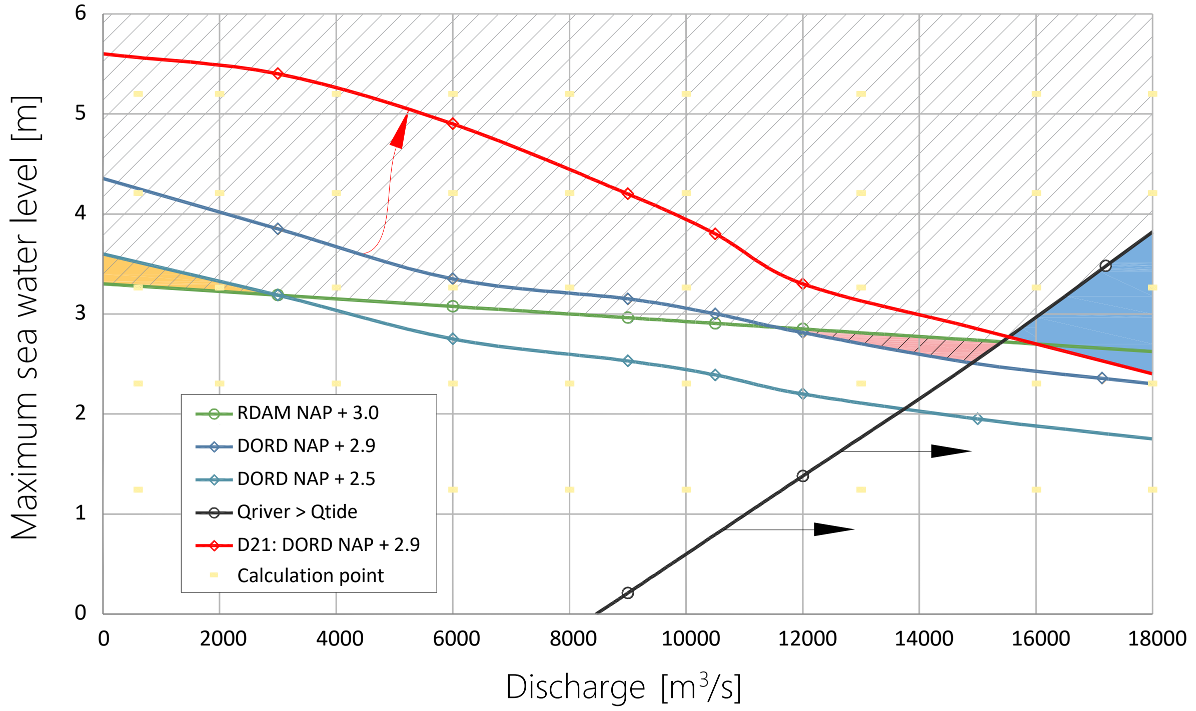


Figure 4.3 Escalation domain grid For the Europoortkering and Delta21

As can be seen in Figure 4.3, the *betrekkingslijn* for Dordrecht reaching a level of NAP + 2.9 m shifts in a system with Delta21, because Delta21 already escalates before that level is reached. The new function is drawn in red. This leads to a changed closure domain for the Europoortkering, whose function is now determined by Rotterdam up until discharges of +/- 15.000 m^3/s. The subtracted area is shaded red. Furthermore, the black line is expected to shift far towards the right and disappear from the figure altogether as Delta21 is particularly proficient in dealing with high discharges. The result is an addition to the Europoortkering closure domain shaded blue. These shaded areas are responsible for changes in closure frequencies.

The closure frequency of a barrier can be calculated with its closure function, and the joint probability density of the area it delineates. It is however crucially important to note how many calculation points lie in or around the functions, presented in the background of Figure 4.3. A total of 54 calculations (the upper row above NAP + 6 m is omitted in Figure 4.3) is performed. Interpolation between these points yields a decent visualization, but the spacing between calculation points is inadequate to give highly accurate quantitative estimations, especially for small areas such as the ones described above (which are unfortunately also the most interesting). Therefore, results are to be interpreted with care and only large deviations can be considered significant.

Table 4.2 presents the computed closure frequencies for the Europoortkering in the current system and with the preliminary configuration of Delta21. The number of calculation points sufficient to provide acceptable accuracy. The model tends to yield closure frequencies that are lower than those computed with WBI2017 datasets, because of the manner in which local wind speed and direction are included. The results must therefore be interpreted in relative sense.

[1] Flow velocities though the Nieuwe Waterweg are always positive (i.e., sea directed), so continuous outflow.

[2] The MHWp5 model is not able to reproduce these conditions. Therefore, the line is obtained from closure domain figures from unpublished Rijkswaterstaat literature.

Due to Delta21 in the preliminary configuration, the Europoortkering closure frequency rises slightly. The change is however too small to conclude a significant difference with adequate certainty. Three phenomena contribute to the rise in frequency:

1 As shown above with the blue and red shaded areas of Figure 4.3 a different closure domain is achieved
2 The tidal prism in the Haringvliet changes because of the different inlet geometry and dredged profile. Combined with the simplified Haringvlietsluizen schematization, this leads to a slightly larger tidal range at Rotterdam and Dordrecht.
3 Because of 2, some calculation points now fall just within the escalation domain, which they did not before. This has a somewhat unrealistically strong effect on the interpolated closure function, as a result of the small number of points.

Table 4.2 Closure frequencies of the Europoortkering in the current system and preliminary Delta21 configuration in the current climate

Configuration	Closure frequency in current climate	Closure frequency in the future climate scenario
Current system	once every 26 years	0.6 times per year
Delta21	once every 24 years	0.7 times per year

The closure frequency of the Europoortkering is of course expected to rise in the future climate scenario. However, the closure function in Figure 4.3 stays more or less the same. The marginal distributions of the se water level and discharge experience a shift, but not necessarily the conditions under which the barriers need to close. Therefore, similar to how Delta21 has little effect on the closure frequency of the Europoortkering in the current climate, it also does not in the future.

4.3 Delta21 influence on sensitivity to changed failure probability

In the area in Figure 2.5 indicated with '*Failure*' the failure probability of the Europoortkering dominates the height of the exceedance frequency curve. Introducing Delta21 might change the borders of this area. To examine where and by how much the borders shift, one can look at the effect of a failure probability reduction on water levels with a return period of 30,000 years. As Appendix M explains in more detail, lower return periods tend to show the same but weakened results. Many normative frequencies around the failure-dominated area are quite large, and for more extreme conditions the effects of the Europoortkering failure probability become more visible.

Figure 4.4 presents the borders where a certain reduction (return period 30,000 years) is exceeded by decimating the failure probability of the Europoortkering. Naturally, closer to the Europoortkering the reductions are largest.

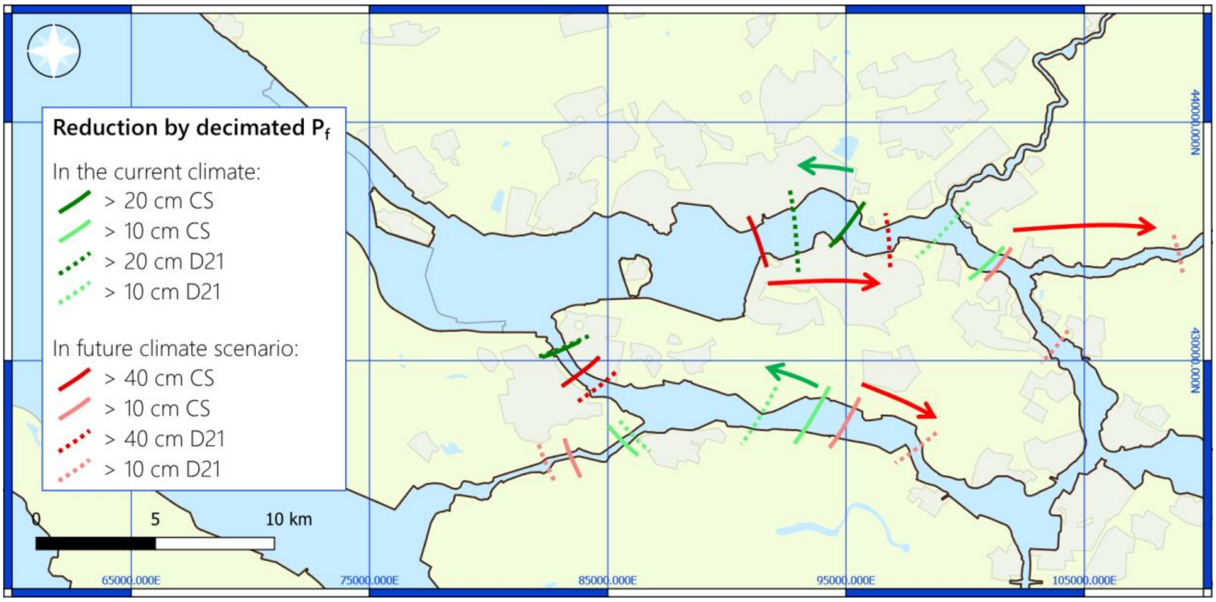


Figure 4.4 Borders of reductions on water levels with return period 30,000 years by decimating the Europoortkering failure probability

In the current climate, a decimation of the Europoortkering failure probability yields results of up to approximately 0.3 m (see Appendix M). This is true for a system with and without Delta21. However, as can be seen in Figure 4.4, the area that benefits from 0.1 m or 0.2 m reduction at a return period of 30,000 years, is slightly smaller for the Delta21 system. failure of the Europoortkering is slightly mitigated in some conditions and the result of a decimation is pushed back geographically. The change is however quite small.

In the future climate scenario, the influence of the Europoortkering's failure probability becomes greater in both systems, simply because the sea level rises. The influence of this boundary condition grows, and thus so does that of the Europoortkering's failure probability. This time however, Delta21 has a different effect of the area that experiences results from a decimated failure probability. It is allowed to extend further into the transition region, especially eastwards. The influence of storage characteristics and/or river discharge have decreased relative to the failure probability. Nevertheless, the effect is still not particularly significant. Remember that Figure 4.4 presents an amplified picture, and changes are not nearly as noticeable for smaller return periods (also see Appendix M).

Nevertheless, a small synergetic effect indeed seems to occur when the failure probability of the Europoortkering decreases further in a future climate scenario. Take for example illustrative normative conditions for Spijkenisse, which lies around the border of the failure-dominated region. In the future climate scenario the reduction at return period 30,000 years is amplified in a Delta21 system by 6% (Europoortkering P_f = 1:1000) to 32 % (Europoortkering P_f = 1:10,000). Illustrative conditions are exceedingly less determined by a situation where the Europoortkering fails in the current system, but not in the Delta21 system. Therefore, the area remains failure-dominated, and obtains larger yields from subsequent decimations. For details on this also see Appendix M.

In summary. the area in which the failure probability of the Europoortkering dominates normative hydraulic conditions for embankments does not significantly change in a system with Delta21, but tends to exhibit a small growth in the future climate scenario. A larger area implies that reinforcement/replacement of the Maeslantkering is **more** effective, so concluding a lifetime increase in order to save funds is not shown to be likely by these results. Note that there **are** some minor signs of synergetic effects, meaning that larger yields for Delta21 can be expected in a system which also has a Maeslantkering with a low failure probability. This is treated in Section 5.2.4.

4.4 Concluding remarks

Delta21 does not have a significant impact on the failure probability per closure of the Maeslantkering (which determines the failure probability per closure of the Europoortkering). Neither does it particularly change the region where a change in this failure probability is noticeable. Finally, the closure frequency of the Europoortkering is dominated by the closure criteria in Rotterdam and sea level statistics in both a system with or without Delta21. Hence, the influence of Delta21 on the closure frequency is negligible. Of course, if the operational control of the Europoortkering is changed, this does affect the closure frequency, but this is not attributable as a direct result to Delta21.

5 REDUCING WATER LEVELS AT NORMATIVE FREQUENCIES WITH DELTA21

4. What is the effect of Delta21 on water levels at normative frequencies in the current and future climate scenario?

The following chapter answers the fourth set of sub questions by producing exceedance frequencies for a variety of configurations and climate scenarios with and without Delta21. Focus lies on effects around normative frequencies as these will subsequentially be used to formulate reductions in failure probability and hence cost-reductions.

- For question 4a, Section 5.1 presents the effects on water level exceedance frequencies of the preliminary configuration of Delta21
- For question 4b, Section 5.2 analyses how these effects change for variations in the Delta21 design
- For question 4c, Section 5.3 analyses how these effects change for operational control configurations of Delta21
- For question 4d, Section 5.4 concludes with a sensitivity analysis to (longer) storm duration in a system with and without Delta21

5.1 Reductions in the reference preliminary configuration

As discussed in Chapter 3, to obviate dike reinforcements, reductions are required of extreme water levels at normative frequencies. In the most recent guidelines, not just *normative highwaters* (MHW's), but the entire exceedance frequency curve must be used to assess embankments. Nevertheless, MHW's are still very descriptive for the assessments. Besides that, no full probabilistic re-assessment is performed for every single dike section in the delta. Instead, fragility curves are evaluated at normative frequencies (also see Section 3.1 and Appendix J) to get a rough estimate of where reinforcements can be obviated, both in the current and future climate. Effects on MHW's are therefore sufficient input for Chapter 6.

The reductions in MHW's do not entail the whole story of Delta21's influence on water level development though. Insight into the effects of various configurations is desirable to properly answer research question 4. Therefore, additional analyses are presented that dive deeper into why certain effects are observed (or not) for every variation. The current and future climate are considered for every variation. The starting point is the current climate, accompanied in every case by a map of MHW effects. For the future climate scenario, additional computations are presented when the sensitivity of MHW's to a particular variation is significantly different.

MHW reduction for the preliminary Delta21 configuration

The answer to research question 4 commences with the preliminary configuration of Delta21 in the current climate. Not only does this provide a basic idea of the magnitude of MHW reductions, but it will also serve as a reference point for variations in the following sections of this chapter. Analysis of this preliminary configuration is also crucial for the selection of relevant variations. Table 5.1 repeats the characteristics of the preliminary Delta21 configuration.

Table 5.1 Preliminary configuration of Delta21 in the current climate

Delta21 design		Operational control		Other	
Spillway sill height	NAP - 4.5 m	Closure criteria D21	Dordrecht NAP + 2.5 m	Storm duration	30 hours
Spillway width	2700 m	Closure criteria Europoortkering	Dordrecht NAP + 2.9 m OR Rotterdam NAP + 3.0 m	Europoortkering failure probability	1:100
Storage lake volume	400 E10^6 m^3			Division at Pannerden	standard
Pumping capacity	10,000 m^3/s				

Figure 5.1 presents the effect that the preliminary configuration of Delta21 has on water levels at normative frequencies throughout the Rhine-Meuse Delta. A more extensive presentation, accounting for all frequencies, is attached in Appendix G. Several important notes are made with regards to these results, prior to heading into the sensitivity analysis.

First of all, attention is drawn to the spatial distribution of reductions in general (see Appendix G) and at normative frequencies (Figure 5.1). Delta21 yields a reduction of extreme water levels throughout the Rhine-Meuse delta, but the spoils are not spread out evenly. The effects are most noticeable in the storage dominated and transition region, and increase for larger return periods. A concentration of large reduction is found around the Kuipersveer in the Oude Maas, but can best be neglected as the employed model does not perform with adequate accuracy here as shown in Appendix C.

The reduction in any location has a maximum value equal to the difference between the maximum water level in the current system and the maximum water level in 'daily' conditions for a particular constant discharge boundary. If Delta21 manages to reduce the water level during a storm below this tidal high water level, the peak water level will take place before or after Delta21 is active. Therefore, no further reduction can be accomplished. Continuing to reduce water levels during the event ultimately does not provide any additional yields. Therein lies a large optimization potential for the employed schematization in this research, where this behaviour is not uncommon.

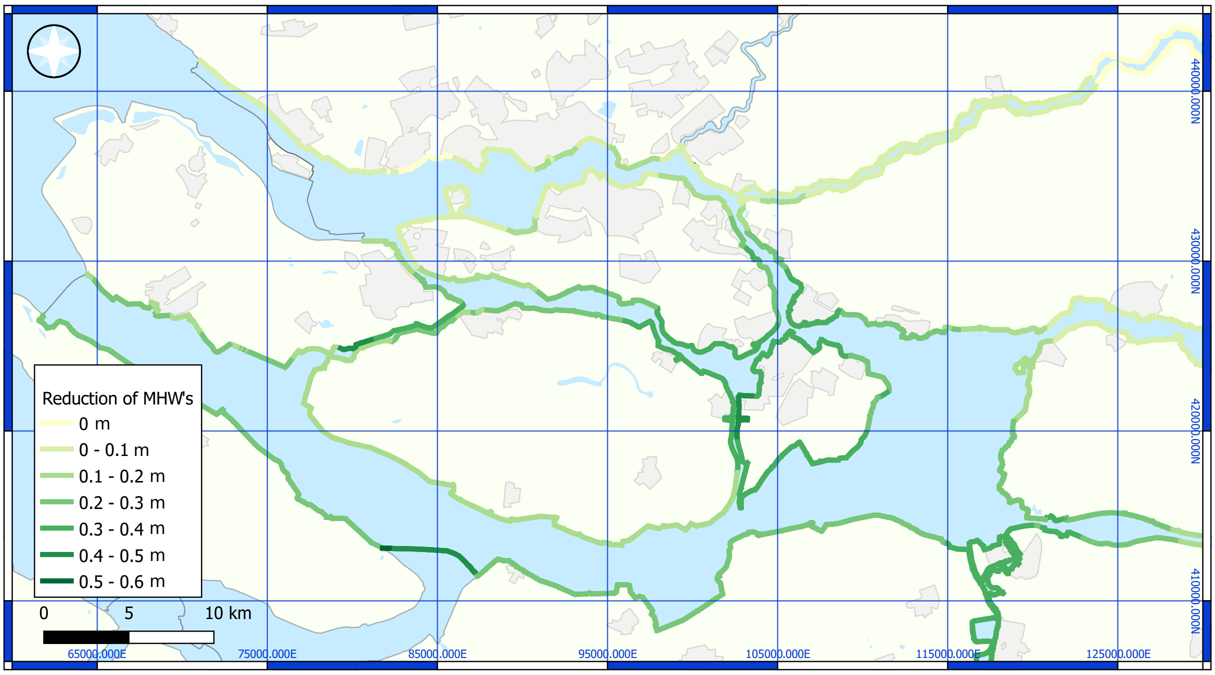


Figure 5.1 Reduction of MHW's in the preliminary Delta21 configuration

In the new system with the preliminary configuration of Delta21, illustrative conditions for numerous areas tend to shift. In particular, the influence of storage is reduced. The transition region river-dominated to storage-dominated becomes more river dominated. The new illustrative conditions are often those just below reaching escalation of Delta21, but with rather significant river discharges. This means on one hand that Delta21 is working as expected. After all, the influence of storage is mitigated. On the other hand, it also means that exceedance frequencies become even more reliant on specific conditions with water levels just below the escalation criteria in combination with reparation of the data in more extreme conditions. Section 2.6 describes this phenomenon in detail.

Interestingly, the largest reductions per return period are not found in the downstream parts of the Haringvliet (closest to Delta21), but in the Hollandsch Diep, especially for return periods larger than 1000-3000 years. Two explanations are given to elucidate this anomaly:

1 In the current system, the Haringvliet can immediately discharge to sea once the Haringvlietsluizen open after a storm, but water levels in the Hollandsch Diep will continue to rise for another couple of hours. With Delta21, this does not occur as discharge is continued throughout the storm event, hence larger reductions are achieved.
2 The hard limit to reductions as explained above is reached for the Haringvliet in numerous conditions with significant contributions to the MHW's. In the Hollandsch Diep, the difference between current illustrative water levels and tidal high waters for given discharge boundary is larger, and Delta21 addresses part of this larger potential.

Occasionally, Dordrecht will be singled out for examples of detailed analysis. It is an excellently suited representative location, centred in the transition region and therefore influenced by processes at sea, in the upstream rivers, and the downstream storage characteristics. Previous research into Delta21 has also focused on Dordrecht, making intercomparison easier. Furthermore, Dordrecht has a large amount of high value unembanked areas with densely populated zones. Exceedance frequencies at this location determine the magnitude of damage reduction in (see Section 6.3), which highlights the appropriateness of using Dordrecht as a representative location. Finally, Delta21 has just one closure criterion, which is defined at Dordrecht.

Figure 5.2 presents the difference in water levels at normative frequencies between the current system and system with Delta21 are both exposed to the future climate scenario. Naturally, in absolute terms these MHW's increase for both systems. Their respective change in relation to the current system in the current climate, is presented in Appendix O. Note that the closure criterion for Delta21 is raised to NAP + 2.9 m at Dordrecht for the future reference configuration. This is due to the computational lower limit for the criterion, which is treated in detail in Section 5.3. The relative difference is larger than in the current climate (review Figure 5.1), despite the raised closure criterion.

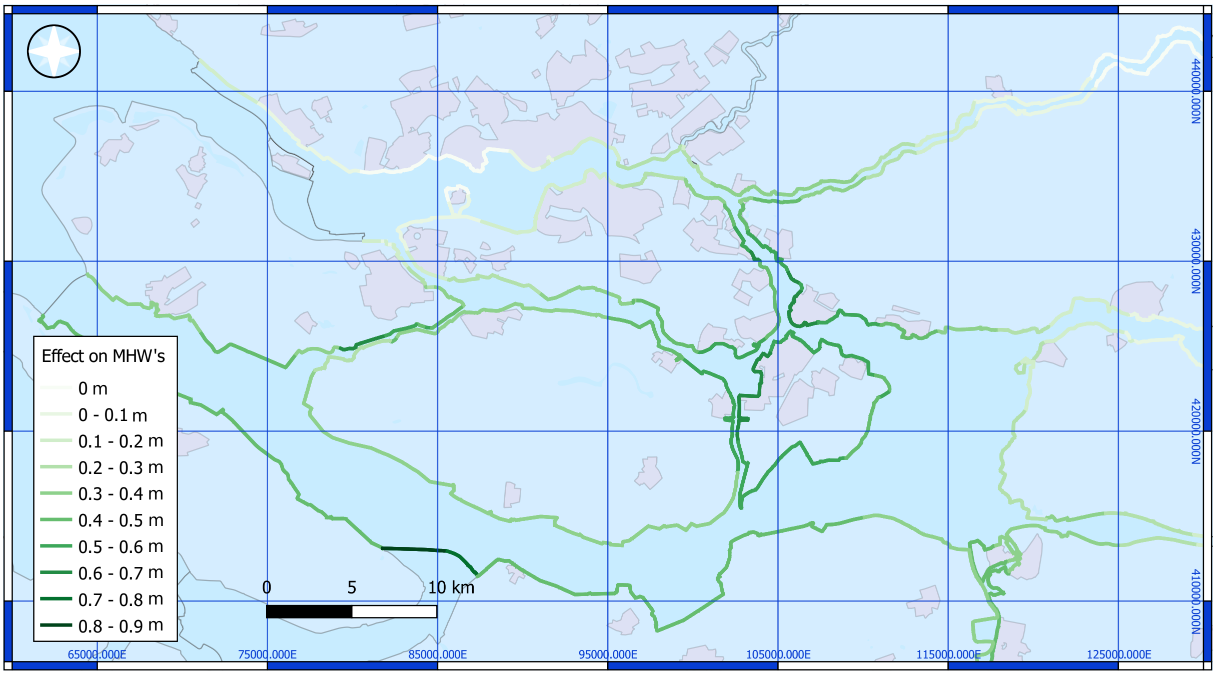


Figure 5.2 Reduction in MHW's in a system with Delta21 relative to the current system in the future climate scenario

Structure of sensitivity analysis

The following sections will treat different variations and analyse the sensitivity of reductions to them. Every variation will be structured similarly, leading with some considerations as to the magnitude and direction of a variation, followed by the effect on reductions, and ended with some more detailed investigation into causes for a concluded (in)sensitivity. Comments and if required additional research/calculations are incorporated for describing sensitivities in the future climate scenario.

The way of choosing a variations magnitude is somewhat makeshift. In for example a study by Rijkswaterstaat (2007a) into the sensitivity of the Rhine-Meuse delta to various parameters, variations were composed using primarily expert judgement. These variations are also very similar in character to the ones presented in this chapter, such as climate scenarios, schematizational assumptions, and changes to the Europoortkering. Any results are comprised to offer a **subjective** and **relative** insight into the (in)sensitivity to a certain variation. This chapter follows a similar approach, but an explanation for a certain magnitude and/or direction that a parameter is varied by is always given. Note once again that the goal of this research is not to optimize the design of Delta21, but to contribute insights to the understanding of how Delta21 works, plausibly to the benefit of streamlining the subsequent design process.

5.2 Reduction sensitivity to Delta21 design variations

This subchapter will assess the sensitivity of MHW's to variations in the component design of Delta21. The four components that together form the complete structural schematization of Delta21 are accounted for. The first two describe the storage capacity of Delta21: The total storage lake volume and pumping capacity. The second two describe the spillway and therefore direct influence on the discharge that Delta21 extracts from the hydraulic system: the spillway width and height. In addition, two other effects are investigated that do not strictly relate to the structural design of Delta21, but rather to broad synergetic effects with other plans. The first is the effect that Delta21 has in a system with a changed discharge division at Pannerden (Section 5.2.3). The second is the effect of Delta21 when both it and the reference system have a reduced Europoortkering failure probability (Section 5.2.4).

5.2.1 Sensitivity to Delta21's lake volume and pumping capacity

The ability of Delta21 to withdraw water from the tidal estuary downstream of the Haringvlietsluizen depends on how much storage volume is available in the storage lake. When the energy storage lake reaches its maximum capacity, the spillway will not be allowed to let more water overflow than the pumps can handle. How quickly and in what conditions this occurs, depends on the pumping capacity and total energy lake volume. In the preliminary configuration (review Table 5.1), these are respectively 10,000 m^3/s, and 400 million m^3. The effect of Delta21 pump failure has already been investigated previously and is excluded from the scope of this thesis.

In some cases where discharge over the spillway is particularly high, the Delta21 storage lake fills up to the maximum allowed level, leading to a reduced maximum spillway capacity. To get a sense of how often such events occur and in which conditions, Figure 5.3 presents the boundary conditions where the Delta21 storage lake is completely filled at a certain point in time. The preliminary configuration of Delta21 is used to obtain these results, with all Delta21 components functioning properly (no failure). Using the location where the closure criterion is defined (Dordrecht) as a distinguishing factor, three areas can be discerned where the storage lake reaches full capacity:

I. **before** the peak water level at Dordrecht occurs
II. **after** the peak water level at Dordrecht has passed
III. **only** in case of a Maeslantkering failure

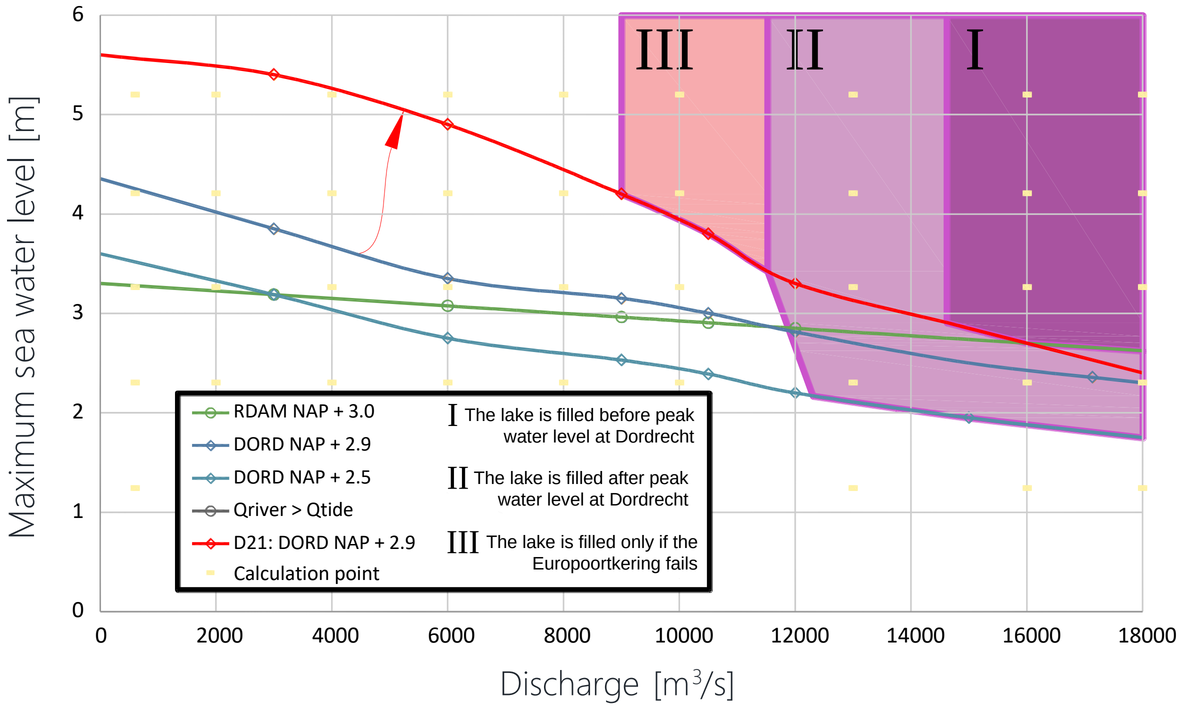


Figure 5.3 Domain where the Delta21 storage lake reaches its maximum capacity with several *betrekkingslijnen*[1]

Occurences tend to concentrate towards the top right corner of the figure, where marginal probabilities are low. Accompanying frequencies therefore are also not particularly large, as can be seen in Table 5.2. The frequency of I. is below 10^{-4} per year and cannot be computed accurately by Hydra-NL. Note that the added frequency by area III. is the product of the delineated joint probability of those boundary conditions and the failure probability of the Maeslantkering (in this case 1:100).

[1] These lines indicate for what boundary conditions a certain water level is reached when no movable components in the system escalate.

Table 5.2 Frequency estimations [per year] of the Delta21 storage lake reaching maximum capacity

Frequency of I. - before peak	Frequency of I. + II. - before and after peak	Frequency of I. + II. + III. - combined with Maeslantkering failure
[$<10^{-4}$]	4.83E-03	4.85E-03

The frequency with which the lake reaches it's capacity is fairly small. When looking at area I exclusively, the event becomes even more extreme. A completely filled storage lake does not even directly say anything about water levels upstream, just a reduced discharge through the spillway. Furthermore, the area of boundary conditions marked in Figure 5.3 is not illustrative for normative conditions basically anywhere. A larger lake volume, or increased pump capacity is therefore not expected to lead to any (significant) changes in exceedance frequencies in the delta. These two design characteristics appear to be very conservative in the context of high water protection. Note that this is not entirely surprising, as they are also determined in the conext of energy storage during daily conditions. To further investigate the sensitivity of the system therefore, just three variations are considered which all entail a decrease of capacity:

1 A decreased lake volume by 25%, to 450,000,000 m^3
2 A decreased pump capacity by 25%, to 7500 m^3/s
3 A combination of 1 and 2.

Figure 5.4 presents the changes in water levels at normative frequencies relative to the preliminary configuration of Delta21. The effects are particularly small, rarely exceeding 0,015 m. Figure N.59 in Appendix N provides the maps breaked down per return period and for all variations. The variations seperately (1 and 2) behave similarly to the combination, simply with slightly smaller effects still. For a given return period, effects are greatest in the storage dominated region, as can be expected. Figure 5.5 presents the deviations in water level per boundary condition combination for Dordrecht. Clearly, any changes only exert influence on maximum water levels in conditions with very extreme discharges of 16,000 m^3/s or more. A similar observation can be made for various other locations (see Appendix N).

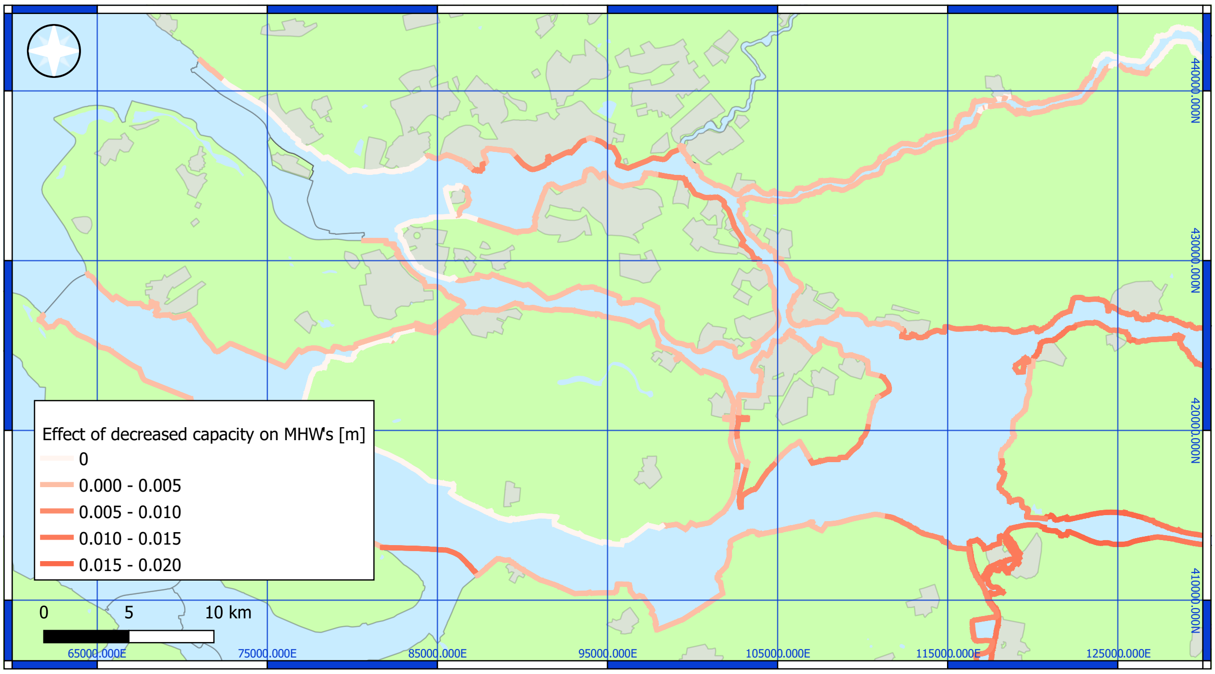


Figure 5.4 Effect of a reduced storage lake volume (25%) and reduced pump capacity (25%) on MHW's in the current climate

Discharges at Lobith that exceed +/- 16,000 m^3/s are only occasionally illustrative for the area that is river dominated. Delta21 does not have a significant effect in these areas, explaining why hardly any deviations are observable in Figure 5.4. When the same exersition is performed for the future climate scenario, the picture does not change much. Although the joint probability of the areas in Figure 5.3 increase, illustrative conditions still have roughly the same discharges for the entire delta. And for these conditions, the capacity of the storage lake is not reached.

Figure 5.5 Changes in peak water level [m] at Dordrecht for a reduced storage lake volume (25%) and reduced pump capacity (25%)

In conclusion, when Delta21 operates within the scope of this research, water levels at normative frequencies exhibit a negligible sensitivity to the capacity of the pumps and storage lake. The energy storage targets of Delta21 are determinant in designing the magnitude of these components. A reduction of 25% is quite considerable, but to properly test the limits of the required storage capacity it is recommended to decrease the capacity of the pumps and storage lake even further, to the point where the influence is noticeable in conditions which are more illustrative for MHW's.

5.2.2 Sensitivity to Delta21's spillway width and height

Whereas the storage lake and pumps are determinant in the amount of water Delta21 can discharge, the dimensions of the spillway determine the speed and reference level at which this is done. The width of the spillway constricts how much discharge can flow over for a given water level in the estuary. The height of the sill of the spillway determines the level in the estuary for a given discharge. As aforementioned, the final Delta21 design will contain multiple gates which can regulate the discharge over the spillway. However, in this analysis and schematization the full capacity is always employed in order to produce the maximum effect. Once again, this leaves a lot of room for optimization, but falls outside the scope of this thesis which aims to shed light on the limits of Delta21.

Similar to the considerations in Section 5.2.1, the preliminary configuration of Delta21 appears to be quite easily able to realize a sufficient discharge at a low enough level to reduce MHW's. A good indicator for this is the slope of the water level development at Dordrecht. Take for example the boundary conditions which are illustrative for Dordrecht in the current system. The development of water levels in Dordrecht for these conditions is presented in Figure 5.6. Whereas the water level continues to rise during a storm event (with closed barriers) in the current system, in the preliminary configuration of Delta21 it remains very stable. A similar slope is found for more extreme conditions, with Delta21 being able to keep the slope approximately horizontal even for discharges of 18,000 m^3/s. The only condition is enough available storage in the lake, but this has already been treated in the previous section.

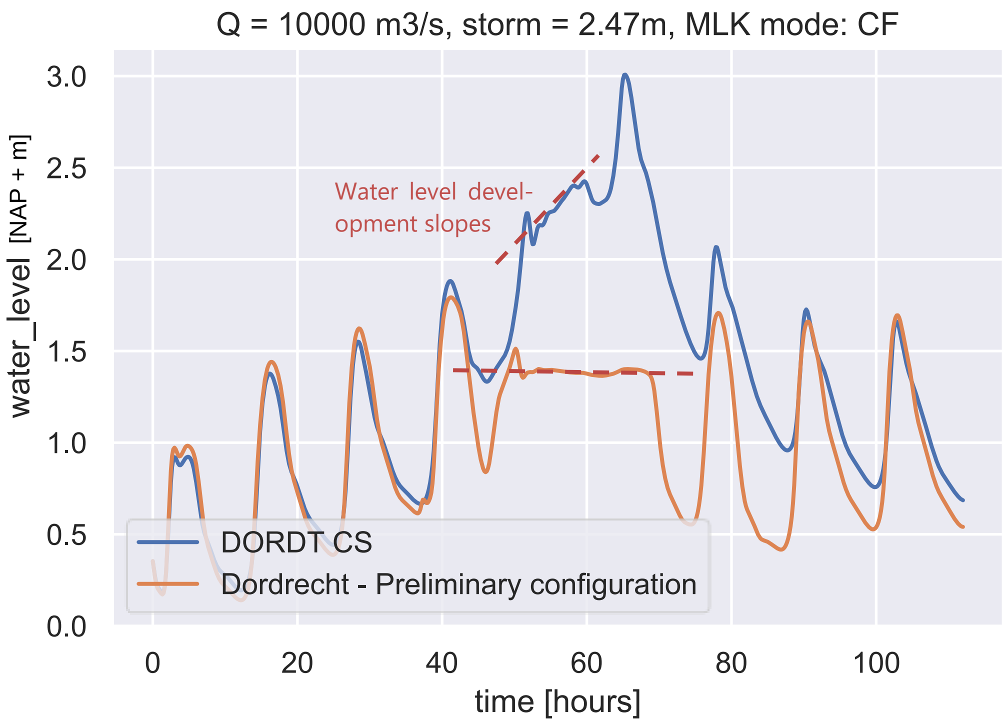


Figure 5.6 Development of water levels at Dordrecht in illustrative boundary conditions in the current system (CS) and preliminary configuration of Delta21; for Correctly Functioning (CF) Europoortkering

Because of this, to further investigate the sensitivity of the system, exclusively variations are considered that significantly reduce the spillway's capacity. Note that a change in the sill of the spillway does not include any additional constrictions to the height of the available profile. A free flow weir is always guaranteed in the employed schematization. Three variations are considered:

1 A decreased width by 25%, to 2000 m
2 A raised sill height by 1 m, to NAP - 3.5 m
3 A combination of 1 and 2.

Figure 5.7 presents the effect on water levels at normative frequencies for a combination of reduced spillway width and raised spillway sill height, relative to the preliminary configuration of Delta21. The changes are particularly small, not exceeding 0.013 m. Figure N.60 in Appendix N provides the maps breaked down per return period and for every variation seperately. For larger return periods effects are most noticable, but are still rather insignificant. The separate variations (1 and 2) also do not deviate strongly from the results in Figure 5.7, but simply show a weaker effect.

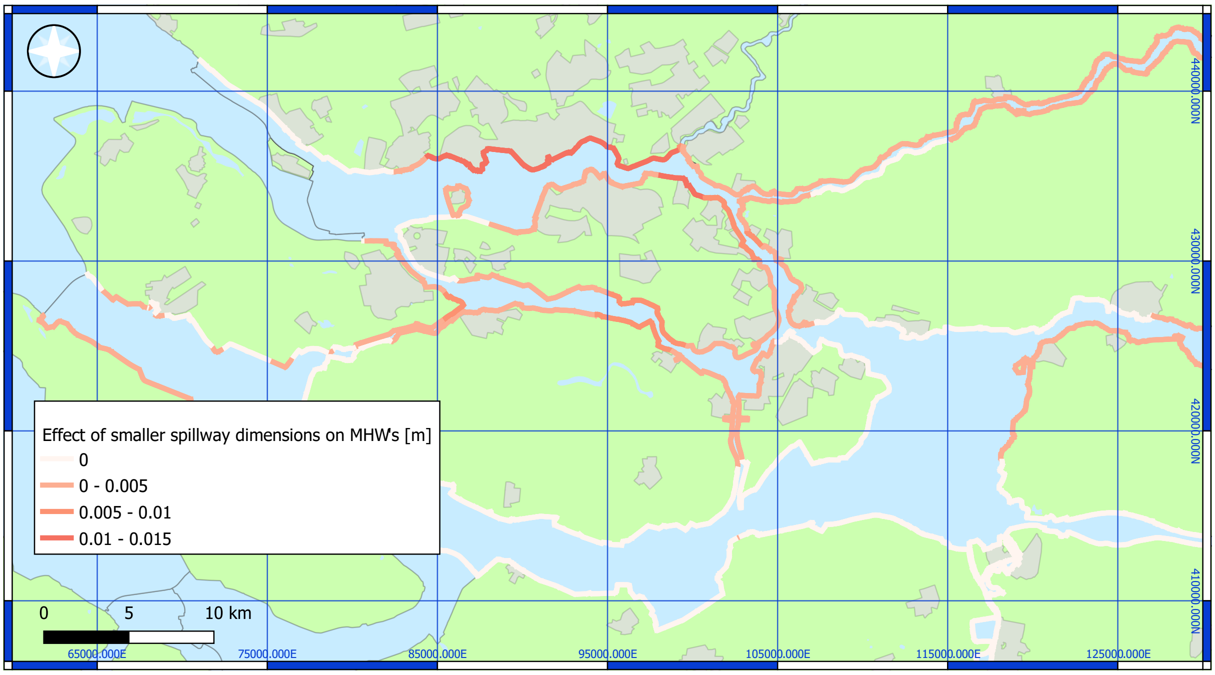


Figure 5.7 Effect of a reduced spillway width (25%) and raised sill height (1 m) on MHW's in the current climate

To elucidate in more detail why the effects are this inconspicuous, Figure 5.8 presents the difference for a reduced width and raised sill height in the example of Dordrecht. The decrease in reduction is never greater than 0.12 m. Table 5.3 summarizes a brief analysis of three most impactful combinations of boundary conditions, of which the corresponding water level development figures are attached in Appendix N.

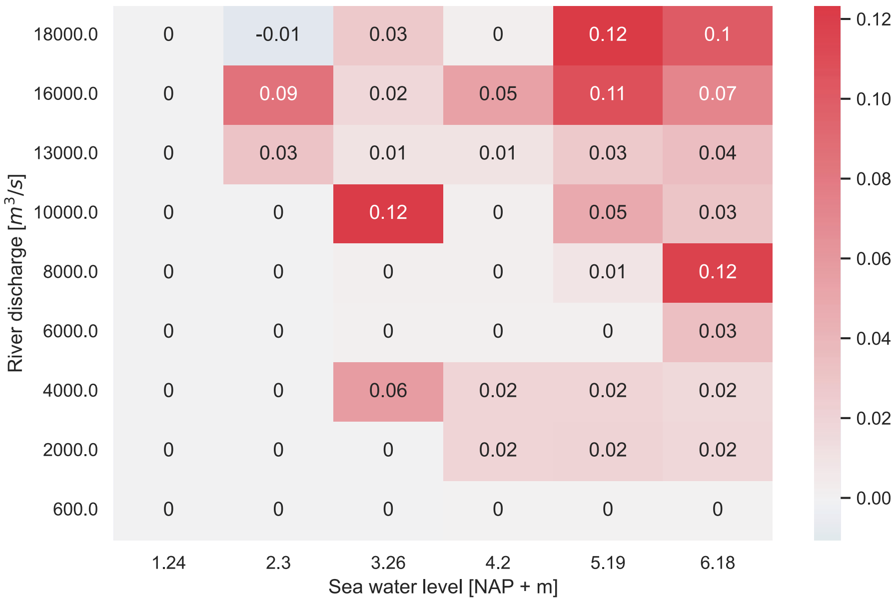


Figure 5.8 Decrease in peak water level reduction [m] by Delta21 in response to a spillway with reduced width and raised sill height

Table 5.3 Summarized examples with noticeable changes in water level response for a changed spillway

Boundary conditions		Decrease in reduction of peak water level	Analysis
Discharge	Sea water level		
10,000 m^3/s	NAP + 3.26 m	0.12 m	Represents illustrative conditions well. But the peak occurs after the storm. The only reason for a 0.12 m decrease in reduction by Delta21 is the fact that Delta21 deescalates a bit sooner. The raised spillway sill height means that a negative water level gradient occurs earlier, allowing the still reasonably high tide after the true storm to penetrate the delta.
8,000 m^3/s	NAP + 6.18 m	0.12 m	The same phenomenon occurs as above. Now however, boundary conditions are not in the slightest illustrative as well. Therefore, contribution to MHW's is particularly small.
18,000 m^3/s	NAP + 5.19 m	0.12 m	A true example of the peak water level occurring **during** the event. The reduction with the raised spillway (regardless of width) is lower. However, the effect is not incredibly large. And more importantly, the boundary conditions are superbly extreme. This will therefore hardly contribute to MHW's.

A final example of another effect we have not seen so far is given by Rotterdam in very specific conditions. For failing Europoortkering and discharges exceeding approximately 15,000 m^3/s, a smaller and higher spillway actually performs better, see Appendix N. Additional reductions of around 0.05 m can be found, indicating that during particularly disastrous conditions, it might be better to use the storage of Delta21 more gradually. Nevertheless, as with the previous examples, contributions of these effects to MHW's are very limited. Again, similar to the storage capacity of Delta21, no significant changes are expected in the future scenario. Probabilities of the most influential events increase somewhat, but illustrative conditions remain for the large part among those with little to no effect.

In conclusion, the size and sill height of the spillway do not appear to have a significant effect on MHW's. Similar to the capacity of the storage lake and pumps, illustrative conditions are simply not often near those where the design magnitudes of Delta21 start reaching their limits. Contrarily to the storage lake and pumps however, the spillway has no double function with regards to energy storage. There is no good reason to design the spillway this conservatively within the scope with which this research assesses Delta21. It is therefore strongly recommended to further research significantly less extensive (and cheaper) spillway designs.

5.2.3 Synergy Delta21 and adapted Pannerdensche Kop discharge division

The discharge division at the Pannerdensche Kop is schematized deterministically for the employed model, but is in reality basically a management choice. The Delta program of the Dutch national government has already put the matter into question, and suggests that a different division might be more optimal (Rijksoverheid, 2021). More specifically, ideas are desired that contain a more lenient flow into the Nederrijn-Lek branches during medium to high discharges, and focus on high water protection in a single branch: the Waal. In his research, Buijs (2021) indicates that a recurring issue with Delta21 is getting the water 'Southwards' or towards the Haringvliet. An increased fraction of water that discharges through the Waal might yield the desired effect.

To concretise the variation, it is possible to look at a long term strategy as proposed by for example Beaufort (2022), which may be particularly compatible with Delta21. His plan is in summary to designate the Waal, Hollandsch Diep, and Haringvliet as a large discharge corridor. Specifically, he mentions that for a discharge boundary of 18,000 m^3/s at Lobith, about 14,000 m^3/s (78%) should enter the Waal. For reference, the current share would amount to approximately 11,000 m^3/s (61%). Note that the share of the IJsselkop is kept roughly the same in both cases. Using the Millingse dam and Pannerden control weir, the discharge division at the Pannerdensche Kop can be adjusted by approximately 1,000 m^3/s in both directions during high water conditions (Schropp, 1999) (Lemans, 2007). Although this is insufficient for Beaufort, it does indicate that this order of magnitude is realistic and achievable without too many additional interventions.

This variation is therefore schematised as follows. The relation between the discharge at Lobith and at the upstream boundary locations (see Appendix A) is adapted to reroute approximately 50% of the Lek's discharge. The addition to the boundary in the Waal (Tiel) is then equal to the difference, adjusted for the additional discharge that would have gone into the IJssel. The result is presented in Table 5.4. Note that the relative increase becomes more apparent for higher discharges. The discharge through the Waal for 18,000 m^3/s at Lobith resembles closely the 14,000 m^3/s

at Lobith that Beaufort proposes. Note once again that the goal here is to assess how large the synergetic effect of such a division with Delta21 is, and not to assess the absolute impact of this specific variation.

Table 5.4 adapted discharge boundary to represent a changed division at the Pannerdensche Kop

Lobith	Tiel			Hagestijn
Discharge in [m³/s]	Discharge in [m³/s]	Share of total discharge	Increase relative to the current division	Discharge in [m³/s]
600	569	95%	3%	13
2000	1632	82%	16%	154
4000	3260	81%	21%	375
6000	4866	81%	22%	579
8000	6475	81%	22%	786
10000	8063	81%	24%	1031
13000	10540	81%	24%	1351
16000	12549	78%	25%	1691
18000	13929	77%	26%	1934

Figure 5.9 presents the MHW effects of a changed discharge division in a system with the preliminary Delta21 configuration. The same result for the current system is attached in Appendix N, which also contains maps for given return periods. The most noticeable effects are, unsurprisingly, towards the river-dominated areas. Branches of the Lek benefit from the reduced discharge, and branches of the Waal see a rise in exceedance frequencies. For the rest of the delta, the effect is limited but shows a tendency towards a slight increase in the southern areas for both the current and Delta21 system.

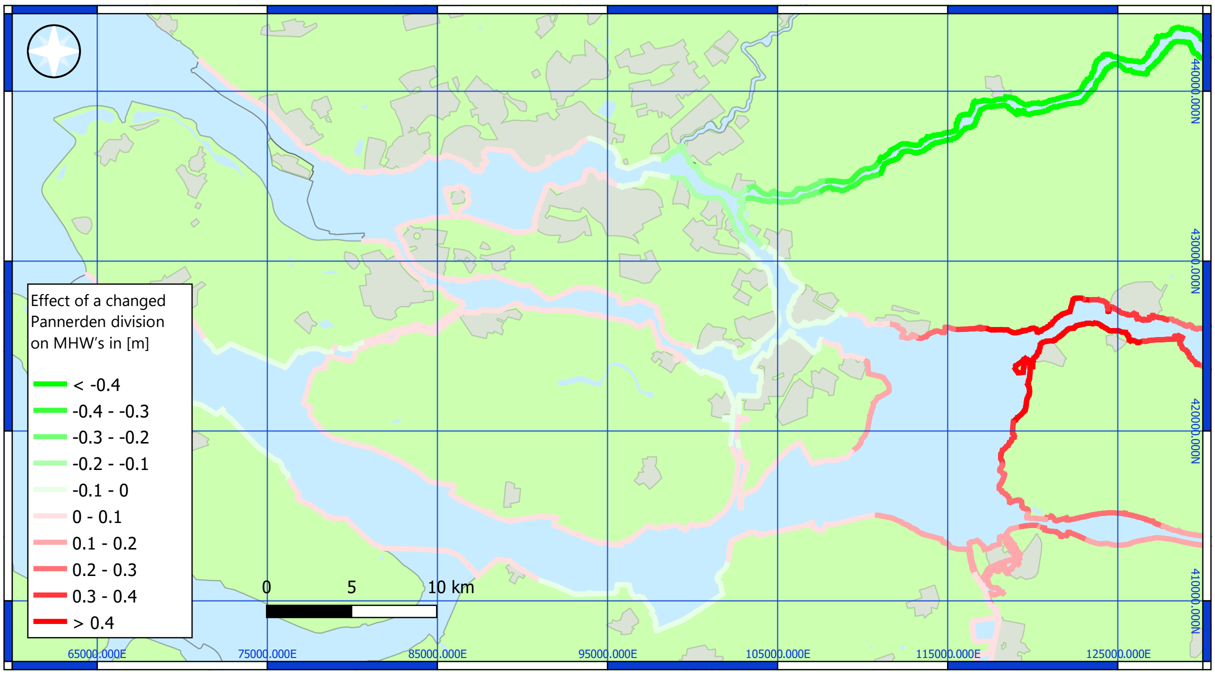


Figure 5.9 The effect of a changed discharge division at the Pannerdensche Kop on MHW's in a system with the preliminary Delta21 configuration

That the area dominated by the Waal experiences a steep increase in MHW's is not particularly telling of a synergetic effect. For that, it is more useful to observe the difference in response between the two considered systems: the current one, and one with Delta21. Figure 5.10 presents this difference, where a positive value resembles a better performance (extra reduction) in the current system. In the Delta21 system, the effect on the river dominated areas appears to intensify. The Lek experiences an even larger reductions, while the Waal experiences an ever steeper increase. The former is about an extra reduction of 0.15 m, whereas the latter does not exceed an additional 0.06 m. In the rest of the delta, their appears to be a small synergetic effect in the Delta21 system for larger return periods. For lower return periods, Delta21 generally does not escalate. Besides that, the 'normal' average discharge through the Haringvlietsluizen is slightly reduced due to the more constricted/longer flow profile that Delta21 introduces with the employed schematization. This leads to a tiny overall increase of approximately 0.01 to 0.02 in those areas with lower normative return periods, such as the trajectories along the Haringvliet and Hollandsch Diep.

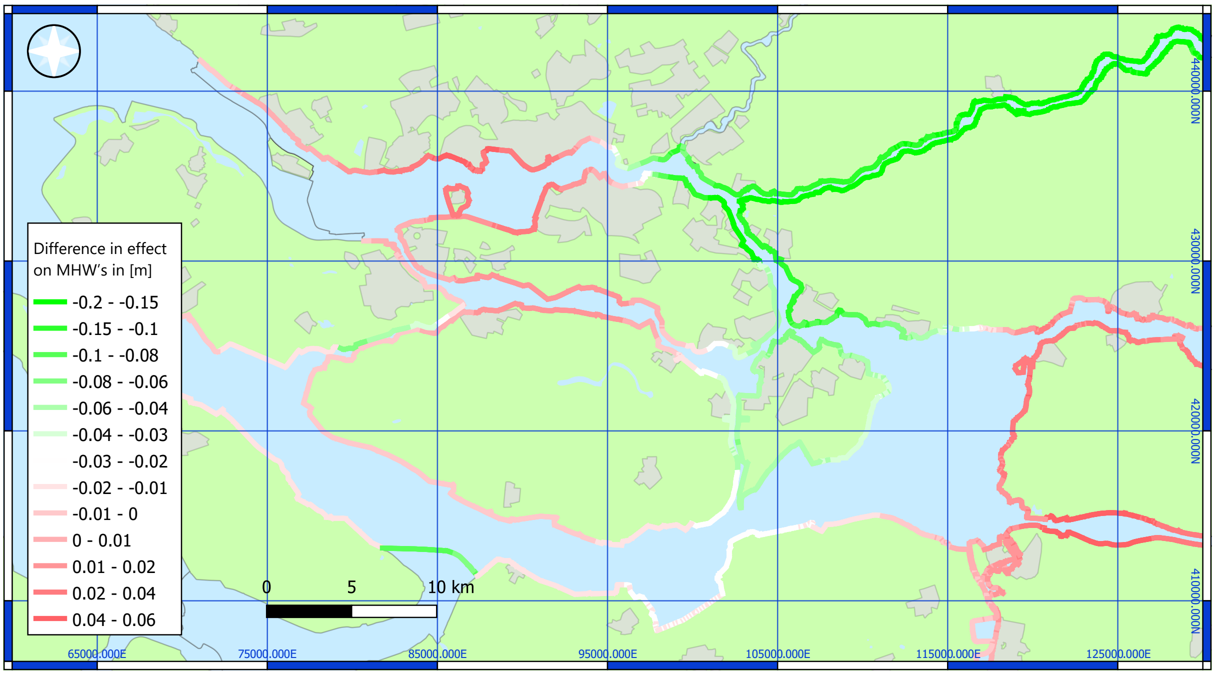


Figure 5.10 Difference in the effect of a changed discharge division at the Pannerdensche Kop on MHW's between the current and Delta21 systems

For the area Dordrecht and Ridderkerk, the combination of relatively strict norms and more effective discharging by Delta21 provide the most promising results. Elsewhere, there is no particularly significant synergetic effect of combining Delta21 with a changed division at Pannerden. Once again, illustrative conditions are often such that Delta21 does not escalate. Therefore, yields are limited when considering variations that primarily affect very extreme conditions. Delta21 occasionally reduces peak water levels more with a changed discharge division at Pannerden, but in most cases it simply wont affect the more frequent extreme water levels.

5.2.4 Synergy Delta21 and reduced Europoortkering failure probability

As discussed in Chapters 1 and 2, previous research into Delta21 suggests a significant interaction between the Europoortkering and Delta21. As indicated by for example Buijs (2021), an improved Maeslantkering will be essential for Delta21 to be successful. Section 4.3 has already concluded that the area influenced by the Europoortkering's failure probability (P_{f-EPK}) is not particularly different in a system that contains Delta21. However, some minor indications of synergetic effects were found, which is why this section will shed light on whether the reduction by Delta21 is significantly different in a system that contains a reduced P_{f-EPK}.

Naturally, a system that has both Delta21 and a reduced Europoortkering failure probability (P_{f-EPK}) will result in the lowest exceedance frequency curves. This section however addresses whether the reduction as a result of Delta21 exclusively, is larger in a system which already has a lower P_{f-EPK}. This synergetic effect can be detected by comparing the reductions of Delta21 where the reference system also has a lower P_{f-EPK}. The considered failure probability for the Europoortkering is 1:1000 per closure (a single decimation).

In the current climate, where any synergetic effects are noticeable at all, they are very small. Several maps that present the effects on MHW's are attached in Appendix N. When both the system with and without Delta21 have a decimated P_{f-EPK}, the resulting reduction by Delta21 is in fact slightly smaller on average. It is limited however to approximately one to three centimetres, and not considered particularly significant.

Figure 5.11 presents the synergetic effect in the future climate scenario. Note that Delta21 has a slightly different configuration here, due to a minimal closure criterion as explained in Section 5.3. Although the effect is still not incredibly large, there **is** a clear noticeable positive synergetic effect. It is most apparent in the transition areas close to the failure-dominated area, as would be expected given the considerations of in Section 4.3. Occasionally, MHW's are reduced by an additional 0.1 to 0.2 m when Delta is combined with an improved Europoortkering. Synergy tends to increase with a rising sea level and further declining P_{f-EPK}, which was already supported by the example of

Spijkenisse in Section 4.3. Nevertheless, it must be said that the effect is still nowhere near as large as predicted in previous research, especially for the area around the island of Dordrecht.

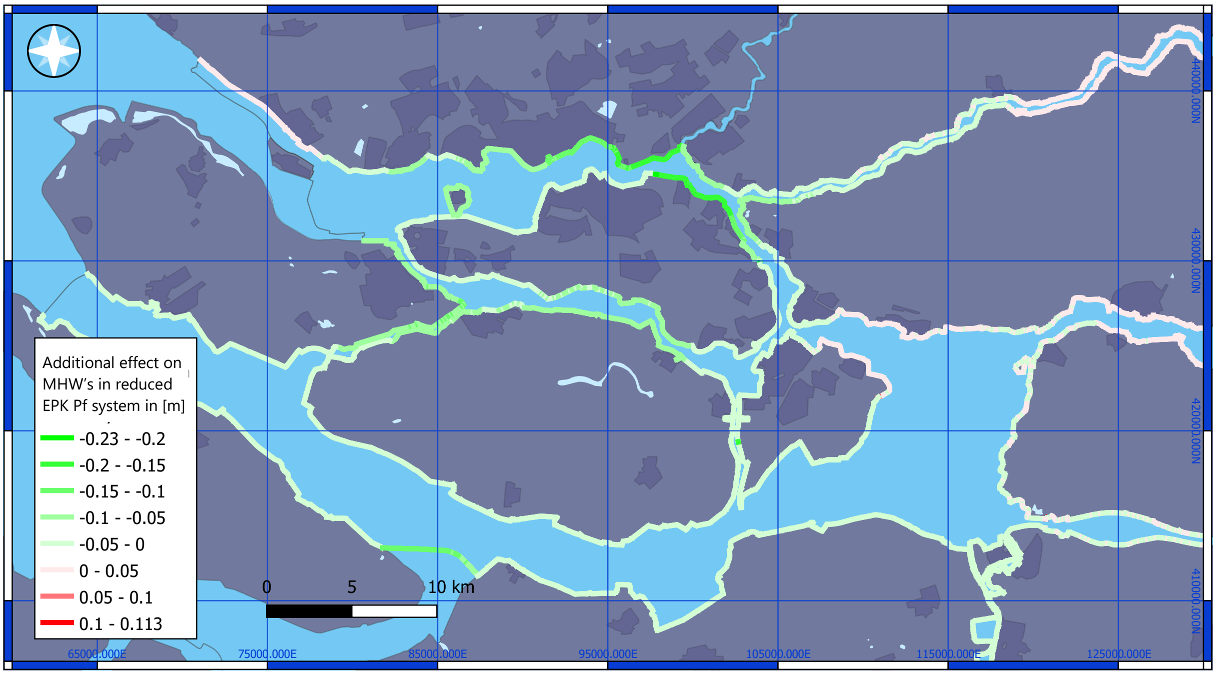


Figure 5.11 Additional effect of MHW reduction by Delta21 when the Europoortkering failure probability is decimated

The idea that Delta21 and the Europoortkering have to be considered inseparable, is therefore not reproduced by the model of this research. This goes against the recommendations of previous research and even in part the motivation for this research. The suspected reason for the incongruity is that the two are, perhaps unintentionally, coupled through other means. For example, Buijs (2021) connects the closure criteria of the Europoortkering and Delta21 with sea level rise. Delta21 is not particularly sufficient in combination with an open Europoortkering (see Section 5.3), and thus by coupling the closure operation the effectivity of one depends on the other. Delta21 does not yield large reductions in the failure-dominated area, and is therefore not able to directly obviate dike reinforcements there. Buijs (2021) also draws this conclusion. That however does not necessarily mean that the two have a strong influence on the other. The conclusion that illustrative conditions at Dordrecht (focus of his research) are strongly dependant on an Europoortkering failure, is incorrect. The illustrative conditions indicate an **open** Europoortkering, where water can flow freely into the Nieuwe Waterweg. However, the conditions are such that it does not need to close in the first place. It is unsurprising then, that the reduced P_{f-EPK} provides little reduction at Dordrecht, even though previous research suggests it should have in a system with Delta21.

5.3 Reduction sensitivity to operational control

This subchapter will investigate the sensitivity of the peak water levels to various changes in the operational control of Delta21 and the Europoortkering. Operational control refers to all the code or software that decides on what every movable component should do, and when. For the Europoortkering and Delta21 respectively, Chapters 2.3 and 2.4 describe the decision flowcharts including corresponding benchmarks that must be met. The key parameter in the entire operational control, is called the closure criterion. This is a certain water level in a certain location, which once predictions indicate will be reached, lead the control to start escalating. Escalating is a general term for moving a component from its rest state to a state in which it benefits the delta's flood protection. For a storm surge barrier, escalating is synonymous with closing. Therefore the term '*closure criterion*' is used. For e.g. a spillway that opens up, an *opening criterion* would be more appropriate, but to prevent confusion the more common closure criterion is retained for the remainder of this chapter. The operational control in general is a far more flexible parameter, as opposed to for example structural elements of Delta21. The Software can easily be updated with adapted schemes or criteria.

The closure criterion/criteria determine in part the timing, but more importantly the conditions for which escalation of the component is present. For the Europoortkering, the current criteria are a predicted water level of NAP + 3.0 m at Rotterdam, or NAP + 2.9 m at Dordrecht. Note that predictions are made for 24 hours into the future. For the preliminary configuration of Delta21, a single closure criterion of NAP + 2.5 m at Dordrecht is used. In principle, a lower closure criterion implies a higher closure (or escalation) frequency, which comes at a cost. This section however assesses the effects of several variation in operational control on water levels at normative frequencies, not the optimization of operating costs. A closure frequency estimation of Delta21 is provided, but not analysed in further detail. The closure frequency of the Europoortkering is already dealt with in detail in Section 4.2. For the preliminary configuration (variation 0 - reference) the closure frequency is approximately once every 17 years.

Table 5.5 presents the variations that have been used to compute differences in water levels at normative frequencies. Both the criterion for Delta21 and the Europoortkering are varied, but only at Dordrecht. Delta21 does not have a noticeable effect in Rotterdam, and hence does not have a closure criterion defined at this location. The Europoortkering does have a criterion for Rotterdam, but changing it would only obscure and needlessly complicate the sensitivity to operational control of Delta21.

Table 5.5 Considered variations in operational control - closure criteria

Variation number	Climate scenario	Closure criterion Europoortkering (Dordrecht)	Closure criterion Delta21
0 (reference)	Current	NAP + 2.9 m	NAP + 2.5 m
1	Current	NAP + 2.5 m	NAP + 2.5 m
2	Current	NAP + 2.9 m	NAP + 2.9 m
3 (reference)	Future	NAP + 2.9 m	NAP + 2.9 m
4	Future	NAP + 2.5 m	NAP + 2.5 m

Figure 5.12 presents the deviation of MHW's for variation 1 (reference: 0). The effect is corrected to account for the fact that a lower criterion for the Europoortkering would also yield slightly lower MHW's without Delta21 too. This difference is subtracted from the total reduction, to indicate how the effects of Delta21 exclusively are affected. Although the result is not incredibly large, a noticeable effect can be observed for larger return periods around the transition area.

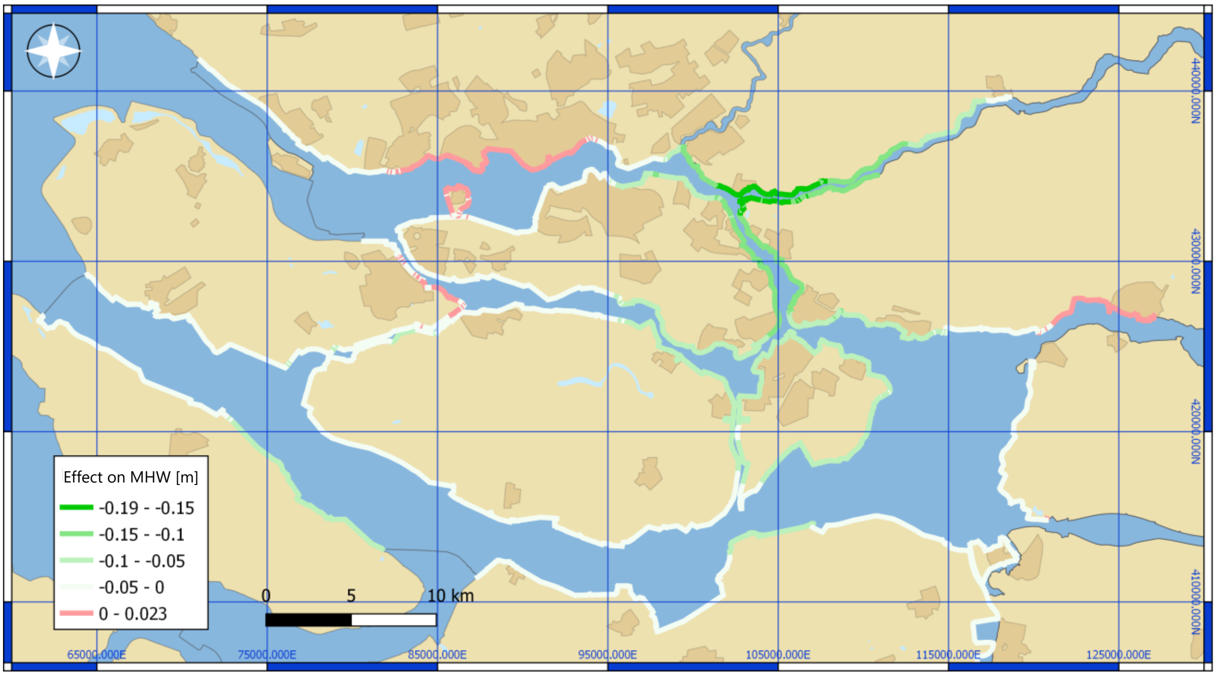


Figure 5.12 Change in MHW's for the closure criteria of variation 1

Figure 5.13 presents the deviation of MHW's for variation 2 (reference: 0). The higher closure criterion for Delta21 is immediately visible as a significant increase of MHW's throughout the Delta. Especially where Delta21 is most effective in the preliminary configuration, the attenuation is largest.

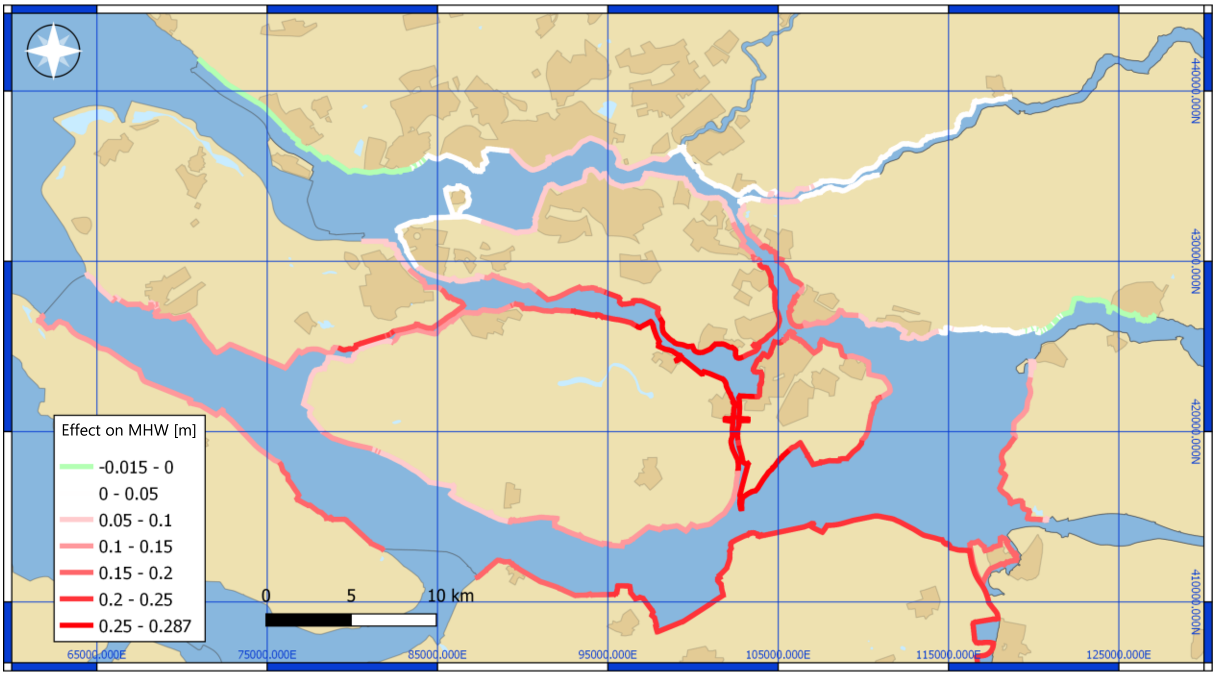


Figure 5.13 Change in MHW's for the closure criteria of variation 2

The difference in MHW's between variation 3 and 4 is presented in Figure 5.14. A lower closure criterion may imply more frequent closures, but it is also particularly effective. In large parts of the storge-dominated and transition regions, additional MHW reductions of 0.2 to 0.4 m can be found. The following analytical sections describe the effect of these particularly low criteria in more detail, and why corresponding model issues can also lead to a rise in MHW's for especially higher return periods.

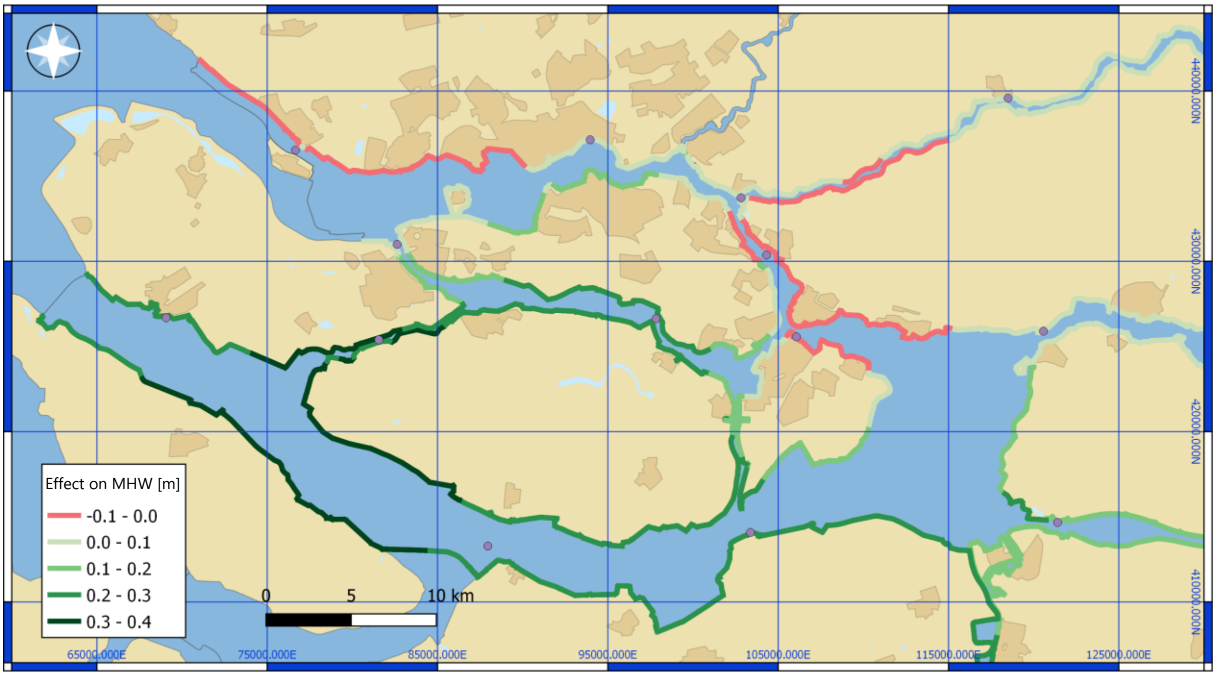


Figure 5.14 Change in MHW's for the closure criteria of variation 4, relative to variation 3 (reference in future climate)

Dissimilar closure criteria for the Europoortkering and Delta21

The reference is the preliminary configuration of Delta21. Notice how it has dissimilar closure criteria at Dordrecht for Delta21 and the Europoortkering. This means that in some cases, Delta21 will escalate while the Nieuwe Waterweg remains open. A hydraulic shortcut is the result, which means that large amounts of water are pumped round. Due to the limited density of calculation points there are only a few computations available where Delta21 escalates without the Europoortkering. Overall these occur for low (but not zero) storm surges in combination with high discharges, exceeding 13,000 m^3/s. Delta21 is not at all effective in reducing peak water levels in these conditions. For example, Figure 5.15 shown the reductions of peak water levels of the preliminary configuration at Dordrecht, with an indicated area of an open Europoortkering and escalated Delta21.

Nevertheless, the reduction of MHW's is still considerably larger than for example variation 2, where Delta21's criterion is raised. There are two reasons for this. First, when discharges as low and the Europoortkering fails to close, Delta21 **can** in fact effectively lower peak water levels. The contribution to MHW's is not particularly significant though, especially for the example of Dordrecht. The second and far more important reason, is that the Europoortkering is closed when the criterion at Rotterdam is reached too, even if it is not at Dordrecht. The result is that Delta21 and the Europoortkering escalate for different reasons, in the other area highlighted in Figure 5.15. In this case Delta21 is very effective, lowering the peak water level at Dordrecht from NAP + 2.74 m to NAP + 1.27 m. A similar result is obtained for much of the delta. Because these conditions also happen to contribute heavily to the illustration point of normative frequencies, the resulting MHW-reduction is significant.

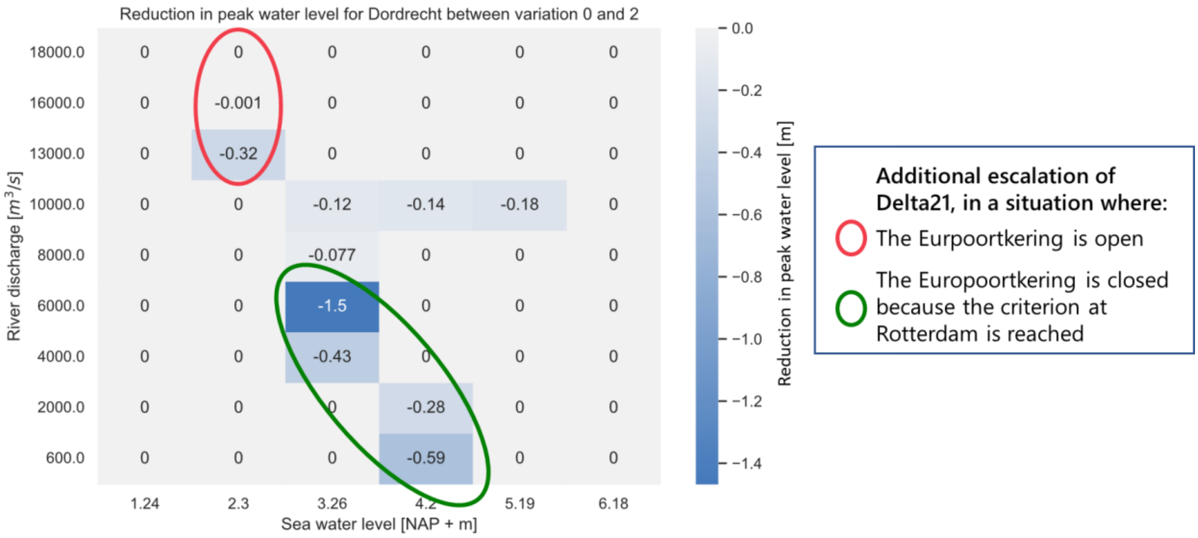


Figure 5.15 Peak water level difference [m] in Dordrecht for all boundary condition calculation points between variation 0 and 2

Deliberately escalating Delta21 when the Europoortkering is open does not yield an effective reduction of peak water levels. Dissimilar closure criteria are therefore discouraged, and noticeably absent from the other variations. Further improved operational control is strongly recommended for future research, to account for all the exceptions as described above.

Lower limit to the closure criterion

The employed schematization demands that Delta21 does not escalate when there is no storm. Delta21's objective within the scope of this thesis is to reduce peak water levels during approximately 30 hours periods. This however poses a lower limit to the closure criterion. When it is too low, the water level at every high tide for a given (generally large) discharge will exceed the criterion. Because no storm surge is required and the model employs a constant discharge for approximately 7 days, this would yield a week with 14 closures of the Delta21 storm surge barrier. This is a type of 'flippering' and doesn't reflect a realistic operation particularly well. Figure 5.16 presents the bidaily tidal high water levels for medium to high discharge boundary conditions in the current and future climate.

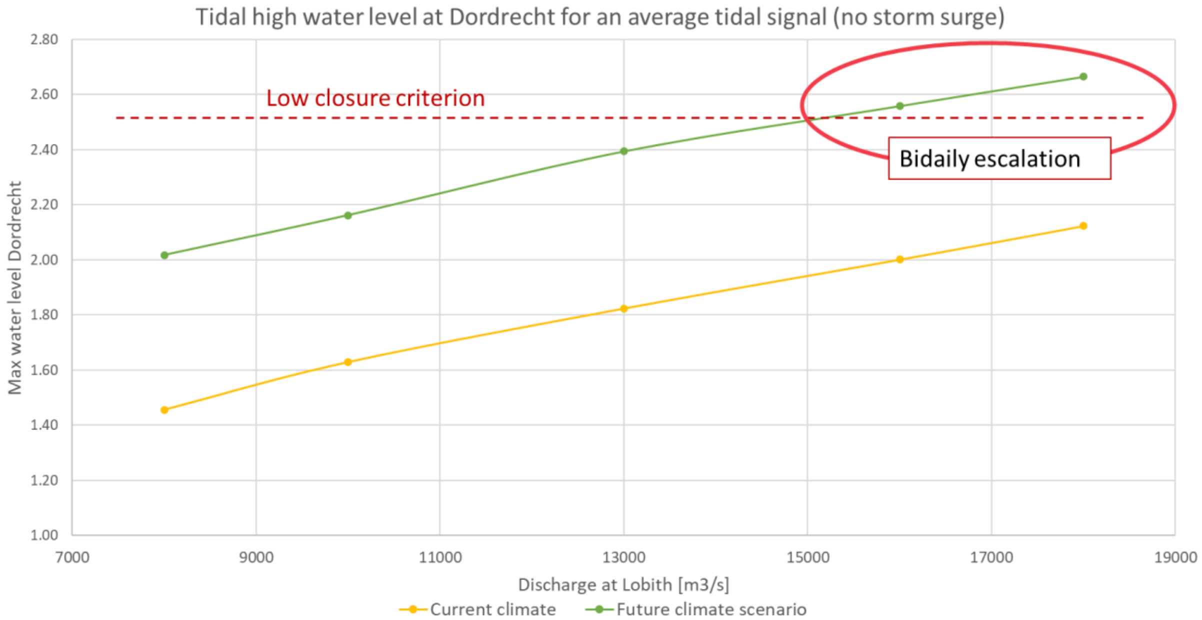
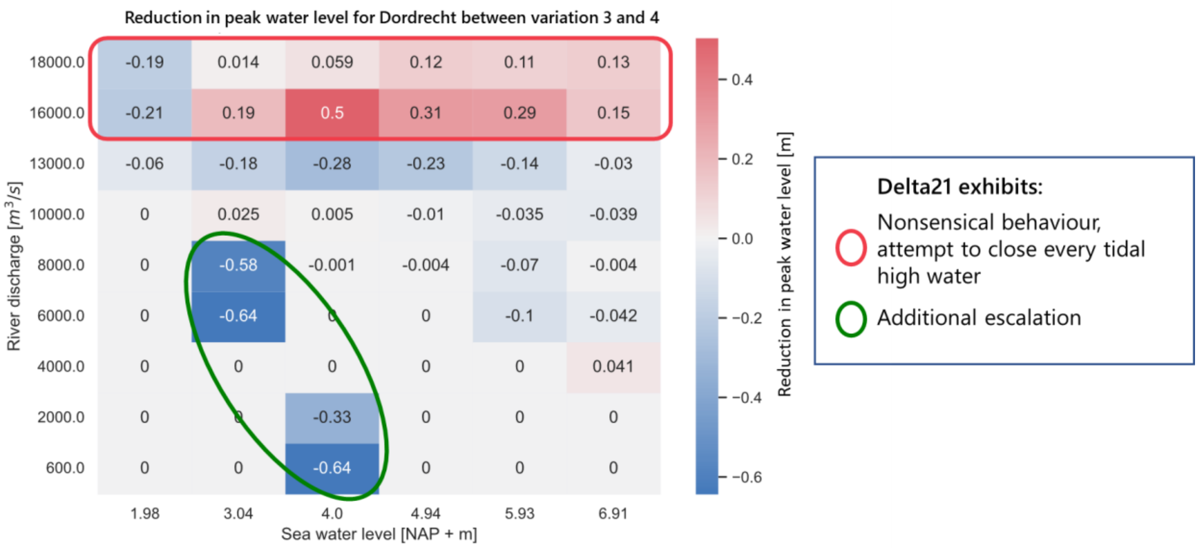


Figure 5.16 Bidaily tidal high water level at Dordrecht for a given (high) discharge and open barriers

Especially for significant sea level rise, this poses a problem increasingly often. This is why the preliminary configuration of Delta21 is no longer used to compute savings in Chapter 6 for the future climate scenario. Rather, variation 3 is considered the most appropriate, which does not exhibit unpredictable and unrealistic behaviour of the movable components. Nevertheless, variation 4 does appear to have a positive effect on MHW's, even though the model is not able to properly control Delta21. The reason for this becomes apparent in Figure 5.17, with Dordrecht once again as a representative location. For discharges of 15,000 m^3/s and higher the model produces nonsensical and unpredictable behaviour of Delta21 and the Europoortkering. However, there is also a couple of situations where a massive reduction in peak water level is obtained due to a new escalation, shown in green in Figure 5.17. Moreover, these occur around illustrative conditions for Dordrecht, and therefore strongly influence water levels around normative frequencies. It is strongly recommended to further investigate an operational control that adapts on upstream discharge, so that the increased reductions can be realized without having nonsensical behaviour during high discharge conditions.



River discharge [m³/s]	1.98	3.04	4.0	4.94	5.93	6.91
18000.0	-0.19	0.014	0.059	0.12	0.11	0.13
16000.0	-0.21	0.19	0.5	0.31	0.29	0.15
13000.0	-0.06	-0.18	-0.28	-0.23	-0.14	-0.03
10000.0	0	0.025	0.005	-0.01	-0.035	-0.039
8000.0	0	-0.58	-0.001	-0.004	-0.07	-0.004
6000.0	0	-0.64	0	0	-0.1	-0.042
4000.0	0	0	0	0	0	0.041
2000.0	0	0	-0.33	0	0	0
600.0	0	0	-0.64	0	0	0

Figure 5.17 Peak water level difference [m] in Dordrecht for all boundary condition calculation points between variation 3 and 4

Concluding analysis of all variations

The resulting influence on MHW's of the operational variations as presented above, is generally very strong. To clarify the primary reason for this, observe Figure 5.18, which is applicable to the majority of the area where Delta21 has significantly effects on MHW's. It shows a typical qualitative picture for peak water levels given a certain boundary condition. In combination with marginal distributions of those conditions, it yields exceedance frequency curves. Three areas are distinguished, each with an example illustration point.

The highest area describes particularly extreme conditions, which are illustrative only for very low frequencies (or high return periods). In this region, water levels increase for intensifying boundary conditions because they cannot be reduced any further. This relates to the capacity of Delta21, as treated in Section 5.2.

The second area describes a plateau where maximum water levels are approximately equal. The height of this plateau is determined by the height of water levels just along the 'escalation' line. The model often produces lower values, but these are repaired (see Section 2.2.5), or can be optimized so that they equal at least the value at which Delta21 is escalated.

The third area describes situations where Delta21 does not escalate at all, and is illustrative for conditions with high frequencies. The peak water levels rise from daily conditions in the lower left, to levels for which closure criteria are met.

A certain variation succeeds in changing the water level at normative frequency, if it can influence the result around the illustration point for that location and norm. Specifically: if illustrative conditions most resemble the red point in Figure 5.18, the operational control variations will not exert much influence. If illustrative conditions most resemble the orange point, a change in operational control will most strongly influence the MHW's. Finally, if illustrative conditions most resemble the green point, Delta21 does not escalate and any variation is likely to be of little influence, unless the escalation criteria are lowered beyond this point, in which case the new Illustration point will most likely drop to just below the escalation line. This however means a lower water level for that illustration point regardless.

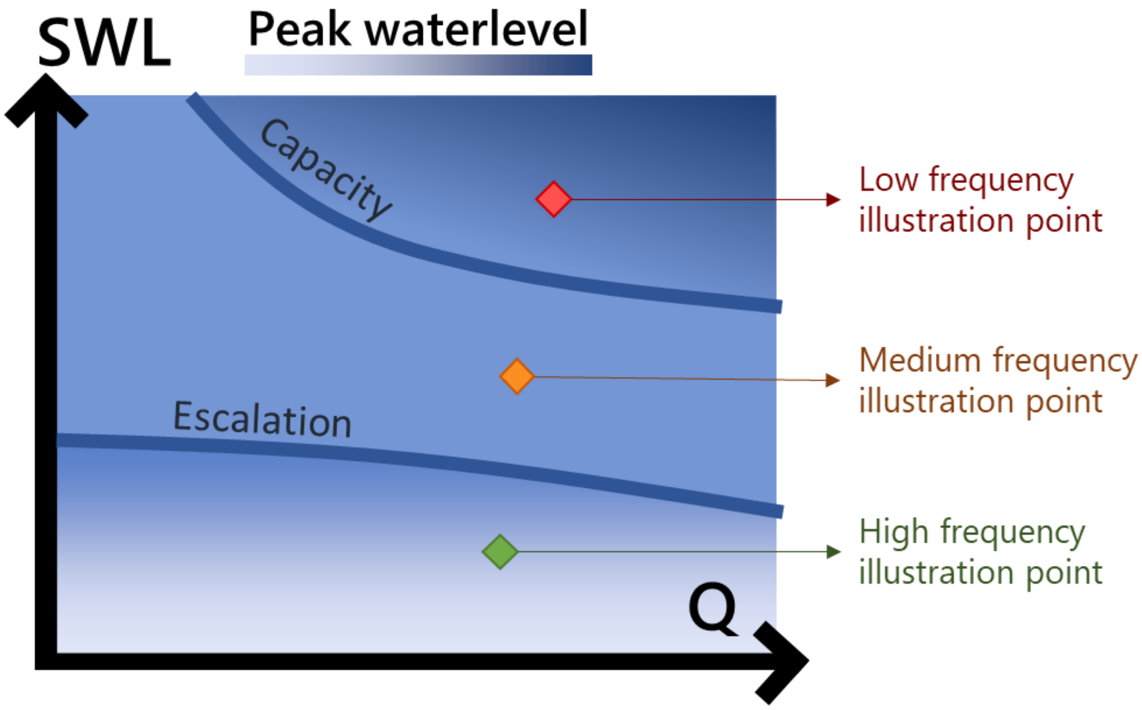


Figure 5.18 Behaviour of illustrative conditions in the majority of the storage-dominated and transition regions in a system with Delta21

For the preliminary configuration of Delta21, nearly all illustration points in the storage dominated and transition regions are best represented by the middle orange point. The height that peak water levels are allowed to reach before Delta21 is escalated (or: criterion), determines the height along the line 'Escalation'. And because of the data reparation (see Section 2.2.5), also the height of the plateau in which the orange point is located. This is the reason why changes in closure criteria have such a profound effect on the water level reductions of Delta21 around normative frequencies. Note that this is not necessarily unrealistic, even though the reparations cause a stronger influence. This simply means that a lower closure criterion, which experiences a weaker reparation, has less room for optimization, and is also definitely more expensive in terms of average expected electricity costs.

5.4 Differences in sensitivity to longer storm durations

During a closure of the storm surge barriers, Delta21 can maintain a minimum discharge capacity whereas the current system cannot until the water level in the delta once again exceeds that at sea. As Section 2 explains, the current deterministic schematization of storm surge duration is deemed acceptable because the effects of shorter and longer storms on extreme water levels at normative frequencies cancel each other out approximately. The in- or decrease of normative water levels would not exceed 20 centimetres (both ways). Individual scenarios of boundary condition combinations however, can have far stronger deviations. The systems water level response is even concluded to be very sensitive to assumptions regarding the schematization of storm surge duration (Rijkswaterstaat, 2007a). When Delta21 is introduced, the deviations might no longer be as balanced and cancel each other out quite as neatly.

To conclude whether the assumptions in the schematization of storm surge duration have to be reviewed, an investigation is required into the sensitivity of a system with Delta21 to longer storm surge durations. The sensitivity to shorter durations might also weaken somewhat, as the parameter as a whole plays less of a role in a system with Delta21. Nevertheless, the effect will be most noticeable in longer storm surges, as the figurative 'bath-tub' that is the delta with closed barriers has less time to fill up during shorter storms anyway. Both the current system and system with the preliminary Delta21 configuration are therefore subjected to an increased storm surge duration. The new schematization has a deterministic storm surge duration of 38 hours, a 27% increase. Figure 5.19 presents the updated storm surge schematization. Because the storm surge peak and tidal peak do not overlap, the new schematization yields a slightly higher sea water level (see the blue dashed line in Figure 5.19). However, the sea water level statistics do not change and therefore this is accounted for in the probabilistic computations.

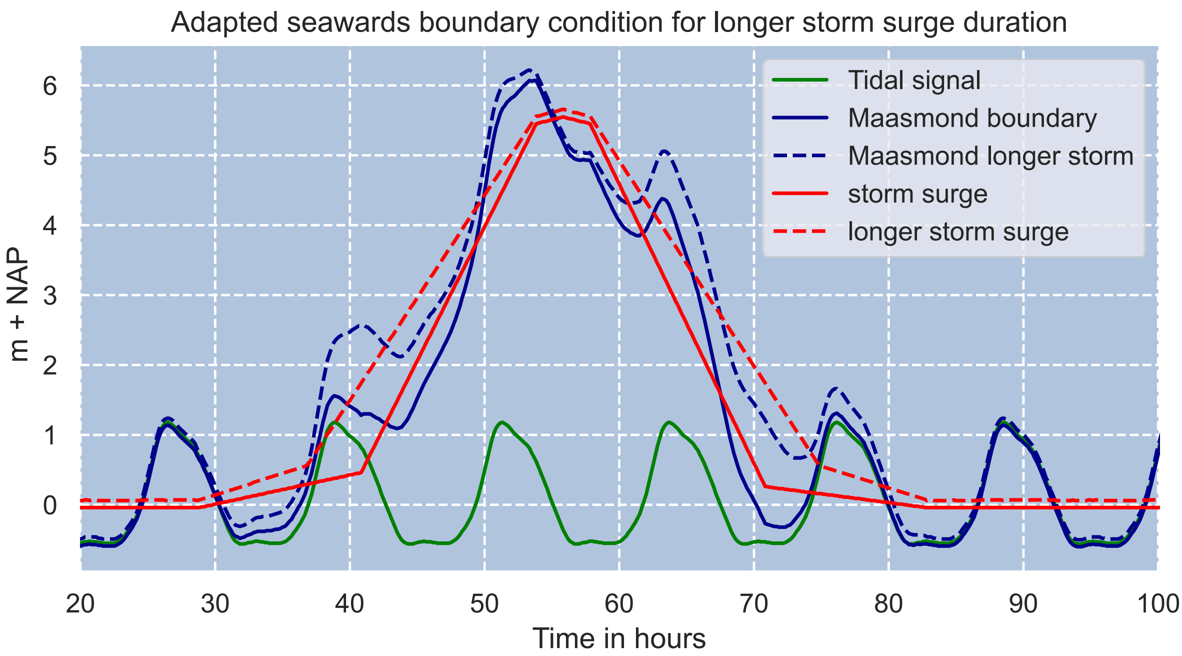


Figure 5.19 Resulting schematization of the seaward boundary for an increased storm surge duration (+8 hours or +27%)

Figure 5.20 presents the resulting effect on water level at normative frequencies (MHW's) for the current system. These simultaneously function as a rough validation of the method, as the order of magnitude on MHW's does indeed range from 0.0 to 0.2 m, as predicted by Chbab and Groeneweg (2017). Effects are most visible in the storage region and transition region, as is to be expected and also predicted by Chbab and Groeneweg (2017). Furthermore, extreme water levels with large return periods tend to be more sensitive than more frequent levels (see Appendix N).

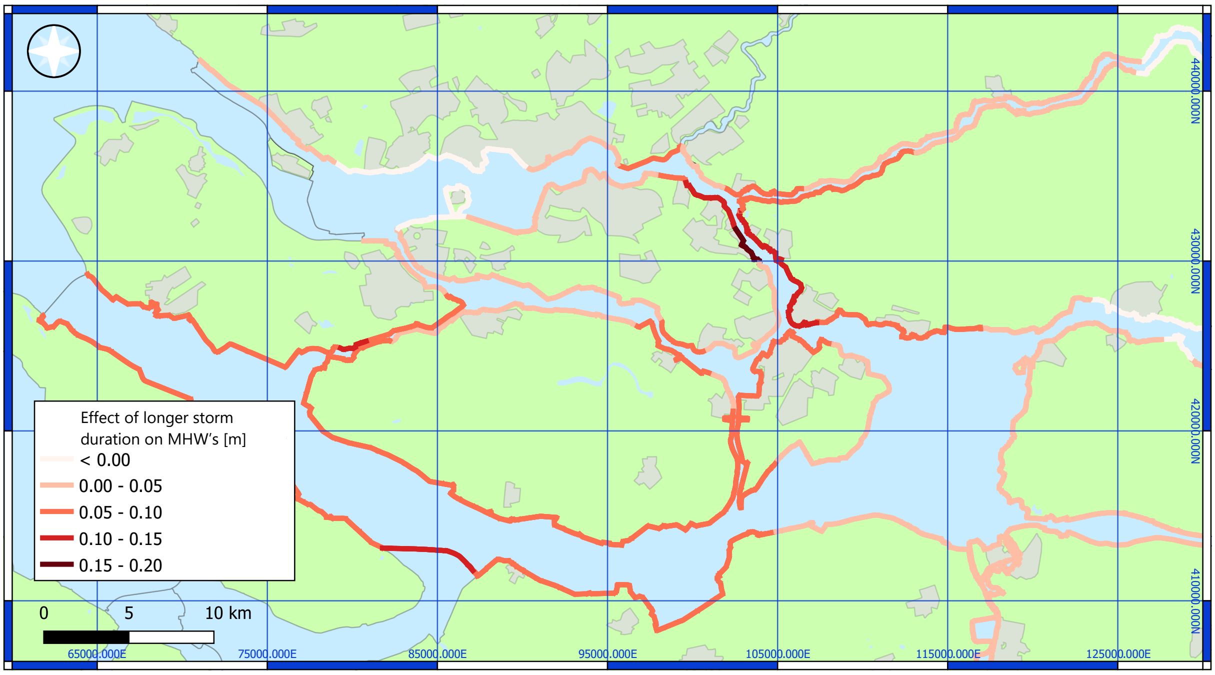


Figure 5.20 The effect of increased storm surge duration (27%) on MHW's in the current system (no Delta21)

The same results are presented for a preliminary Delta21 system in Figure 5.21. As is immediately visible, the water levels at normative frequencies do not rise by more then 0.05 m anywhere. In certain cases there even appears to be a reduction in MHW's for longer storm surge duration. However, the reason for this has very little to do with sensitivity to storm surge. In the new schematization, a handful (two or three) calculation points[1] now fall just within the domain where Delta21 escalates. This has a dramatic effect on the resulting maximum water level in that particular point, especially in those areas where Delta21 is 'effective' - the storage dominated and transition regions. For example in the Haringvliet, this particular combination of boundary conditions also happens to be particularly illustrative for normative conditions. Section 2 already describes why this point is so influential on exceedance frequencies due to database reparation. Regarding the sensitivity to storm surge duration however, this effect merely obscures the real results, and should not be heeded as particularly important.

[1] A single combination of boundary condition input, see for example the whole set in Figure 5.22

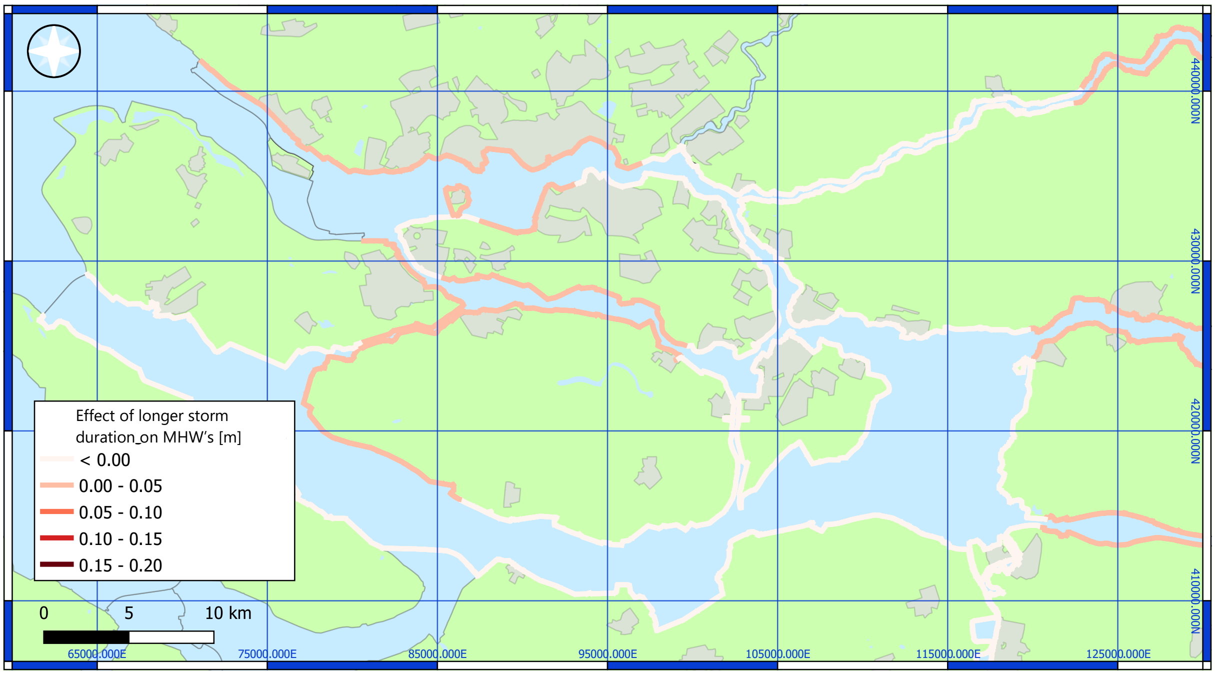


Figure 5.21 The effect of increased storm surge duration (27%) on MHW's in a system with the preliminary Delta21 configuration

Looking beyond these few calculation points allows for a better insight into the effect of longer storm surge duration, even though these do not contribute as heavily to exceedance frequencies. Figure 5.22 presents the results for the example the Haringvliet. Positive values indicate a larger sensitivity in the current system to the prolonged storm surge. For conditions where the discharge at Lobith does not exceed 15,000 m^3/s, Delta21 indeed does exhibit a far weaker sensitivity to a longer storm surge duration. Discharges exceeding 15,000 m^3/s are not at all illustrative for this location, and it can be said with sufficient certainty that Figure 5.21 provides a realistic picture, assuming that the effect on MHW's is at least equal to zero.

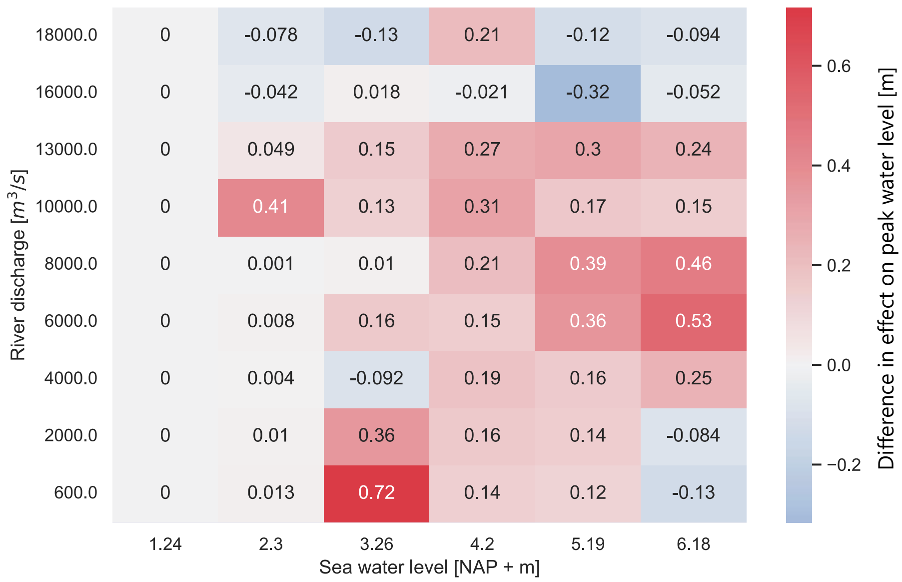


Figure 5.22 Difference in sensitivity [m] between the current system and preliminary configuration of Delta21 in the Haringvliet. Positive values indicate a larger MHW increase due to a longer storm in the current system (more sensitive)

A clear difference in sensitivity to storm surge duration can thus be concluded. In a system with Delta21, a stochastic inclusion of storm surge duration may yield increased MHW-reductions. In the future, when the sea level rises, this is only expected to get worse. Initial water levels at the start of a storm event will be higher in light of sea level rise. This means that water levels will climb to normative conditions even faster when no discharge can be guaranteed when the storm surge barriers are closed. Therefore, even though the distribution of storm surge duration is not expected to change particularly much with climate change (see Section 2), the sensitivity to the model parameter will. Hence, the recommendation to review the deterministic schematization of storm surge duration becomes even more pressing with climate change.

5.5 Concluding remarks

Delta21 is able to reduce peak water levels with increasing effectivity for large return periods and proximity to the storage dominated region. In the current climate, reductions around normative frequencies range from 0.2 m to 0.5 m in the storage dominated and transition regions. For the future climate scenario this increase to 0.3 m to 0.8 m. These reductions are not sensitive to deviations in the design of Delta21, an Europoortkering failure probability reduction, or changed river discharge division at Pannerden. Synergy with an improved Europoortkering failure probability only becomes noticeable in the future scenario in combination with even lower probabilities than a single decimation. Changes in operational control, and specifically the closure criterion, do strongly influence water levels at normative frequencies. In a system with Delta21, Illustrative conditions are regularly those where the water level stays just below the criterion. Lowering it therefore strongly influences exceedance frequencies. Stochastic inclusion of storm surge duration in further modelling with Delta21 is recommended. For this research however, the deterministic inclusion suffices.

6 COST REDUCTIONS ATTRIBUTABLE TO DELTA21

5. How high are the savings or cost-reductions attributable to Delta21?

This chapter translates the hydraulic influence on water level exceedance frequencies to cost savings attributable to Delta21, required for an appropriate cost-benefit comparison. First, savings due to prolonged Europoortkering life-time are estimated in Section 6.1 (question 5a). Then, the cost-reductions due to obviated dike reinforcements on short and long term are approximated with fragility curves and HWBP budgets in Section 6.2 (question 5b). Section 6.3 provides the reduced estimated yearly damage in unembanked areas, using the same changes in water level exceedance frequency (question 5c). Finally, all values are appreciated with a net present value calculation in Section 6.4 (question 5d).

6.1 Estimated savings Maeslantkering lifetime prolongation

Chapter 4 discusses the three approaches that Delta21 takes to achieve potential savings. Unfortunately, none of these have been found to lead to significant results. Therefore, no significant change is the expected lifetime of the Maeslantkering is found, and no savings are expected either.

6.2 Estimated savings of dike reinforcements

6.2.1 Approximate the cost of dike reinforcements

Every dike reinforcement project requires an individual design, and costs per kilometre can vary wildly. To obtain a precise estimate, crude designs and cost analysis for every separate obviated project would be needed (Vuren, et al., 2017). This falls well outside the scope of this research, which aims to sketch a general picture for all the dikes in the Rhine-Meuse delta area. The high water protection program (HWBP) uses indicative values as presented in Table 6.1. These however offer very limited precision, and a narrowing down of these ranges is required.

Table 6.1 HWBP reference values for costs per kilometre (incl. btw, pp 2021) (Haga, et al., 2021)

Project size:	Projects with limited task/complexity	Projects with average task/complexity per km	Projects with large task/complexity per km	Exceptional projects
Total investments cost per km:	€0 - €5 mil./ km	€5 - €10 mil./ km	€10 - €15 mil./ km	> €15 mil./ km
Percentage of dikes in category:	Ca. 30-40%	Ca. 40-50%	Ca.10-20%	Ca. 10%

Fortunately, numerous reinforcements have already been budgeted in the definitive HWBP proposal for 2023 - 2035 (HWBP, 2023), of which several are representative for the Southern and middle branches of the Rhine-Meuse delta. The average cost/km in corresponding water boards *Hollandse Delta* and *Brabantse Delta* is €6.7 million/km. For details see Appendix I.

There are definitely some considerations to take into account with this estimate. The HWBP of the entire country has a slightly higher average of €7.8 million/km. Water boards tend to program those reinforcements projects that are needed the most sooner (meaning an overestimation of the average). Simultaneously it is also not uncommon that the 'simple' projects appear on the budgets first, because the more complex instances are still being worked on. Furthermore, the few typical reinforcements at for example the Hollandsch Diep that Delta21 may obviate, are surprisingly 'cheap' at ca. €5 million/km. To describe the uncertainty of these estimates, Figure I.31 presents a brief statistical analysis of all budgeted HWBP dike reinforcements, with a fitted a distribution (GEV). The 90% confidence interval of the reinforcement costs per kilometre becomes approximately [€2 mil./km, €25 mil./km].

An embankment can also be disapproved on multiple tracks (see Section 3.1.2), which raises the task/complexity of the reinforcement. A doubled cost reduction is assumed for these projects if obviated fully, whereas a partial obvi-ation (i.e. Delta21 only manages to reassess one track positively) is assumed to only reduce costs by 25%.

Figure 6.1 Histogram and fitted GEV distribution on HWBP project budget reinforcement costs

6.2.2 Determine the amount of obviated reinforcement project kilometres

A total amount of 127 km, about 30% of the total 418 km of considered trajectories[1], currently needs reinforcement in at least on of the tracks piping (STPH), inner slope (macro)stability (STBI), or height (GEKB). Using the method as described in Section 3.1.2, a required reduction height in water level at normative frequency is assigned to every stretch of dike using fragility curves (for details see Appendix J). Wherever Delta21 is able to reduce by at least this height, a reinforcement project can be obviated. Using the same method for the future climate, a failure probability increase leads to another 269 km of required reinforcements in the current system, with new required reduction heights. It is assumed that the norms are unchanged in this future scenario, as well as the fragility curves.

Obviations in the current climate - within the HWBP

Figure 6.2 presents the possible obviations for the preliminary configuration of Delta21 in the current climate. Out of the total 127 km that would need reinforcement, about 33% no longer requires one anymore. Table 6.2 presents the results for the preliminary configuration of Delta21, and summarizes the results per track, of which detailed maps are also available in Appendix J. Of the segments that were assessed negatively on more than one track, Delta21 yields a positive reassessment in one or two (but not all) tracks in 6.5 km (partial obviation), and 2.9 km for multiple tracks (complex obviation).

Note that approximately 300-400 km of dike in the Rhine-Meuse delta is not included in any of these categories. These are for example sea dikes, or embankments that fall outside of the validated model area (far into the river dominated area). They are denoted as 'No data' in Table 6.2.

Table 6.2 Classification totals of dike trajectories with Delta21 (preliminary configuration)

Preliminary configuration of Dlta21	Already suffices	Not enough to obviate	Enough to obviate	Enough to obviate - complex[1]	Enough to obviate - partial[2]	No Data
STPH	324 km	34.4 km	20.3 km	[1]positive reassessment on two tracks		-
STBI	312 km	59.7 km	11.7 km	[2]positive reassessment on one out two or three tracks		-
GEKB	469 km	12.7 km	12.1 km	(See Section 6.2.1)		-
combined	**383 km**	**85.8 km**	**31.9 km**	**2.9 km**	**6.5 km**	**364 km**

Delta21 has the greatest reductions of water levels at and around normative frequencies for the Storage-dominated and transitions areas. It is no surprise that these regions also exhibit the most obviated reinforcement projects. The sensitivity of a dike's failure probability to a lower MHW depends of course on the considered track. The fragility

[1] All trajectories for which data is available, and excluding sea dikes. See also Appendix J.

curves (also presented in Appendix J) account for this. Particularly embankments disapproved on height, or to a lesser extent piping, tend to profit the most from Delta21. Stability of the inner slope is less sensitive, as factors like duration and saturation weigh in.

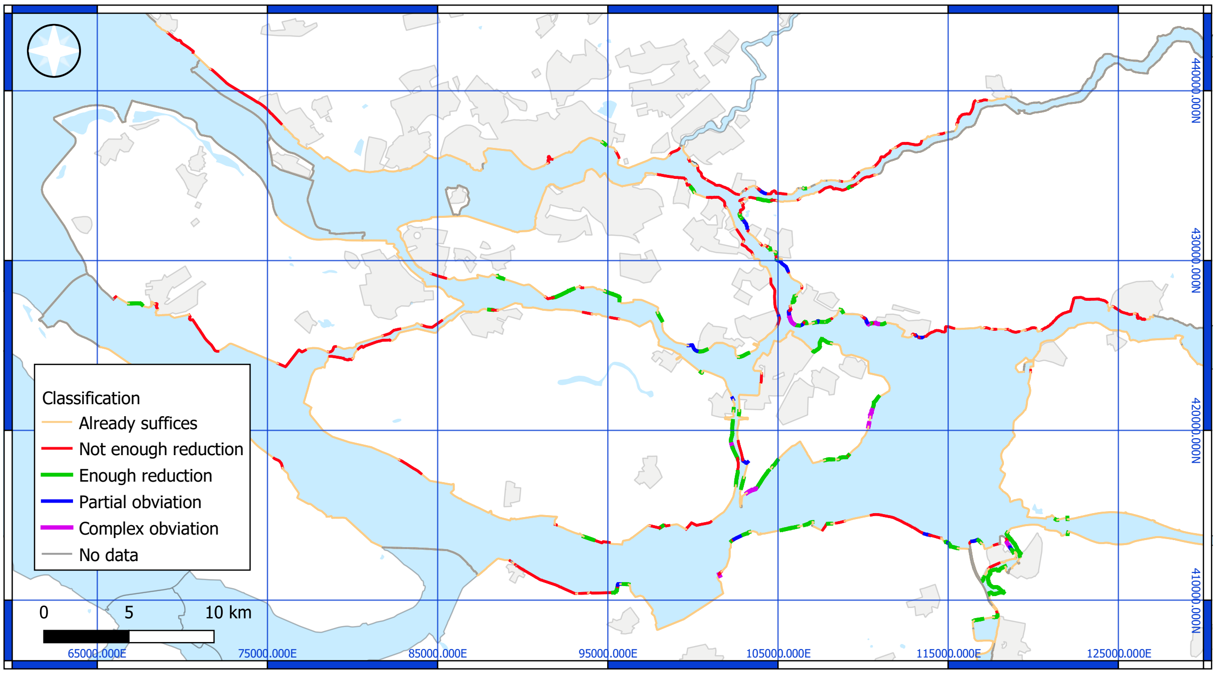


Figure 6.2 Map with classifications of all dike trajectories in the Rhine Meuse delta after implementation of Delta21

Table 6.3 presents the summarized results for various considered operational configurations. As indicated in Chapter 5.3, reductions of water levels around normative frequencies are particularly sensitive the closure criteria, which translates as expected to these values. For a track-specific breakdown of the total values, view Appendix J. For the second variation, the obviation is split into two parts. The first is attributable to implementation of Delta21, but the second is a direct result of changing the closure criterion at Dordrecht for the Europoortkering. Counting these obviated kilometres towards Delta21 would not be appropriate.

Table 6.3 Obviated reinforcement kilometres in Delta21 operational configurations in the current climate

Configuration	Obviation of average complexity reinforcement project	Obviation of more complex reinforcement project	Partial obviation or reduction in task of reinforcement project
preliminary configuration of Delta21	31.9 km	2.9 km	6.5 km
Delta21 and the Europoortkering closure criterion at Dordrecht of NAP + 2.5 m	34.2 km (31.7 + 2.5)	4.3 km (4.3 + 0)	6.0 km (4.4 + 1.6)
Delta21 with closure criterion Dordrecht NAP + 2.9 m	10.6 km	0.7 km	3.4 km

Obviations in the future climate scenario

In the future climate scenario, both a system with and without Delta21 will require additional reinforcements in relation to that same system in the current climate. An increase of water level at normative frequency can is translated to an increase in failure probability, using once again fragility curves (see Appendix J). This is then compared once again to the cross-sectional requirement for the three tracks considered before too: piping (STPH), (macro)stability of the inner slope (STBI), and height (GEKB). The difference between the dikes that now need to be reinforced for a system with and without Delta21 is a defined as a future cost reduction. Using a scenario in 2100 implies that a dike segment which would still suffice in 2101 is not included. Conversely, a dike segment that would yield a positive assessment up unto 2099 is included.

Figure 6.3 and Figure 6.4 present maps of the delta with an indication where reinforcement of primary flood defences will be necessary in the future climate scenario, for the current system and Delta21 system respectively. There is a separate category for dikes that already need to be reinforced within the HWBP on one specific track, and are now disapproved on another track. This is done, because reinforcement projects may affect the failure probability of other tracks too, when the track that it is disapproved on is addressed by the water board. This depends strongly on the authority's preferences and specific solution. When a dike segment is disapproved in 2017, the new design will look ahead for the other tracks too to ensure it suffices completely in 2050. Therefore, the blue indicated areas in Figure 6.3 and Figure 6.4 are very likely to need a reinforcement in the future scenario (2100), but not as certainly as those in red: dikes that are fully approved within the WBI2017, but have too high failure probabilities in the future climate.

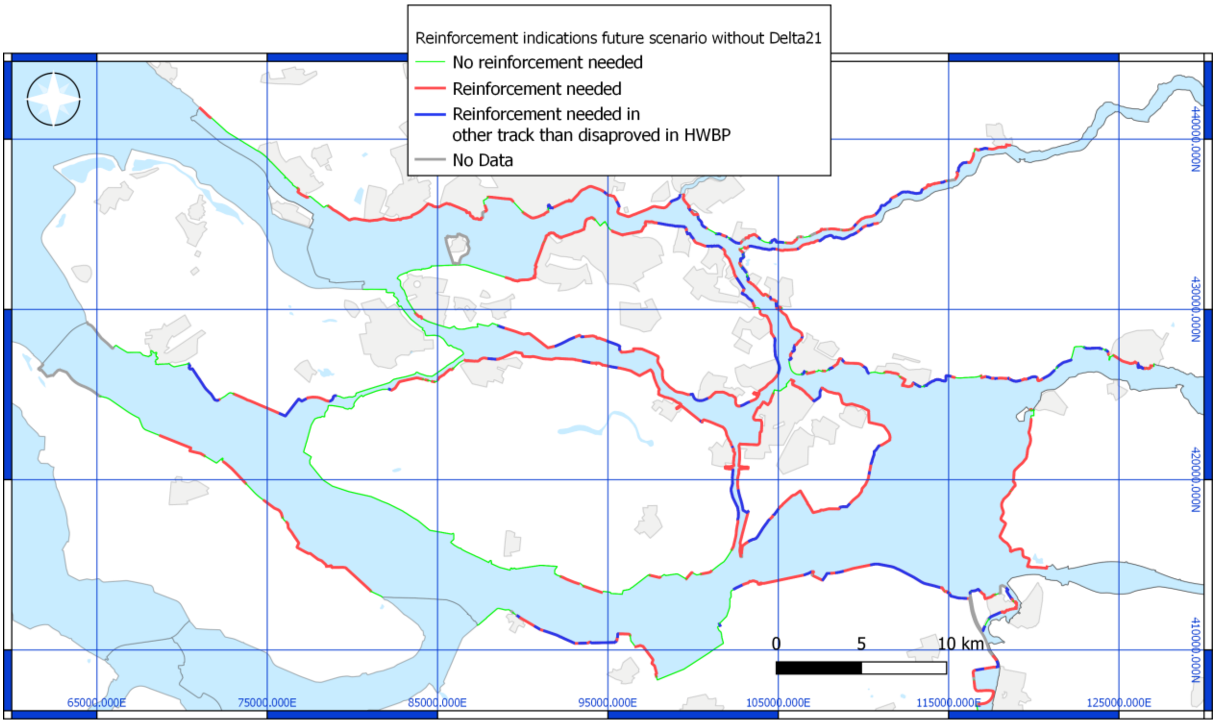


Figure 6.3 Necessary reinforcements in the future climate scenario without Delta21

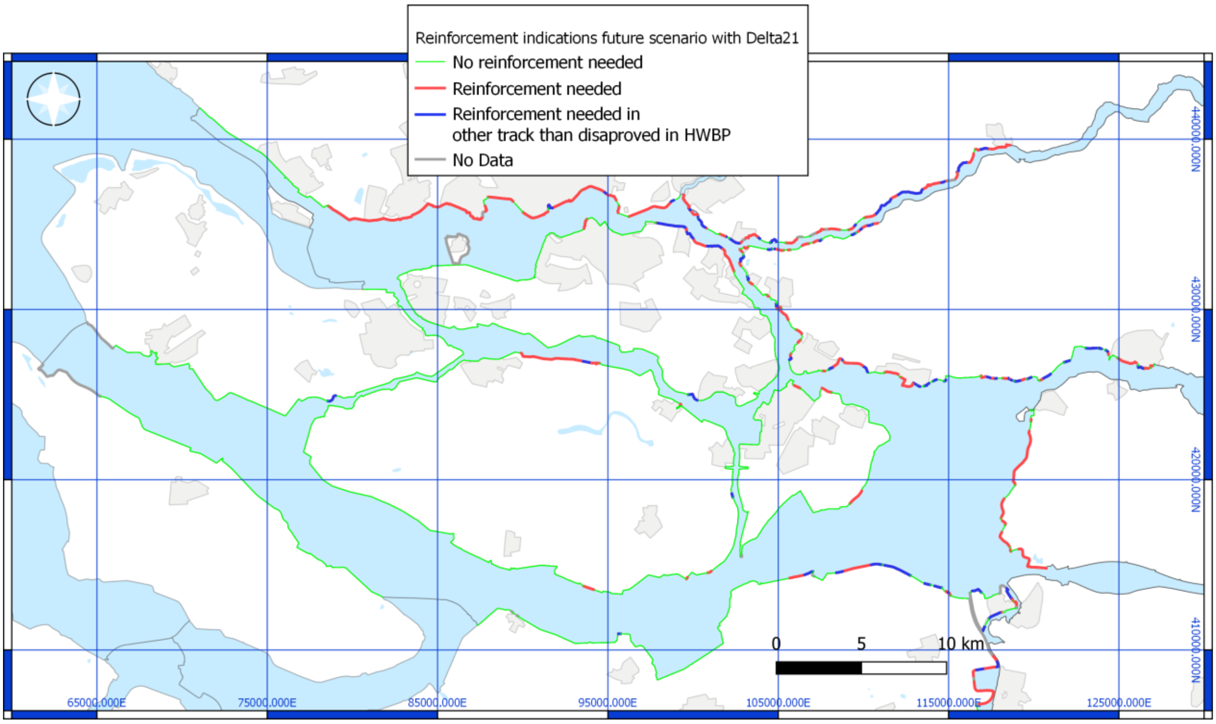


Figure 6.4 Necessary reinforcements in the future climate scenario with Delta21

Table 6.4 presents the summarized reinforcement lengths in the future scenario. Whereas in the current system approximately 269 km of dike have to be reinforced, the Delta21 system will require just approximately 99 km. For the low closure criteria variation of Delta21[1], this number drops by another 40 km. The reinforcement obviation by Delta21 has to be corrected in both cases by subtracting 17.6 km. This is because of the presence of a very specific group of dikes: in the current climate Delta21 can obviate their reinforcement on a specific track. But in the future scenario, the dike stretch is disapproved anyway on that same track. Obviously, these do not appear in the current system, because they have already been reinforced somewhere before 2050. A second reinforcement requirement (which could then be obviated) is not included to retain a conservative and reliable figure.

Table 6.4 Embankment lengths per reinforcement category in the future climate scenario

System	No need for reinforcement	Need for reinforcement - certain	Need for reinforcement - additional	No data
Current (Figure 6.3)	126 km (30%)	196 km (47%)	73 km (17%)	22 km (5%)
Delta21 (Figure 6.4)	295 km (71%) - 17.6 km	72 km (17%) + 17.6 km	29 km (7%)	22 km (5%)
Delta21 and the Europoortkering closure criterion: Dordrecht NAP +2.5 m*	335 km (80%) - 17.6 km	39 km (9%) + 17.6 km	22 km(5%)	22 km(5%)

*Note that this operational control lies below the lower limit described in Chapter 5.3, and contains several instabilities/inaccuracies

6.2.3 Resulting cost reduction from obviated reinforcements

Combining the respective cost estimates with the obviated kilometres previous sections, an indication can be given to the magnitude of the cost reduction from obviated reinforcements. A distinction is made between the short and long term cost-reductions. The former is in the context of the HWBP, and assumed to be spread out approximately evenly between the construction year of Delta21 (2030) and the last year of the current HWBP (2050). The same goes for the latter, which is spread out evenly between the end of the current HWBP (2050), and the reference year of the future climate scenario (2100).

All values presented in this section are nominal. In Section 6.4 a net present value calculation is performed on all savings to transform them to real values. Furthermore, a 90% confidence interval is presented for every value. This uncertainty is dominated by the large range of reinforcements costs per kilometre. The speed of sea level rise does not influence these figures, but does change the year in which the total of reinforcements is expected, which in turn influences the net present value of the obviations.

Table 6.5 presents the results for the preliminary configuration of Delta21 in the current climate, and several operational control variations that chapter 5 has concluded the system is very sensitive to. Akin to Section 6.2.2, results are separated by complexity/task size. The detailed classification lengths split per track are given in Appendix J. For the second variation, the cost-reduction has an indication of what percentage can be attributed to implementation of Delta21. The remainder is a direct result of changing the closure criterion at Dordrecht for the Europoortkering. Counting these savings towards Delta21 would not be appropriate. Nevertheless, the expected cost-reductions due to obviated dike reinforcements attributable to Delta21 rises slightly, from €275 to €285 million.

Table 6.5 Savings within the HWBP by obviation of reinforcements

Configuration	Obviation of average complexity reinforcement project [€M] - 90% confidence	Obviation of high complexity/task reinforcement project [€M] - 90% confidence	Reduced complexity/task of reinforcement project [€M] - 90% confidence	Total savings [€M] - 90% confidence
Estimated saving per km	*€6.7 mil. / km* *90% confidence:* *€2 - €25 mil./km*	*doubled rate* *[€13.4 mil. / km]*	*halved rate* *[€3.35 mil. / km]*	
preliminary configuration of Delta21	€214 [€64 - €798]	€39 [€12 - €145]	€22 [€6.5 - €81]	€275 [€89 - €1108]
Delta21 & Europoortkering closure criterion Dordrecht NAP + 2.5 m	€229 [€68 - €855] 92.7% attributable to D21	€58 [€17 - €215] 100% attributable to D21	€20 [€6.0 - €75] 73.3% attributable to D21	€307 [€92 - €1145] 92.8% attributable to D21
Delta21 with closure criterion Dordrecht NAP + 2.9 m	€71 [€21 - €265]	€9.4 [€2.8 - €35]	€11 [€3.4 - €43]	€91 [€27 - €341]

The reduced costs by obviation of future reinforcements are presented in Table 6.6. In the future climate scenario, Delta21 can reduce costs by a total of €1,007 million by 2100. The values for lowered closure criteria are included too, despite going below the lower limit described in Chapter 5.3. Those calculations contain several instabilities/inaccuracies, but does provide an indicative figure for what might be possible with an improved operational control.

Table 6.6 Embankment lengths per reinforcement category in the future climate scenario

System	Reinforcement costs [€M] - 90% confidence	Reduction by Delta21 [€M] - 90% confidence
Current	€1,802 [€538 - €6,725]	-
Delta21	€795 [€237 - €2,965]	€1,007 [€301 - €3,757]
Delta21 and the Europoortkering closure criterion: Dordrecht NAP +2.5 m*	€527 [€157 - €1,965]	€1,275 [€381 - €4,757]

*Note that this operational control lies below the lower limit described in Chapter 5.3, and contains several instabilities/inaccuracies

Reduced costs in Volkerak-Zoommeer

In a system with Delta21, the frequency by which the Volkerak-Zoommeer must be used for storage is reduced to near-zero. The criterion of NAP + 2.6 m upstream of the Volkeraksluizen is virtually never reached when Delta21 escalates. This does not change for the future climate scenario, or different closure criteria. The additional conditional norm for embankments in the Volkerak-Zoommeer area may therefore be dropped entirely, with a corresponding decrease in water level exceedance frequencies. As Section 3.2.2 already described, currently there are no particular reinforcement costs that can be obviated. In a future without Delta21 however, additional reinforcements may be required in the Volkerak-Zoommeer area if it is used for storage more often. Unfortunately, the employed model cannot accurately reproduce exceedance frequency curves downstream of the Volkeraksluizen, meaning future savings cannot be reliably estimated.

6.3 Estimated savings less frequent flooding unembanked areas

Combining the shifted exceedance frequency curves for Dordrecht with the damage graphs of Figure 3.3 yields the damage as a function of frequency. For the current climate the result is presented in Figure 6.5a. The integral of both functions yields expected annual damage as presented in Table 6.7. As with the previous subsection, all values presented here are nominal, and are made real in Section 6.4 to correct for the time dependency of money. A more detailed exposition of the calculation is given in Appendix K.

For the future climate scenario the result is presented in Figure 6.5b. Again, the integral of both functions yields expected annual damage as presented in Table 6.7. The curves converge (most visibly for the current system) to a damage value of 5.2 * 10^7 €, because the damage profile in Figure 3.3 plateaus at this value. The estimated difference between the two systems is thus conservative, and additional savings can be expected if the damage profile is allowed to extend into these even more extreme regions. Nevertheless, the plateau could be due to for example the damage being equal to the total economic value of the flooded area, meaning that additional research is required for reliable estimates in this range of values.

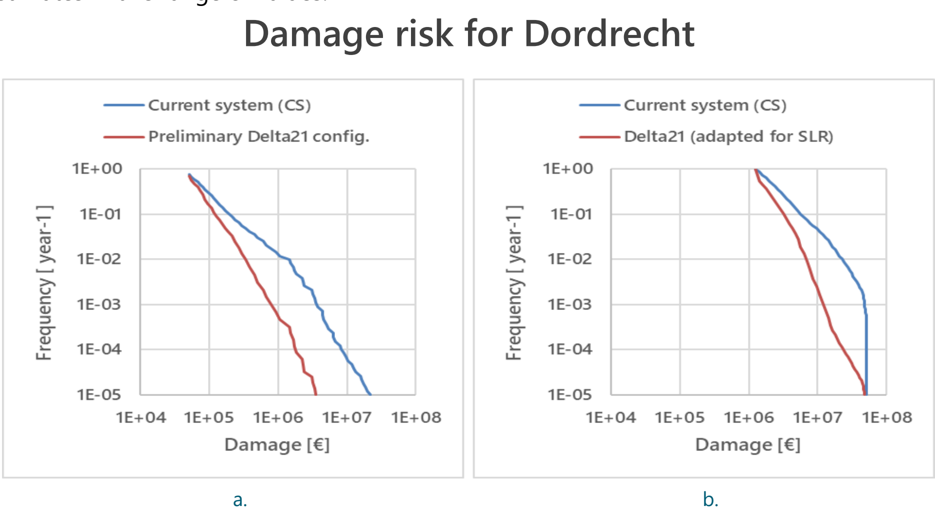


Figure 6.5 Damage risk function for Dordrecht in the current (a) and future (b) climate for a system with and without Delta21

Table 6.7 Expected yearly damages for Dordrecht's historical harbour and flanks

Climate scenario	System	Expected yearly damage	Reduction
Current climate	Current system	€ 122,096	-
	Delta21	€ 69,018	€ 53,078 (43.5%)
Future climate scenario	Current system	€ 3,346,251	
	Delta21[i]	€ 1,981,921	€ 1,364,329 (40.8%)

The reduction in expected yearly damage rises from ca. €50,000 per year in the current climate, to ca. €1,360,000 per year in the future scenario. In both cases, the relative decrease is approximately 40%. Due to the exclusion of model uncertainty in the computation of water level exceedance frequency curves (review Section 2.2.5), these estimates are somewhat conservative. The relative decrease in water level is not expected to change much, but a higher absolute yearly expected damage will yield larger damages across the board, and therefore realise more saving potential. Table 6.8 provides the summarized results for the various configurations to which sensitivity is high, as defined in Section 5.3.

Table 6.8 Expected yearly damages for Dordrecht's historical harbour and flanks in several configurations

	Current climate			Future climate scenario	
Dordrecht closure criterion Europoortkering:	NAP + 2.9 m	NAP + 2.5 m	NAP + 2.9 m	NAP + 2.9 m	NAP + 2.5 m*
Dordrecht closure criterion Delta21:	NAP + 2.5 m	NAP + 2.5 m	NAP + 2.9 m	NAP + 2.9 m	NAP + 2.5 m*
Current system [€/year]	€ 122,096	€ 102,414	€ 122,096	€ 3,346,251	€ 2,806,832
Delta21 [€/year]	€ 69,018	€ 40,653	€ 92,314	€ 1,981,921	€ 1,404,356
difference [€/year]	€ 53,078	€ 61,760	€ 29,782	€ 1,364,329	€ 1,402,476
difference [%]	43.5%	60.3%	24.4%	40.8%	50.0%

*Note that this operational control lies below the lower limit described in Chapter 5.3, and contains several instabilities/inaccuracies

6.4 Net present value of savings

All described cost-reductions do not occur at once. To properly account for the time dependency of money, the net present value (NPV) of the expected savings must be calculated to correctly appreciate the nominal quantities. Only then can a comparison be made with e.g. the costs of Delta21, in light of a costs-benefits analysis. The NPV is calculated using the following equation:

$$NPV = \frac{V_{nominal}}{(1+i)^p}$$

Equation 6-1

Where:

$V_{nominal}$ = the nominal value of a(n obviated) cost in a given year
i = the discount rate
p = the period that has passed since the reference year

The discount rate (i) is set 1.6%, conform HWBP guidelines for obviation of sunken costs, among which dike reinforcement projects belong (Ministerie van Financiën, 2020). Artikel 7.24 of the Waterwet (2009) contains the juridical foundation allowing reduced reinforcement costs to be counted towards the viability of a project. (werkgroep Financiële uitwisseling tussen dijkversterking en rivierverruiming, 2019). For detailed substantiation of this choice see Appendix P.

Section 6.2.3 splits the obviated reinforcements into a short and long term cost reduction. The former is assumed to be approximately spread out evenly among the period 2030-2050, and the latter between 2050-2100. The reduction in expected damage of unembanked areas is assumed to increase linearly from € 53,078 / year in 2017 to €1,364,329 / year in 2100 as calculated in Section 6.3. Naturally, the period 2017-2030 is not included in the contributions, because Delta21 is finalized in 2030 at the earliest. The full calculation is provided in Appendix P.

The net present value of Delta21 in 2030 is €783 million, with a 90% confidence interval of [€251 million, €2,852 million]. The large interval is dominated by the large uncertainty in reinforcement costs per kilometre, as determined in Section 6.2.1. Uncertainty in for example the speed of sea level rise yields a significantly smaller interval. Considering for example the 95% confidence bounds of the IPCC SSP-8.5 scenario, implies that the W+ climate scenario is reached in ca. 2075 (upper bound) or ca. 2150 (lower bound). Assuming that the same reinforcements are still needed, but in a different year, this yields a 95% confidence bound of the NPV of [563 million, €865 million]. Naturally, when other climate change scenarios are considered, this range can become larger, but the SSP-8.5 scenario is principally used in the context of flood protections.

6.5 Concluding remarks

There are no expected savings from prolongation of the Maeslantkering's lifetime, because Delta21 does not accomplish this. Reduced water levels yield reduced failure probability of dike segments, leading to positive reassessment of 40 km on the short term, and another 150 km in the future scenario. The cost of these obviated reinforcement projects is estimated at €6.7 million/km, but has a substantial uncertainty. The obviated project kilometres are therefore more robust results, than the final monetary figures. The reduced damage in the unembanked areas of Dordrecht is initially rather small (€50,000 / year), but grows to a significant €1.36 million / year in the future climate. The net present value of all monetary savings with a discount rate of 1.6% cuts into the final results quite heavily, leaving an estimated 783 million attributable to Delta21.

7 DISCUSSION, CONCLUSION, AND RECOMMENDATIONS

7.1 Discussion

The following sections provide important considerations with regards to the research and results of this thesis. Computational limitations or obstacles are discussed, but attention is also paid to other (more general) aspects.

Hydraulic model performance and limitations

A number of simplifications and assumptions are made along the way to run a model with Delta21. The results are therefore not always as reliable as would be desired. In particular, calculating without model uncertainty is essentially a strong deviation from prescribed methods in the WBI protocols. Also, for very low (and to a lesser extent very high) return periods the model is not validated all that well at all. Validation errors of several centimetres with other model datasets are not uncommon. It is therefore stressed once again, that the results are to be interpreted in a relative sense: reductions in specific water levels between a system with and without Delta21.

The results of Section 5.3 show that the water level exceedance frequencies are very sensitive to operational control of Delta21. However, the amount of calculation points with water levels that lie around the closure criteria is far too small to assess nuanced differences in the operation. When a single calculation point changes from no escalation to escalation (or vice versa) by changed criteria (even if it's just by 0.01 m), it has a very significant impact on resulting exceedance frequencies. The interpolation around the calculation point is sufficient to answer the questions in this research, but not for further detailed research into improved closure control and optimization of Delta21.

Fragility curves usage

To relate the reduction in water level at a certain frequency to a reduction in failure probability of a dike segment, fragility curves of the knowledge program sea level rise (KPZSS) were used. Although these provide a quick and simple way to relate water levels to failure probabilities, caution must be paid to the reliability of these results. There is merely an evaluation of the water level at normative frequency, and not every dike segment has an assigned fragility curve. A rough interpolation is performed to also relate water levels to failure probability for the unclassified dike segments. This interpolation only accounts for the considered segment being rural or urban, its surrounding fragility curves, and those of the other segments in the same trajectory. No attention is paid to the actual cross-sectional characteristics of the segment, which is principally what determines the fragility curve type. summarized, the method is crude and can only give approximations of changes in failure probabilities. In specific local assessments or detailed cost-benefit calculations for Delta21, this method is no longer sufficiently accurate. The influence of Delta21 in terms of changes in water level statistics is a significantly more robust description then corresponding changes in dike failure probabilities.

Model uncertainty and database reparation

Even though model uncertainty is excluded from the entirety of the calculations in this research, the effects of database reparation are still noticeable. Section 2.2.5 describes the phenomenon in detail. Shortly put, when conditions increase in extremity, the computed water level cannot get lower. This holds, even if barriers start to escalate or pumps turn on. The problem presents itself not only in the results of a system with Delta21, but also in the results for the current system, and even in official WBI databases. The more extreme event naturally has a smaller probability than its neighbouring boundary condition calculation point. The contribution to water levels at the same frequency is therefore smaller, but not necessarily negligibly small. There is a massive potential for obviating reinforcements if this problem is addressed in detail.

Optimization of Delta21

As discussed above, the databases often contain a lower water level for an increasing extremity of boundary conditions. This is hence repaired and thus removed from the final results. However, it does indicate that there is (a lot of) room for to suit, because some there is some (unknown) amount of unnecessary discharge. Nevertheless, if Delta21 optimized for a single location, say Dordrecht, surrounding locations lose some of their reduction in water level. Specifically, those place less sensitive to Delta21 might have profited from a slightly further opened spillway. An economic consideration will determine where the optimal value lies, because using pumps costs electricity. What this will approximately turn out to be, is outside of this research's scope, but it will definitely be somewhere below the maximum value as is used in the current schematization. Therefore, reductions of water level exceedance frequencies will ultimately be a bit smaller. Similarly, higher operation and maintenance costs could be expected for a configuration of Delta21 with a lower closure criterion. When it is used more often, those costs will increase. Using the pumps can however also be very cheap, or even generate money at times where the electricity demand is particularly low (Berke, personal communication). In situations with only moderate extremity, pumping can be pre- or postponed until a moment where demands are low, using the storage lake in the meantime. The determination of these influences is deserving of its own research, and therefore not included in the operational variations of Section 5.3. Those results give merely a range of possible hydraulic influence by Delta21, with no regard for what is economically optimal.

Storm surge duration schematization

The effect of a longer storm surge duration has been analysed in detail. It is concluded that a system with Delta21 has a far weaker sensitivity to longer storms (see Section 5.4). It is however very plausible that the sensitivity to shorter storms is also weaker. If true, the recommendation of including storm surge duration stochastically has to be attenuated somewhat. It's possible that a deterministic duration can still be found where the effects of longer and shorter storms cancel each other out approximately, similar to how this happens in the current system. More research is needed to indicate whether this is possible, and if so, how long this duration should be.

Operational control of the Hollandsche IJsselkering and Volkeraksluizen

The operation of the Europoortkering, Delta21 components, and the Haringvlietsluizen are adapted so suit this research, as Section 2.2.4 discusses. However, the control of other barriers is left the same as originally present in the MHWp5 model. The Hollandsche IJsselkering and Volkeraksluizen keep their original operational control. It is not investigated if this operation is still realistic and/or optimal in a system with Delta21.

Uncertainty in dike reinforcement costs per kilometre

The monetary results of Chapter 6 contain particularly wide confidence intervals. The reason for this is the large uncertainty of the estimated dike reinforcement costs per kilometre, which dominates the reliability of all calculations that use it. The figures that describe the number of kilometres that can be obviated are therefore far more robust, than the values that describe a cost-reduction in euros. Because it is known exactly where kilometres of reinforcement can be obviated, higher accuracy can be obtained with specific reinforcement estimations for reinforcing those dike trajectories. This is however not done in this research, which therefore merely provides a contextualisation to the aforementioned obviated kilometres. Prior to for example a decision to start construction of Delta21, higher precision of reinforcement costs is imperative.

7.2 Conclusions

To what extent is Delta21 capable of providing a cost-effective alternative to the current flood protection policy in the Rhine-Meuse delta?

Delta21 yields significant reductions in water level exceedance frequencies in the Rhine-Meuse delta. This increases for larger return periods and proximity to the storage dominated region. Around normative frequencies, reductions reach up to 0.5 m in the current climate, and 0.8 m in the future scenario, which allows a dike reinforcement obviation of 41 km by 2050, and 150 km more by 2100. The net present value of cost-reductions by Delta21 is €783 million, with a 90% confidence interval of [€251 million, €2,852 million] due to large uncertainties in reinforcement costs.

This covers about 20% of the total construction costs, and is insufficient to make Delta21 viable alone. However, not all costs are related to flood protection exclusively. If the components required for energy storage are viable on their own, merely the additional costs of the spillway and storm surge barrier would have to be included in an updated cost-benefit analysis. Smaller design dimensions or pump capacity of Delta21 has been shown to be just as effective, and would further cut costs. Additional savings beyond 2100 are plausible, but outside of this research's scope. Furthermore, less people displacement or flooding of unembanked areas may achieve additional societal value, but is difficult to quantify. More research will have to indicate whether lower cost attribution and additional value sources ultimately lead to Delta21 being feasible in the context of flood protection.

The sections below provide supporting concluding answers to all sub questions.

7.2.1 Influence of Delta21 on the hydraulic system

1. How does Delta21 influence the hydraulic system?

Water level exceedance frequencies in the Rhine-Meuse delta are dominated in subregions by the sea water level, rivers discharge, storage characteristics, or a combination of these. Delta21 affects the hydraulic response by extracting large amounts of discharge from the Southern delta branch. This reduces water level exceedance frequencies proportionally to how strongly the current response is dominated by storage characteristics of the system, and to a lesser extent the domination of river discharges.

1a. How does the Rhine-Meuse area function as a hydraulic system including Delta21?

The sea (downstream) and the rivers (upstream) determine the boundary conditions to which the delta is exposed. Controllable barriers influence the water level response, and with Delta21 the Haringvlietsluizen lose their primary storm surge barrier function. Delta21 introduces a large storage component, and changes the storage characteristics of the system.

1b. How can this system and the influence of Delta21 be schematized and quantified?

One-dimensional hydraulic modelling can generate water level databases that describe peak water levels for every combination of boundary conditions. Integrating the data with boundary statistics yields exceedance frequency curves. The difference at normative frequency is indicative of how large Delta21's effect is. The schematization of Delta21 is improved on many aspects, and now more accurately represents its storage characteristics and operational control.

7.2.2 Potential cost reduction strategies with Delta21

2. How can Delta21 accomplish cost reductions in the context of flood protection?

Delta21 has three primary strategies to reduce costs in the context of flood protection (see below). Delta21 contributes to all strategies by attenuating water levels in various conditions. The most sizable contributions to a strategy originate from water level reductions in specific conditions. These are not the same for each strategy. The most promising is the obviation of dike reinforcements, requiring reduced water levels in illustrative conditions for normative frequencies.

2a. What are potential strategies for saving costs in the delta?

Three considered potential approaches are defined as follows:

1. Lengthen the lifetime of the Europoortkering (specifically, the Maeslantkering component)
2. Obviate dike reinforcement projects on short and long term
3. Reduce the expected yearly average damage at the unembanked areas of Dordrecht

2b. How can Delta21 contribute to those strategies?

The contributions towards those strategies by Delta21 is as follows:

1. The Europoortkering's lifetime can be prolonged through a lowered failure probability per closure, lowered closure frequency, or shrinkage of the failure dominated region. Delta21 can contribute to the respective approaches by preventing double closures due to temporarily high inner water levels or calmer closing conditions, keeping water levels below the closure criteria of the Europoortkering, and mitigation during a failure.
2. Fragility curves of dikes describe the failure probability conditional on water level. Reducing water levels, particularly in illustrative conditions, decreases exceedance levels around normative frequencies. For several trajectories this may yield a positive reassessment of dikes.
3. Reduced extreme water levels across all frequencies, integrated with damage profiles, gives a decreased expected yearly average damage at Dordrecht.

7.2.3 Delta21 influence on the Europoortkering's lifetime

3. What is the influence of Delta21 on the lifetime of the Europoortkering?

Delta21 does not have any significant effect on the Europoortkering. No prolongation of its lifetime is expected.

3a. What is Delta21's influence on the Europoortkering's failure probability per closure?

The failure probability per closure, which is dominated by the Maeslantkering's operational software, does not decrease due to Delta21. Double closures cannot be removed from the operational control, and the time of closure is not preponed enough to close during calmer conditions.

3b. What is Delta21's influence on the Europoortkering's closure frequency?

The closure frequency of the Europoortkering is dominated by its closure criterion at Rotterdam, especially with a rising sea level. This location is mostly unaffected by Delta21, and thus so is the Europoortkering closure frequency.

3c. What is Delta21's influence on regional sensitivity to the Europoortkering failure probability?

The area that is affected by a decimation of the Europoortkering failure probability is slightly smaller in a system with Delta21. The effect of a failure is slightly mitigated in the current climate. In the future climate scenario, the effect reverses slightly, and a larger area experiences noticeable changes from a decimated failure probability, due to a higher sea level. Both effects are small and do not lead to a prolonged lifetime.

7.2.4 Delta21 reducing water level exceedance frequencies around norms

4. What is the effect of Delta21 on water levels at normative frequencies in the current and future climate scenario?

Delta21 is able to reduce peak water levels with increasing effectivity for large return periods and proximity to the storage dominated region. These reductions are not sensitive to deviations in the design of Delta21. Synergy with an improved Europoortkering failure probability only becomes noticeable in the future scenario in combination with even lower probabilities than a single decimation. Sensitivity to a changed discharge division at Pannerden is also limited to Dordrecht and Ridderkerk. These effects on water level exceedance frequencies get overshadowed by changes in operational control. Specifically the closure criterion strongly influences water levels at normative frequencies. This is because in a system with Delta21, illustrative conditions are regularly those where the water level stays just below the criterion. The various control configurations are considered separately in the determination of cost-reductions, to contextualize how important this sensitivity is. Stochastic inclusion of storm surge duration in further modelling with Delta21 is recommended for future research, as a system with Delta21 shows a much weaker sensitivity to longer storm durations.

4a. What is the effect of the preliminary reference configuration of delta21 on water levels at normative frequencies?

The preliminary configuration of Delta21 is able to reduce water levels around normative frequencies most effectively in the storage and transitions regions. In the current climate, MHW's in theses regions are reduced by approximately 0.2 - 0.5 m, as presented in Figure 7.1. In the future climate scenario, MHW reductions by Delta21 are even more prominent, ranging from approximately 0.3 to 0.8 m in the storage-dominated and transition regions, as presented in Figure 7.2. The future preliminary Delta21 configuration has an adapted closure criterion of NAP +2.9 m at Dordrecht. This is to prevent instabilities due to bidaily escalation during tidal high waters when discharges at Lobith exceed 15,000 m^3/s.

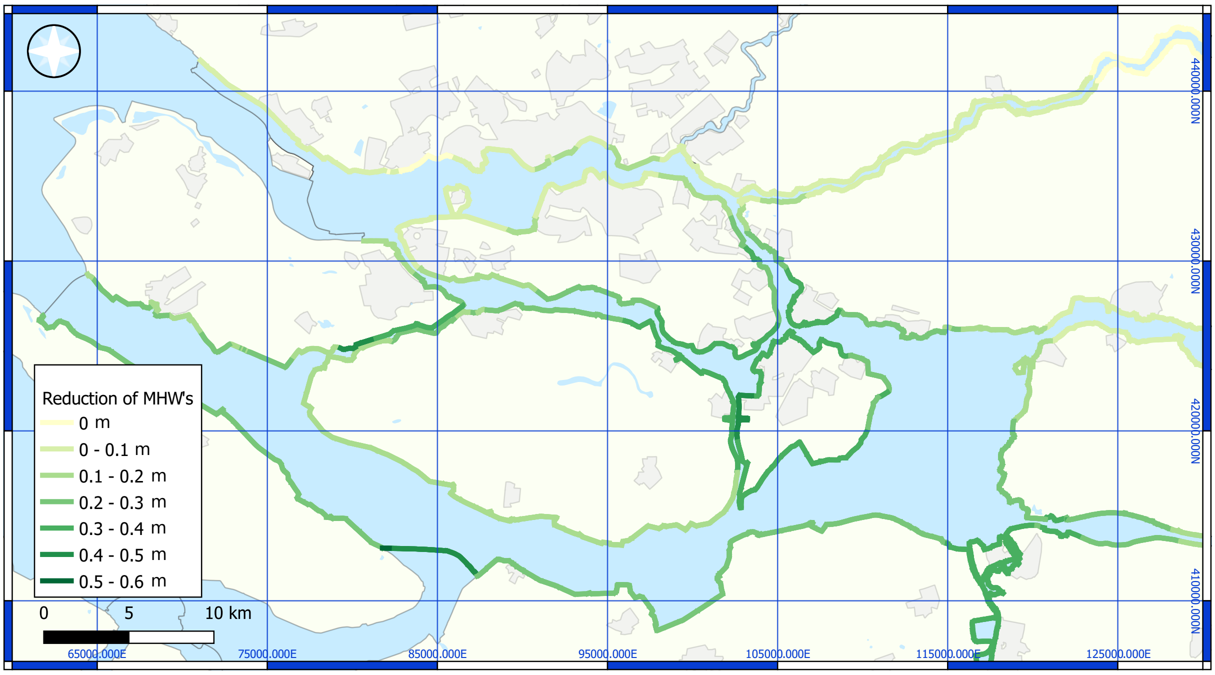


Figure 7.1 Reduction of MHW's in the preliminary Delta21 configuration

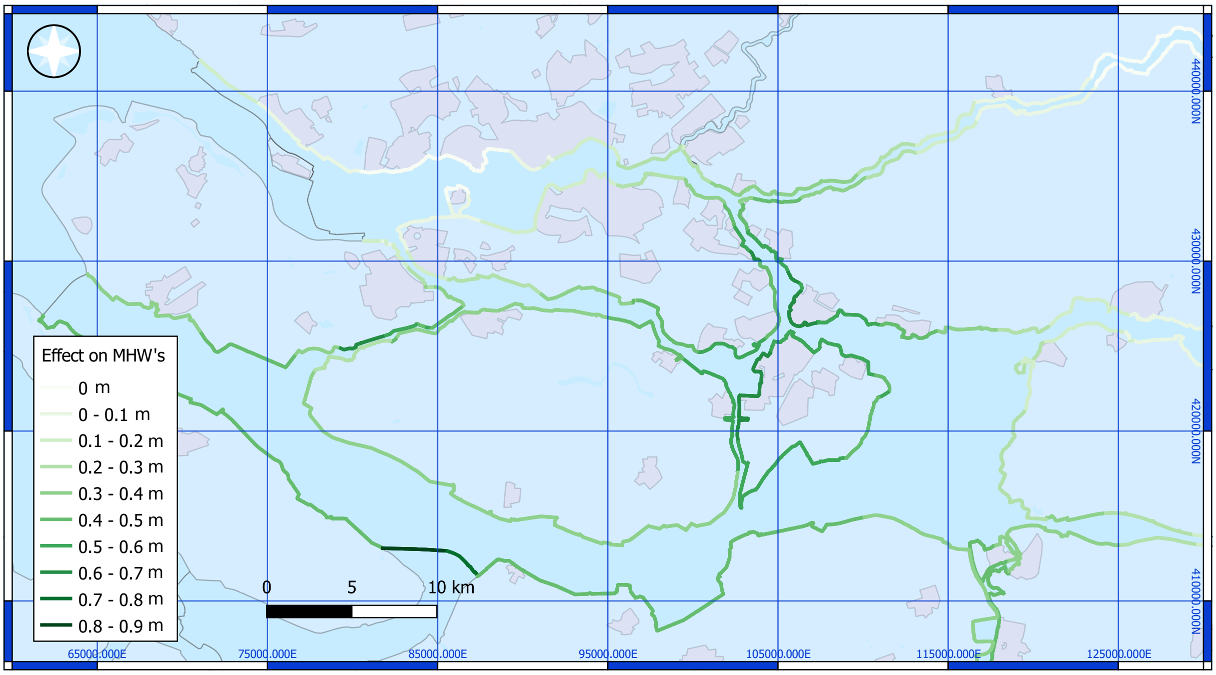


Figure 7.2 Reduction of MHW's in the future climate scenario, for a system with Delta21 relative to the current system

4b. How sensitive is this influence to variations in the Delta21 design?

The preliminary design of Delta21 is very conservative in terms of the pumping capacity, storage volume, and spillway dimensions. Reductions of these components, which determine the maximum capacity of, hardly makes a difference for water levels around normative frequencies.

Synergetic effects of combining Delta21 with an improved Europoortkering are small, if not negligible, in the current climate. For the future climate scenario, a small synergy can be observed in the failure dominated area and bordering transitions areas. An additional MHW reduction of 0.05 - 0.2 m can be attributed to Delta21. For even smaller Europoortkering failure probabilities and further sea level rise, the effect becomes more noticeable.

A changed discharge division at the Pannerdensche Kop does not have any particular synergies with Delta21, except for the area around Dordrecht and Ridderkerk which profits from an additional 0.1 - 0.2 m MHW reduction due to the relatively strict norms.

4c How sensitive is this influence to variations in the operational control of Delta21?

In a system with Delta21, illustrative conditions at normative frequencies in the storage dominated region and bordering transition region become very similar: a situation where water levels stay just below the escalation criterion. Because of this, a change in that criterion has an enormous impact on water level exceedance frequencies around norms. The reparation of the databases[1] is partly responsible for the large sensitivity too. Peak water levels in conditions slightly more extreme than illustrative (so with escalation of Delta21) are in truth much lower, but get artificially raised. Although not the most illustrative, the contribution to MHW's is not negligible. Nevertheless, the sensitivity to operational control strongly outweighs that of the other variations.

4d. Does a hydraulic system with Delta21 exhibit a significantly different sensitivity to storm duration?

The current system exhibits some sensitivity to a longer storm surge duration of 8 hours (25%): MHW's increase by 0.0 to 0.2 m. Contrarily, a system with Delta21 is almost completely insensitive to the longer storm surge duration, with the effect on MHW's not exceeding 0.05 m. A small underestimation of Delta21's effects is therefore plausible.

7.2.5 Estimated saving by Delta21

5. How high are the savings or cost-reductions attributable to Delta21?

The net present value of Delta21 is €783 million, with a 90% confidence interval of [€251 million, €2,852 million], dominated by large uncertainties in reinforcement cost estimates. Most cost reductions originate from obviation of dike reinforcements (96%), with an additional 4% from reduced damage in unembanked areas. Supplementary cost-reductions of up to €150 million are possible for maintaining a closure criterion of NAP + 2.5 m at Dordrecht for Delta21 and the Europoortkering. No optimization has however been performed yet, and operational costs also increase for more frequent usage.

5a. How much is saved by a lengthened lifetime of the Europoortkering?

Because the Europoortkering is virtually unaffected by the implementation of Delta21, no lifetime prolongation is expected. Therefore, no savings can be attributed to Delta21 via this approach.

5b. How much is saved by obviation of dike reinforcements?

On a short term (2030-2050) ca. 40 kilometres of obviated reinforcements yield a cost-reduction of €275 million with a confidence interval of [€89 million - €1108 million]. An additional €10 million can be attributed to Delta21 when the Europoortkering employs the same (low) closure criteria for Dordrecht. On a longer term (2050-2100) ca. 150 additional kilometres can be obviated, reducing costs by €1,007 million [€301 million - €3,757 million]. Maintaining a closure criterion of NAP + 2.5 m at Dordrecht has the potential to reduce costs by another €268 million, if an improved closure control can be formulated without instabilities. The large interval is dominated by the large uncertainty in reinforcement costs per kilometre, which are estimated to be €6.7 million/km with confidence interval of [€2 mil./km, €25 mil./km].

5c. How much is saved by less frequent flooding of unembanked areas?

The average yearly damage reduction in the unembanked areas of Dordrecht is approximately €53,000 per year, and grows to €1.36 million per year in the future climate scenario (2100). The decrease in relation to the current system is a stable 42%, but the absolute values rise greatly with sea level rise. Implementation of lower closure criteria variations can yield an additional +20% now, and +10% in the future scenario. The contribution to the total cost reductions is relatively small in comparison to the obviation of dike reinforcements: approximately 4%.

5d. What is the net present value of all cost reductions?

The net present value of Delta21 in 2030 is €783 million, with a 90% confidence interval of [€251 million, €2,852 million]. Within an IPCC SSP-8.5 climate scenario, uncertainties in sea level rise speed yields a confidence interval of [563 million, €865 million]. The uncertainty of reinforcement costs is therefore still dominant.

[1] For more extreme conditions, the water level cannot ever be lower than a less extreme event.

7.3 Recommendations

7.3.1 Costs and viability of Delta21

The cost-reductions in the context of Delta21 does not yield a net present value that covers all of its costs. However, neither does it have to, because other sources of value are generated with Delta21, in particular due to energy storage and generation. The storage lake and pump-turbines will likely be the first components to be constructed, if those separately have a positive cost-benefit relationship (which has to be shown first, but is deemed plausible). In that case, the question arises how high the additional costs are for using Delta21 in the context of flood protection. In essence, the spillway and storm surge barrier costs are split from the total construction costs. Then, a new cost-benefit balance emerges, which better indicates the feasibility of Delta21's alternative flood protection strategy.

The savings attributed to Delta21 in this report merely look into large and easily quantifiable value sources. Delta21 however also has benefits of a more societal nature, which are notoriously hard to quantify. For example, reducing the frequency of flooding in the unembanked areas of Dordrecht does not only reduce the damage risk, but also projects an image of safety and confidence in Dutch water management. What are governmental bodies and people in general willing to pay for not having the area flood with every year in 2100, but 10 to 100 times less often for water levels of NAP + 2.5 m to NAP + 2.8 m; a situation where the whole historical harbour is inundated? Another example is not having to displace as many people and buildings due to reinforcement projects. Of course this is already very expensive, but the societal impact of such measures is not as easily captured in euros. A full societal benefit analysis would likely lead to additional value attributable to Delta21, increasing its feasibility.

Besides construction costs, and some regular maintenance, Delta21 also has a significant operating cost when escalating during an extreme event. In essence, these are comprised of pumping costs, and are closely related to the operational control of Delta21. Therefore it is a key aspect in the optimization of Delat21, recommended in more detail in the next paragraphs. In principle, average pump costs grow along with the frequency by which Delta21 is used, which increases roughly from 0.06 times per year in 2030 to 0.7 times per year in the future climate scenario (given the preliminary configurations of operational control). Crude first order approximations indicate that pumping costs grow from about 5-10% (currently) to 20-30% (future scenario) of the yearly cost-reductions. Nevertheless, this ignores several aspects:

- The head difference over which the pumps have to discharge can be very small in less extreme, and therefore more common, events. If the discharge over the spillway never has to exceed that of the pumping capacity, the water level in the lake may be allowed to rise before the pumps turn on, to decrease the head difference.
- The current schematization is not at all an optimal one, and is therefore likely to overestimate pumping costs.
- Pumping can at times be much cheaper than average energy prices, or even generate money when the electricity demand is particularly low (Berke, personal communication). In moderately extreme conditions, pumping can be pre- or postponed until a moment when electricity demands are low, using the storage lake in the meantime.

In conclusion, improvement of operational control (see next recommendation), pump costs should be included in the optimization and detailed cost-benefit analysis of Delta21's flood protection related components. Separating the flood protection related costs of Delta21, and including societal benefits are the next steps in determining Delta21's feasibility.

7.3.2 Improving and optimizing Delta21's operational control

As shown in Section 5.3, the operational control of Delta21 is the most important parameter in determining the reductions of water levels at normative frequencies. Therefore, it is strongly recommended to further research variations of the closure operation, and specifically the closure criteria. One key suggestion is to research a closure criterion that adapts based on the discharge boundary. Using Delta21 when there is no storm is still not helpful, but it is possible to escalate for small storms when the closure criterion for Dordrecht is proportional to the discharge boundary. In particular for upstream boundary discharges that exceed the pumping capacity, this can affect water levels for illustrative conditions. The new lower limit is now the maximum bidaily tidal high water **given** a certain discharge. Such a flexible lower limit could be introduced in the current climate already, which may yield even greater reductions on the short term. Whether the additional cost-reductions as a result of this outweigh the increased escalation frequency of Delta21 and pump operation costs, is a matter of optimization.

Optimization of the closure control will ultimately determine what the most economic criterion is. In addition, not the full capacity of the spillway has to be employed in every event where Delta21 escalates. In the current schematization, the full capacity of Delta21 is always used to investigate where it's limits are, but this is not necessarily the most realistic or optimal configuration. Delta21 regularly reduces peak water levels during an event below the tidal bidaily level, or below the level in a condition where it does not escalate. During such conditions, some (unknown) amount of unnecessary discharging is being done. Naturally, locations in areas more sensitive to Delta21 reach this point much earlier, and once again optimization is needed to determine what fraction of the capacity is best used for what conditions. Operational costs i.e. pump costs will also start to weigh into the consideration when to use how much of Delta21.

Changing the closure control affects the line in the boundary condition grid above which Delta21 escalates. Because of this and the conclusion that the determination of extreme water level exceedance frequencies is very sensitive to operational control (see Section 5.3), a proper description of water level development around these escalation borders is of paramount importance during optimization. The current density of calculation points is not able to provide this. In many cases, a variation in operational control will only show itself in one or two calculations. The effect of one point exhibiting such a switch has a massive consequence on the final interpolated and repaired results. A nuanced assessment of various closure criteria hence becomes impossible, because a change of 0.1 m may completely change everything one time, where another time I changes nothing. A flexible mesh where the density of calculation points is larger around the closure function is strongly advised for future research. When performed cleverly, it will not be strictly necessary to recalculate every point for a variation in operational control, just those that are expected to show a change in response.

7.3.3 Miscellaneous recommendations

Stochastic inclusion of storm duration for modelling with Delta21

As Section 5.4 shows, the sensitivity to longer storm surge durations is significantly different in a system with Delta21. This means that the assumptions supporting the deterministic duration of 30 hours are no longer valid. Including this input stochastically, or an adapted deterministic value may yield larger and more accurate water level reductions by Delta21. It is advised to further investigate this in subsequent research.

Long term adaptation strategies

A quantitative analysis of Delta21's position in various long term adaptation strategies to climate change does not fall within the scope of this thesis. To conclude how well Delta21 manages to accomplish this final flood protection target a scope expansion would be necessary into more extreme climate scenarios and combinations with system-changing measures elsewhere. Generally speaking, only the cornerstone direction of '*meebewegen*' in Figure 1.6 does not really combine well with a plan such as Delta21. Synergies with measures in the other three directions may vary strongly and are deserving of their own specific research. Delta21 will in any case suit any strategical direction that relies increasing heavily on pumps (and/or temporary storage) to discharge the rivers.

Reinforcement cost accuracy

The monetary results of Chapter 6 contain particularly wide confidence intervals due to the large uncertainty of the estimated dike reinforcement costs per kilometre. To obtain a more precise estimate of the total cost-reductions with Delta21, this is where to start reducing uncertainties. Especially in the context of assessing whether Delta21's flood protection related components are viable, increased precision is imperative. Generating global budgets for all specific reinforcement projects that face obviation is not particularly restricted in any way, other than by being a rather laborious process.

Flow speeds

The system with Delta21 tends to have increased peak and average flow speeds during an event throughout the delta. The increase is strongest just after Delta21 escalates in combination with low discharges, which is not surprising given that there is no optimization of the control yet, but Delta21 simply attempts to reduce water levels as much as possible. For example the Dordtsche Kil, Spui, and Oude Maas are notorious branches when it comes to high flow speeds, but overall the peak and average speeds of a range of conditions is not found to increase by more than approximately 30 - 50%. In this thesis therefore, no limiting factors are applied to attenuate this somewhat. It is certainly recommended to dedicate further research to this, but **only after** the operational control has been further improved and optimized. Right now, it is not possible to draw useful conclusions with sufficient accuracy in regard to erosion problems as a result of large(r) flow speeds.

APPENDICES

Appendix A Details on model schematisation 82
Appendix B Rhine-Meuse delta system overviews 90
Appendix C Exceedance frequency results validation 93
Appendix D Estimation error through exclusively statistically included sea level rise 96
Appendix E Historic determination of closure criteria 98
Appendix F Justification of simplifications and assumptions in the hydrodynamic model 99
Appendix G Spatial distribution of Delta21 peak water level reductions 102
Appendix H Determination of escalation frequencies 103
Appendix I Reinforcement cost estimation 105
Appendix J Obviated project km's within HWBP 109
Appendix K Risk calculations for unprotected areas on the island of Dordrecht 118
Appendix L Time of closure of the Europoortkering 122
Appendix M Influence of an Europoortkering failure probability decimation 123
Appendix N Water level exceedance reductions in variations of Chapter 5 for all frequencies 127
Appendix O Fault tree of the Europoortkering failure probability 140
Appendix P Net present value (NPV) calculations 142
Appendix Q Full hydraulic model and control 145

Appendix A Details on model schematisation

The following appendix provides details on a range of schematizational components, and includes the implementation of WBI guidelines to which no noteworthy changes are made in the context of this research.

Graphical representation of real-time-control module with cached runs.

Whenever an event takes place that affects water levels in the system, a new 24-hour prediction run is made upon which the RTC makes decisions. The final result is the water level development along the green line.

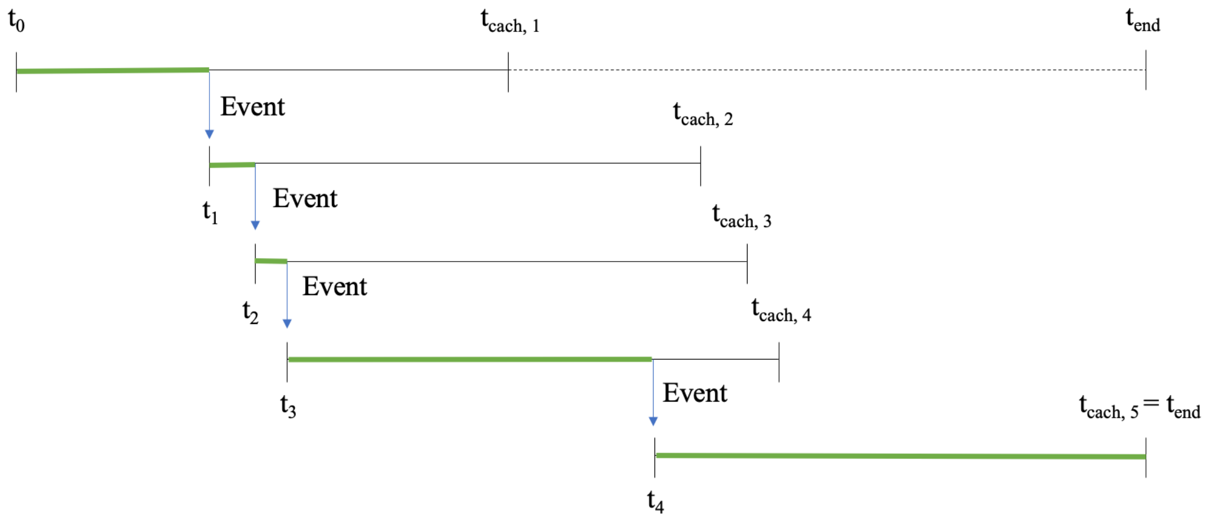


Figure A.1 Scheme of real time control with cached runs (Buijs, 2021)

Determination of closing time of Delta21 storm surge barrier

The code below is what determines the closing time of Delta21, once the decision to close has been made.

```
# Determine moment of closing (last moment when upstream < trigger)
# WZ close 1.5 hours before this moment if possible, or half hour if a late low water
i_low_enough = [i for i, val in enumerate(self.upstream_values) if
                val < self.param[self.p_decision_criteria][self.p_laagwater_trigger]]
if len(i_low_enough) == 0:
    logging.info("Water level in Rotterdam or Dordrecht too high, but waterlevel is never below laagwater trigger")
    i_lowest = np.argmin(self.upstream_values)
    if i_lowest == 0:
        self.closing_time = current_time
        logging.info("No other laagwater found so closing immediately at %s", str(self.closing_time))

    else:
        self.closing_time = current_time + self.time_step * (i_lowest - 3)
        logging.info("Another laagwater found so closing at %s", str(self.closing_time))
else:
    self.closing_time = current_time + self.time_step * (i_low_enough[-1] - 9)
    logging.info("perfectly nice closing LW found.")

self.state_history_lst.append(
    (current_time, SVKD21BarrierState.Gemobiliseerd,
     self._svkd21_position(self.param[self.p_barrier_variables][self.p_gle_open])))
logging.info("Escalate to GEMOBILISEERD. Scheduling close at: " +
             str(self.closing_time) + ". No new cached run necessary.")
```

SOBEK 1D grid definition of the hydraulic model

In the figure below is a detailed view of the one-dimensional grid used in SOBEK. It is littered with observation points and flow profiles throughout the waterways. Red arrows indicate lateral sources and green circles indicate the beginning or end of a flow section (possibly being a bifurcation or confluence).

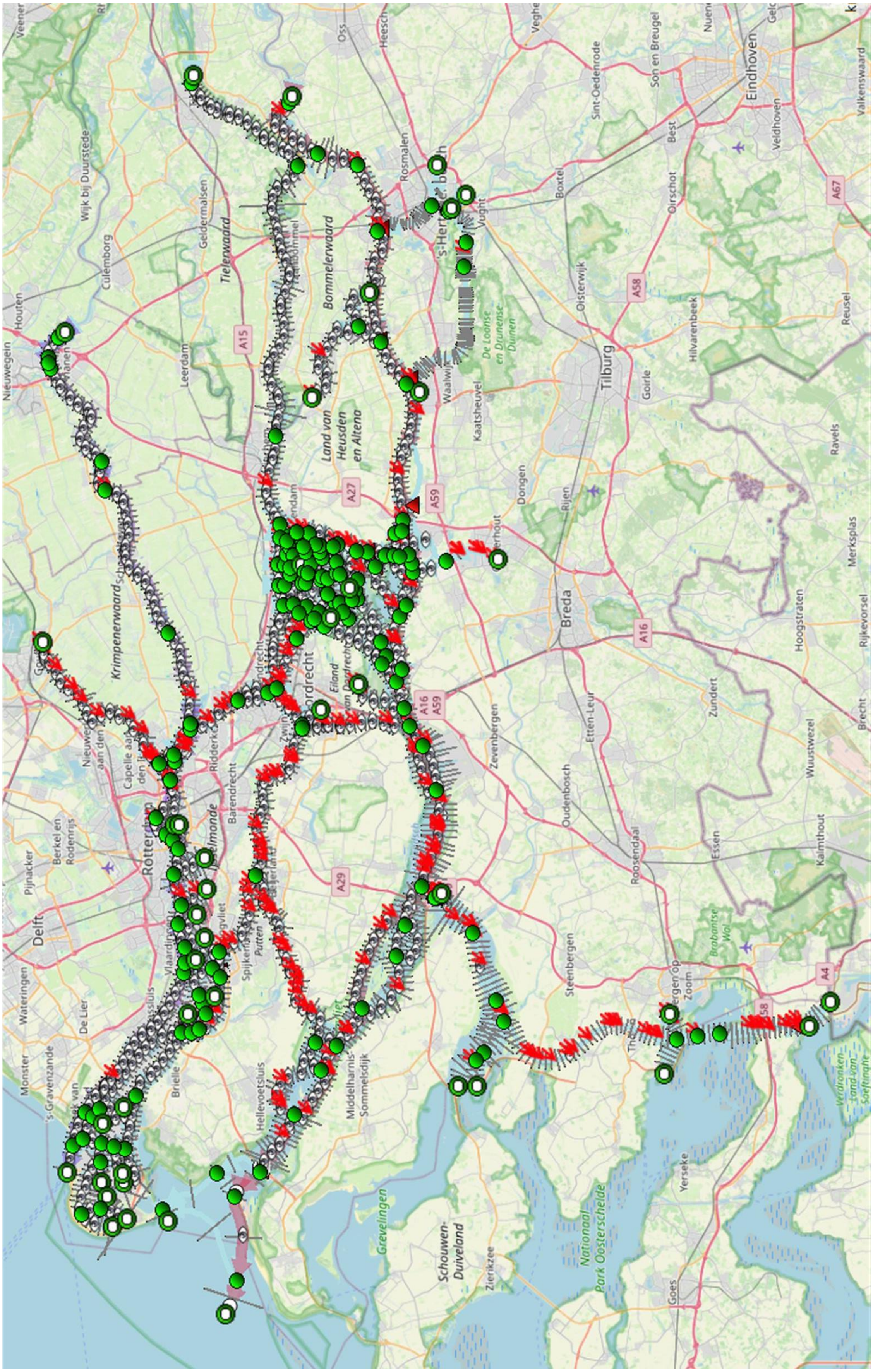


Figure A.2 detailed map of SOBEK model.

Essential SOBEK solving method and corresponding assumptions

The SOBEK software, developed by Deltares, computes the water flow "by solving the complete De Saint Venant (1871) equations for unsteady flow" (Deltares, 2019). Four assumptions are at the core of this procedure and are as follows (Deltares, 2019):

1. *"The flow is one-dimensional i.e. the velocity can be represented by a uniform flow over the cross-section and the water level can be assumed to be horizontal across the section.*
2. *The streamline curvature is small and the vertical accelerations are negligible, hence the pressure is hydrostatic.*
3. *The effects of boundary friction and turbulence can be accounted for through resistance laws analogous to those used for steady flow.*
4. *The average channel bed slope is small so that the cosine of the angle it makes with the horizontal may be replace by unity. "*

Having a one dimensional system, solving the continuity (mass) and momentum equations using the 'Delft-scheme' yields the flow within the system. The exceptions are at locations of barriers (weir type structures). Here the up- and downstream water level or energy level serve as input for basic discharge formulae used to compute flow. The roughness is defined for the whole area through a Chezy coefficient of 45 $m^{1/2}/s$, which is appropriate given the degree of verification that has been done. It should be noted that this holds only for 'extreme' situations. The roughness and perhaps even profiles may not be accurate at modelling regular everyday situations, but neither do they need to.

WBI conform schematization of boundary conditions in the RMM-model: river discharge

As described in Section 2.1.1, extreme river discharges in the Rhine tend to increase with climate change. Regardless of the changes in probability distribution of upstream discharges, the schematization follows the procedure as described below.

The hydraulic model contains three locations at which a discharge condition is imposed: Hagestijn (Lek), Tiel (Waal), and Lith (Maas). These locations mark the transition into fully river dominated regions, Hagestijn and Lith even having a hard boundary in the form of a weir. The three discharges are fully dependant, scaling linearly with the denoted discharge at Lobith (this includes the boundary in the Maas river). This allows the 'discharge' to be described by a single variable, enabling later statistical conclusions to be drawn with significantly more ease. In addition, extreme discharge statistics at Lobith are particularly well known and used often for hydrodynamic modelling. The translation of a certain discharge at Lobith to that at Tiel, Hagestijn, and Lith, is the result of extensive calculations in WAQUA (Agtersloot & Paarlberg, 2016), presented in Table 0.1, with a schematization example given in Figure 0.3.

Table 0.1 Relationship discharge at Lobith with discharges at upper boundaries of the 1D model

Lobith [m^3/s]	Tiel [m^3/s]	Tiel [%]	Hagestijn [m^3/s]	Hagestijn [%]	Lith [m^3/s]	Lith [%]
600	550	92%	25	4%	55	9%
2000	1401	70%	308	15%	217	11%
4000	2697	67%	750	19%	687	17%
6000	3997	67%	1158	19%	1156	19%
8000	5296	66%	1572	20%	1626	20%
10000	6516	65%	2062	21%	2095	21%
13000	8514	65%	2701	21%	2800	22%
16000	10012	63%	3382	21%	3504	22%
18000	11028	61%	3868	21%	3974	22%

The shape of the high water discharge wave in the Rhine and the lower branches of the Meuse (read: downstream of Lith) exhibit a typically broad character with little change of the relative peak position (NL: topvervlakking) (Geerse C. , 2013). It is because of this that the shape of the discharge wave is recommended to not approach as a stochastic variable (Chbab, 2016). Moreover, this report dictates that shape of the wave shape does not play a role for regions 3 and 4 (incl. 17), because the temporal order of magnitude of discharge waves is much larger than that of the seaward boundary (storms). The upstream boundary can thus be described by a permanent (yet extreme) discharge, exemplified in the figure below.

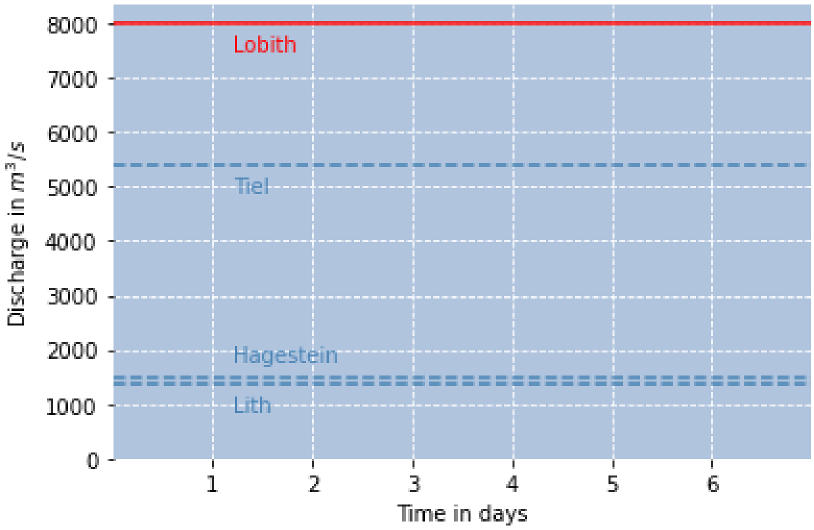


Figure 0.3 Upstream boundary condition for Q = 8000 m^3/s

In preceding research on the hydraulic influence of Delta21, redirecting large quantities of water towards the more southern river branches early on may prove to enhance the effectivity of Delta21 (Buijs, 2021). In essence, if less water enters the delta through the Lek, known bottlenecks such as the Oude Maas, Dordtse Kil, and Spui are alleviated once the spillway of Delta21 is opened. The Pannerdensche kop may allow for some adjustment by regulating the division ratio, having a potential controllability of up to $1000\ \mathrm{m}^3/s$ (Schropp, 1999) (Leemans, 2007). It goes without saying that such a change would have massive consequences for hydraulic conditions at Lek & Waal levees, and possible advantages would have to weigh heavy. Furthermore, in principle no changes to the division at Pannerden are made at least until 2050 (Rijksoverheid, 2021), although the option is kept open. That is why this research limits itself to investigating whether such an intervention yields promising results, in which case further recommendation can be made.

Schropp (1999) concludes in his report that, using primarily the Millingse dam and Pannerden control weir, during high water the discharge can be adjusted by approximately $1000\ \mathrm{m}^3/s$ in both directions (Leemans, 2007). What has been neglected so far is the influence that Delta21 might have on the Pannerden division instead of the other way around. Since the Waal has no complete overflow weirs, a lowered water level might have a backwater effect traveling upstream and by these means 'automatically' divert more water into the Waal.

WBI conform schematization of boundary conditions in the RMM-model: sea level

The downstream boundaries are located downstream of the Haringvliet (North of Stellendam) and Nieuwe Waterweg (Maasmond). The boundary condition is a superimposed signal consisting of three components: the tide, man sea level rise, and storm surge. The first component is an average tidal signal, an example of which is given in Figure 0.4. Note that that every tidal cycle is identical to the next, and phenomena such as spring/neap tide are not represented here, but rather incorporated in the extreme sea level statistics. The signal at Stellendam is slightly different, but otherwise no significant similarities exist between the two downstream boundary conditions.

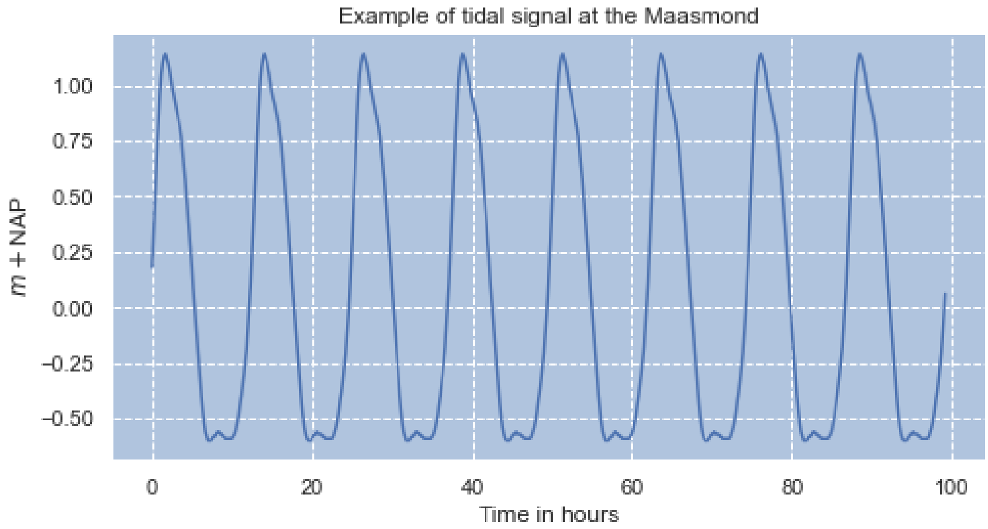


Figure 0.4 Tidal component of downstream boundary (average signal 1991)

The second component is the storm surge, which is schematised by a standardized trapezoidal signal (Chbab, 2012). An example of this given in Figure 0.5 with a storm surge height of 5.59 m. The duration of the storm surge is in principle fully determined by the standardized shape. Considering surge duration as a stochastic variable has been shown to not particularly change the resulting normative high waters, as shorter and longer storms cancel each other out fairly equally (Tijssen, 2010). Nevertheless, concerns about longer (possibly less extreme) storms are becoming more vocal (Delta21 v.o.f., 2021a), also as a result of rising mean sea levels (Valk & Steelzel, 1997). In the sensitivity analysis therefore, a reconsideration of this schematisation is included to allow for recommendations regarding long storms and Delta21. Of particular interest is whether a system with Delta21 is better equipped to deal with longer storms, as this might throw off the previously described balance. The height of the storm surge is also related to a wind speed realistic for that storm, which is constantly imposed on the waters surface. The direction is set deterministically at North-West. Note that the probabilistic distributions of the wind in the statistical calculations **does** include several wind directions to determine exceedance probability of a certain surge.

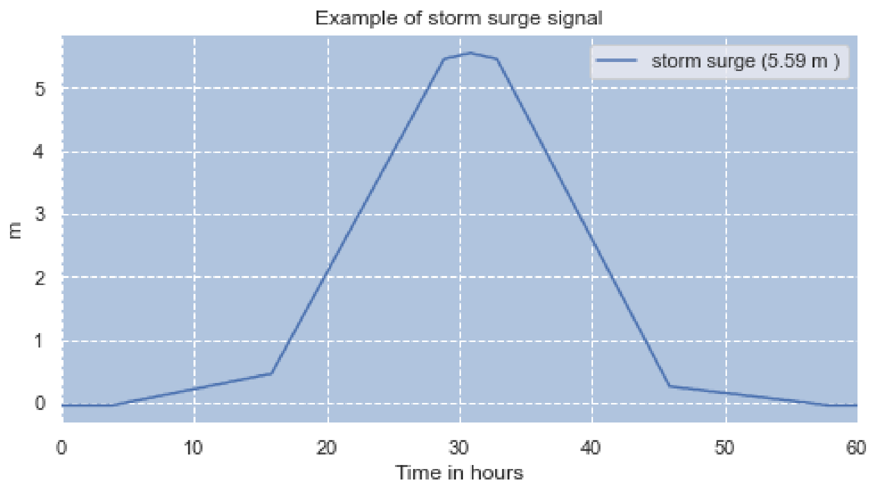


Figure 0.5 Storm surge component of downstream boundary

The third component represents mean sea level rise. This is simply a uniform addition to the boundary condition, equal to the value for that run. Note that because the reference situation is in 2017, an SLR of 10.5 cm is already added to the tidal signal from 1991 (Agtersloot & Paarlberg, 2016). The resulting signal is a superimposition of these three components. Alternatively, sea level rise can be excluded from the boundary conditions of the hydraulic model, but only schematized as a shifted distribution of max sea water levels. This can give good estimations as long as the deviation from a proper included calculation is limited. The expected errors for a shift of 0.30 and 0.84 m are presented in Appendix D. For small average sea level changes (order 0.2 m) errors are not expected to exceed more than order 0.05 m.

The phase at which the storm occurs relative to the tide has a significant influence. The phase shift between the peak of the tide and the storm determines the resulting shape of the signal, with the highest intensity when the peaks coincide and longest (effective) duration when the storm peak coincides with vertical ebb. Phases around of $\phi = -4.5$ hours and of $\phi = +3.0$ hours tend to occur far more often than those around $\phi = 0$ hours (Chbab, 2010). Because phase shifts of - 4.5 and + 3 hours exhibit a similar resulting signal shape and a phase of -4.5 occurs the most of the two (Chbab, 2010), it is safe to assume a constant (deterministic) phase shift of $\phi = -4.5$ hours (Chbab, 2016). This yields the boundary condition as shown in Figure 2.7.

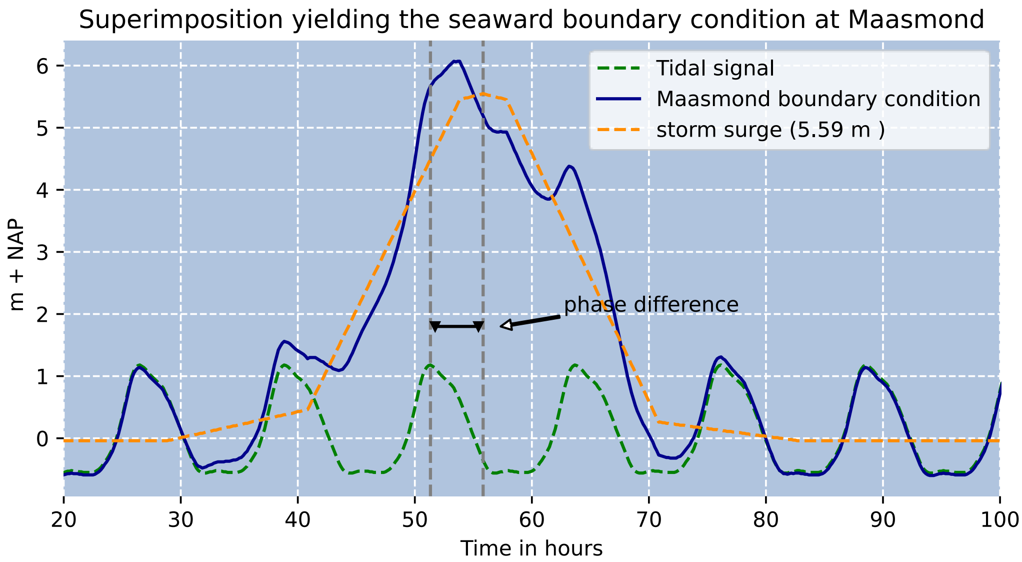


Figure 0.6 Resulting downstream boundary condition at the Maasmond for an example storm with peak value 5.59

Delta21 components in SOBEK

The following figures provide the schematised cross sectional representations of Delta21 in the 1D SOBEK model.

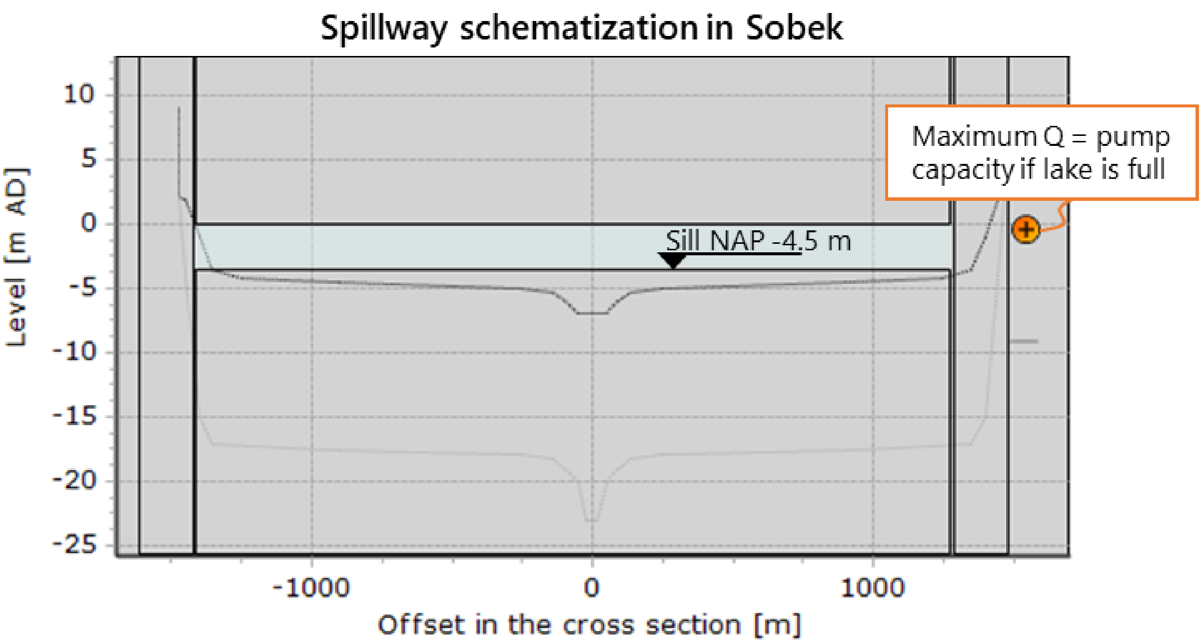


Figure 0.7 Delta21 spillway cross section in SOBEK (background shows flow profiles)

Two main design characteristics determine the discharge over the spillway: it's width W_s and the sill height z_s. The formula used to compute the free weir flow in D-FLOW 1D is as follows (note that the downstream water level is not used):

Free weir flow:

$$A_f = W_s \; \frac{2}{3}(\zeta_1 - z_s)$$

$$Q = c_w W_s \; \frac{2}{3}\sqrt{\frac{2}{3}g} \;\; (\zeta_1 - z_s)^{3/2}$$

Free gate flow:

$$A_f = W_s \mu \, d_g$$

$$Q = c_w \, W_s \, \mu d_g \sqrt{2g(\zeta_1 - (z_s + \mu \, d_g))}$$

Q	Discharge across orifice $[m^3/s]$
A_F	Flow area $[m^2]$
μ	Contraction coefficient $[-]$ Normally 0.63
c_w	Lateral contraction coefficient $[-]$
W_s	Crest width $[m]$
d_g	Opening height $[m]$
g	Gravity acceleration $[m/s^2]$ (≈ 9.81)
ζ_1	Upstream water level $[m]$
ζ_2	Downstream water level $[m]$
z_s	Crest level $[m]$

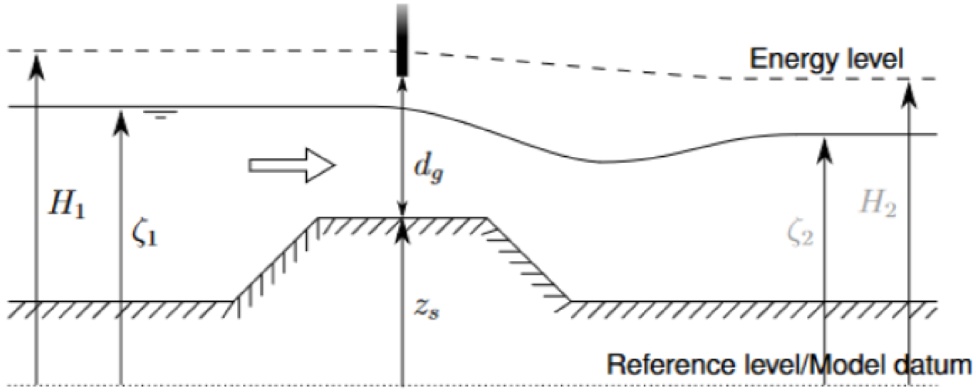


Figure 0.8 D-FLOW 1D weir flow computation. Adapted from: (Deltares, 2019)

When the upstream water level rises to the lower gate edge, an underflow situation will be the result. The formula changes somewhat to the free gate flow , where opening height d_g and contraction µ start to play a role. Nevertheless, because the upstream energy level in the delta21 situation is hardly affected by the new situation, the discharge does not change strongly. The gate height is thus of secondary importance to the spillway's width and sill height.

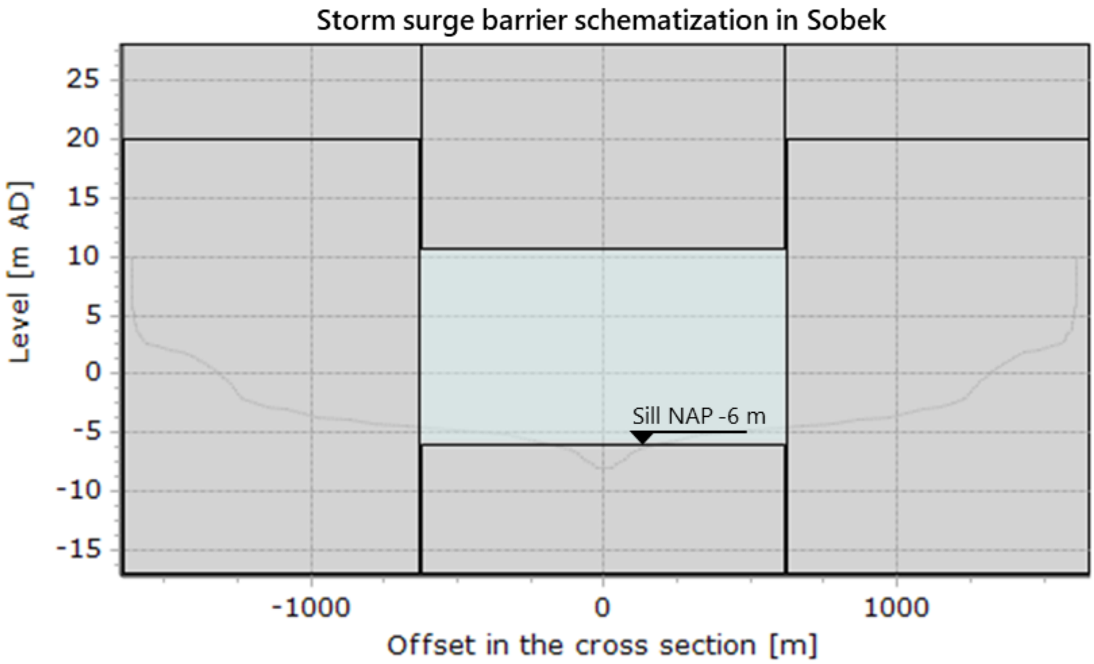


Figure 0.9 Delta21 storm surge barrier cross section in SOBEK (background shows flow profiles)

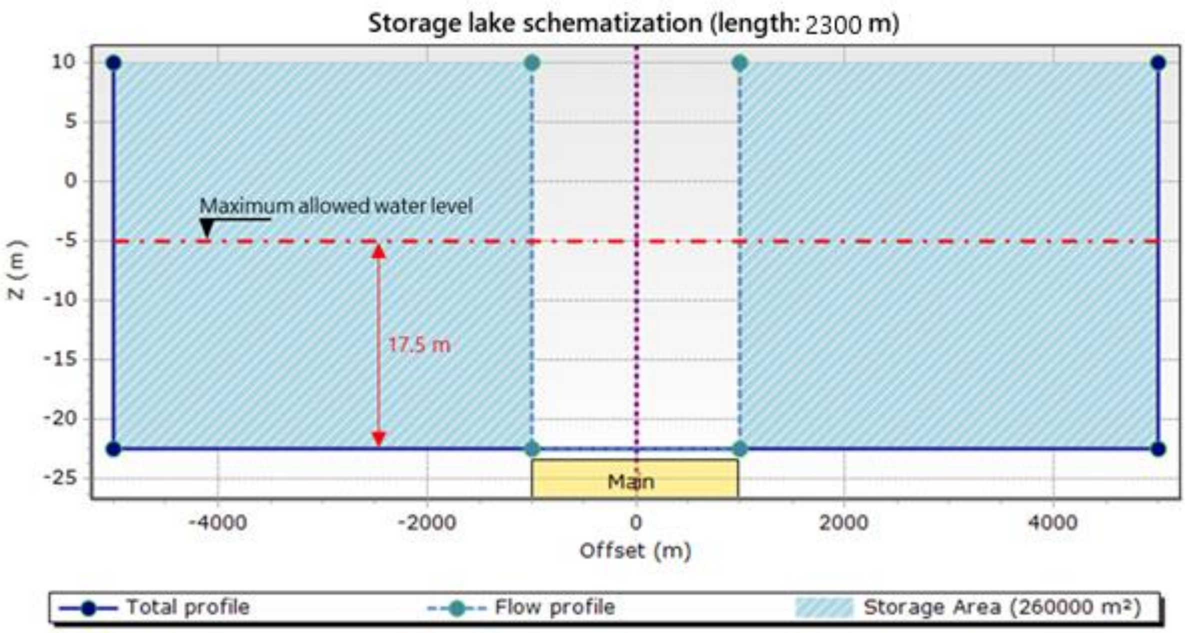


Figure 0.10 Delta21 storage lake cross section in SOBEK

Appendix B Rhine-Meuse delta system overviews

This Appendix provides a collection of figures of and related to the Rhine-Meuse delta. Numerous references are made to the data in the figures throughout Chapter 1 and 2.

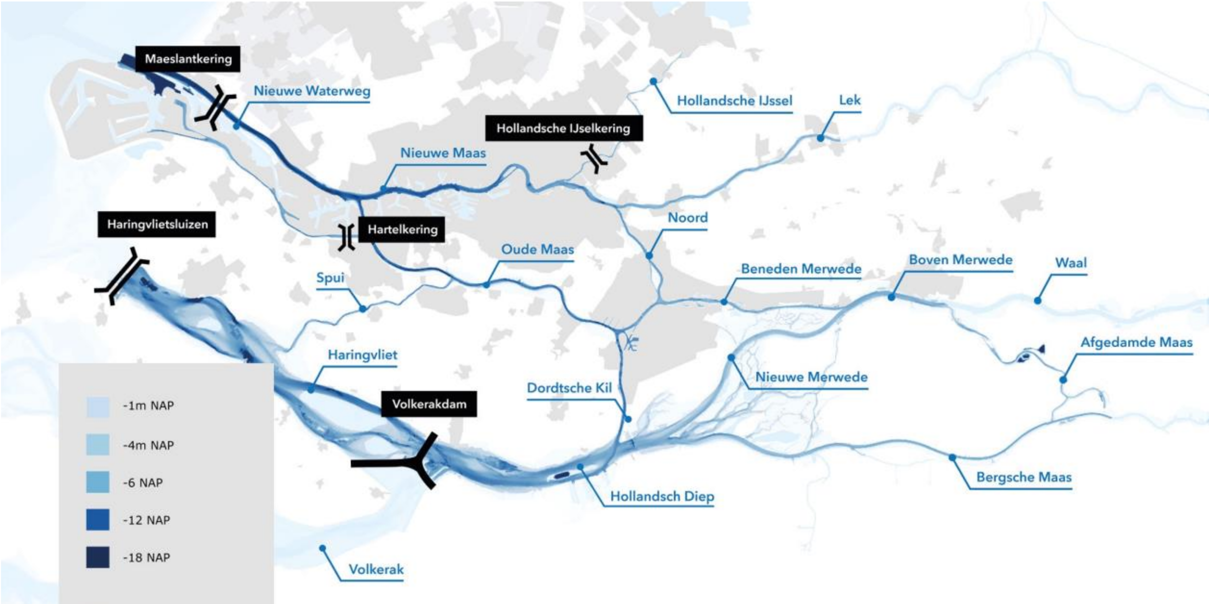


Figure B.11 Overview of the Rhine-Meuse delta with names of channels & deltaworks, and channel depth. (Balla, et al., 2019)

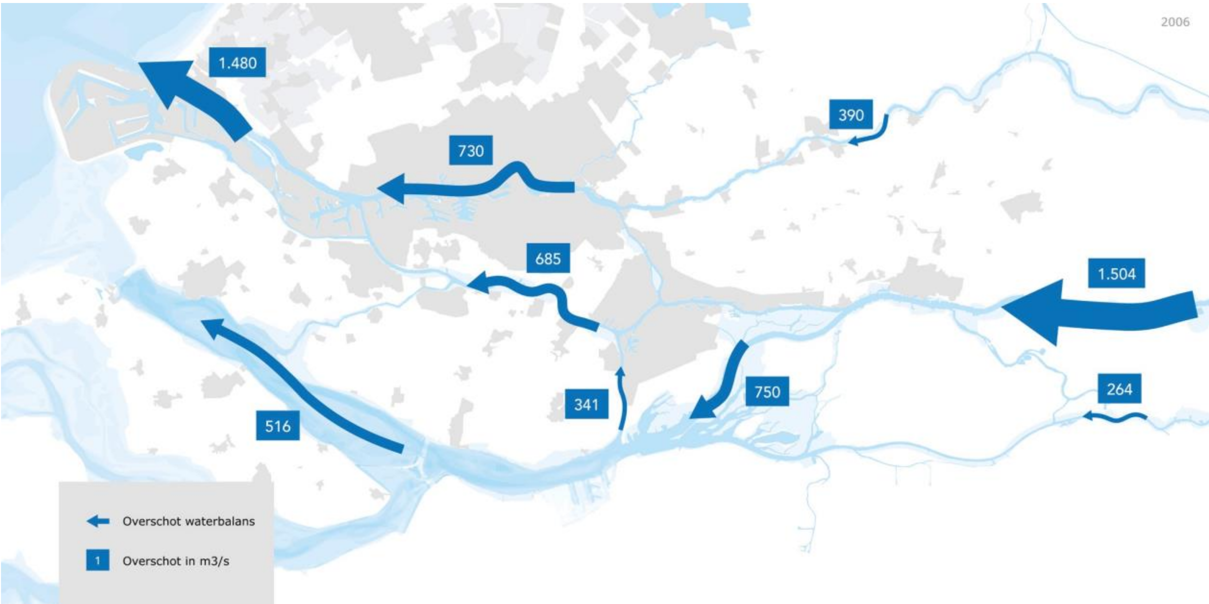


Figure B.12 Overview of average Rhine-Meuse delta discharges as of 2006 (Balla, et al., 2019)

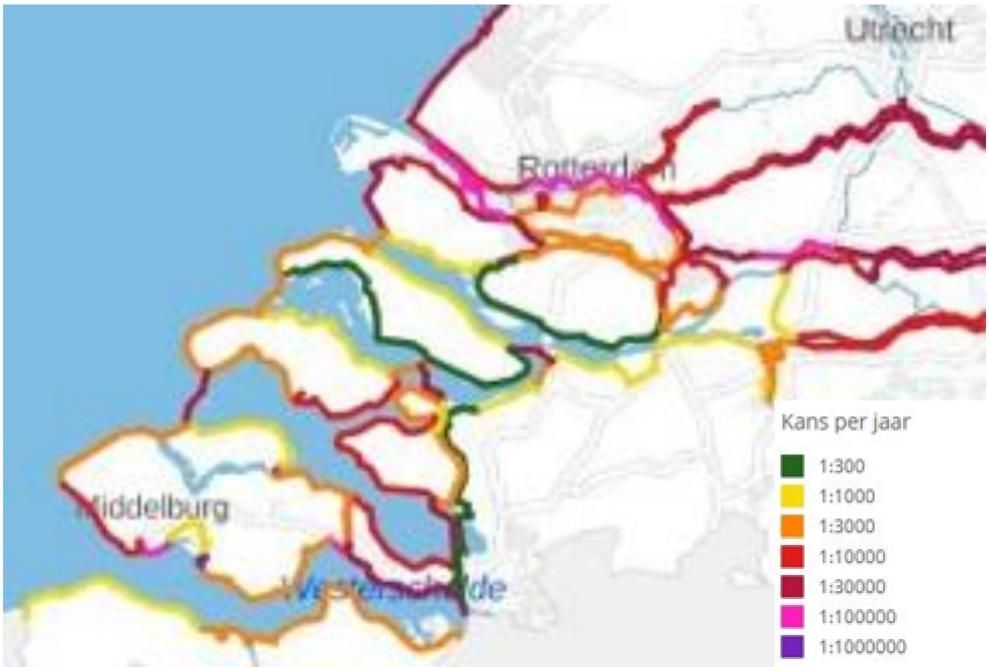


Figure B.13 New probabilistic safety norms - signal values (HWBP, 2020). Lower boundary is 1/3 times the signal value

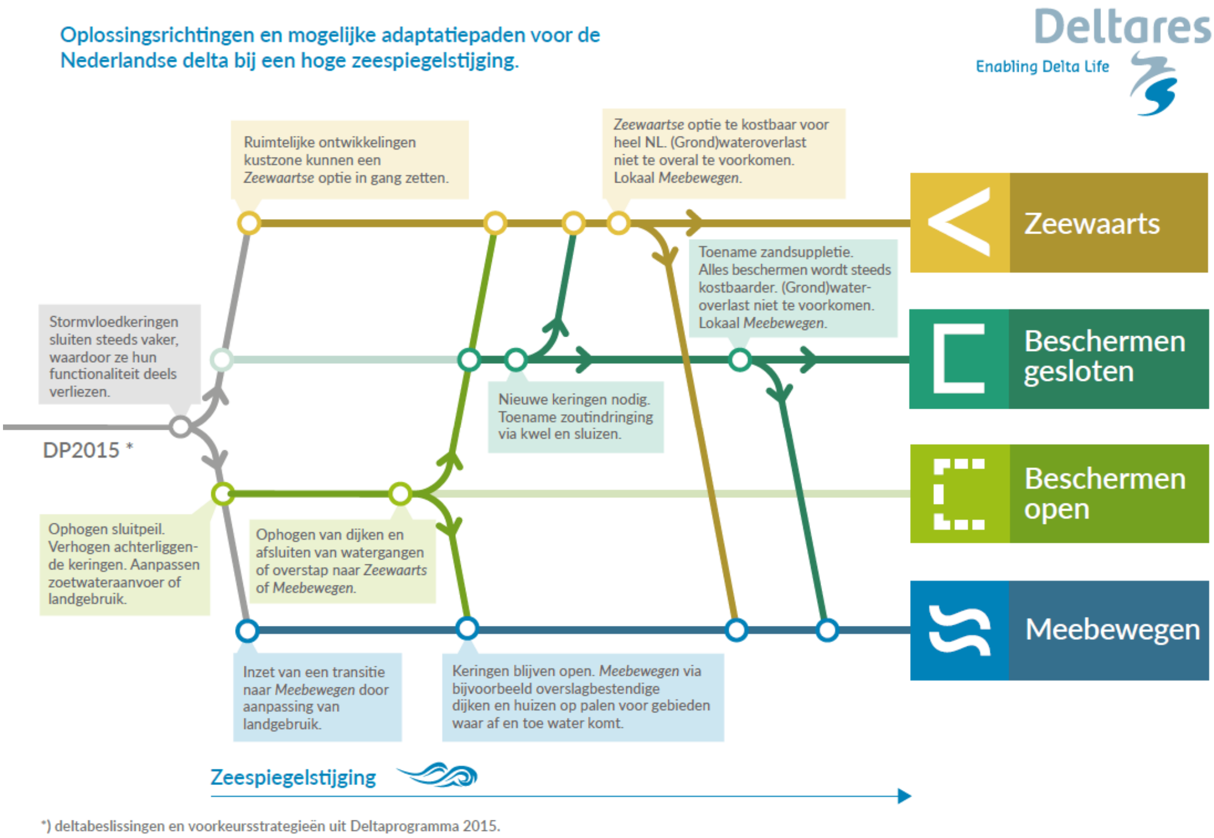


Figure B.14 Directions and adaptive pathways for large sea level rise scenarios (Haasnoot, et al., 2019)

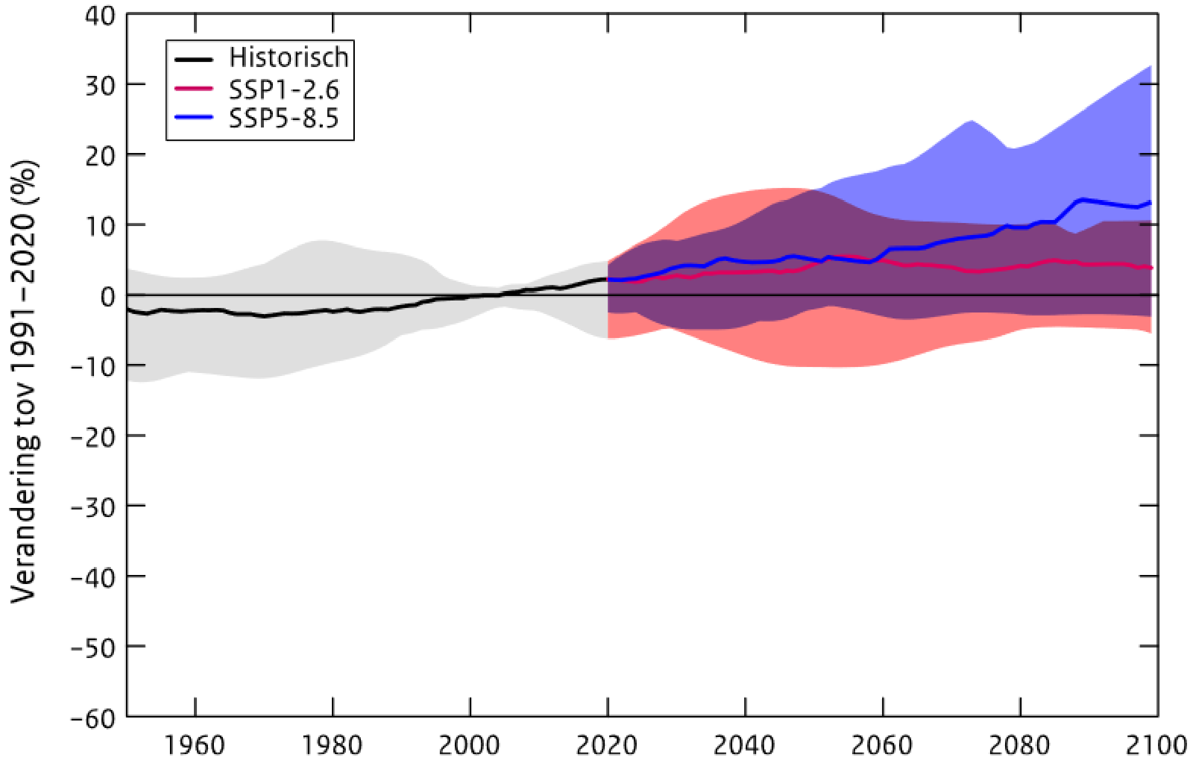


Figure B.15 Change in high precipitation indicator with 90% confidence bounds (Koninklijk Nederlands Meteorologisch Instituut, 2021)

Appendix C Exceedance frequency results validation

To confirm that the model performs sufficiently, the results can be compared against WBI databases. These are currently regarded as the most up-to-date and reliable databases for flood protection design, and a very similar approach and model are used to generate them. The model upon which this research builds forth is that of the Rhine-Meuse Delta (RMM). The WBI2017 database *Benedenrijn* (Downstream Rhine branches) is used to overlay exceedance frequency curves at one location per dominant region, listed below and shown in Figure C.16. An additional location is included to investigate whether the region where the Maas dominates the water levels is also properly reproduced by the model of this thesis. An important difference is that for this location/region a different WBI database is available: *Benedenmaas* (Downstream Meuse branches). Since the model only considers Lobith stochastically (see Section 2), and infers that information to a discharge at Lith, one might expect the performance to worsen significantly towards these branches.

Considered validation locations:

1	Dordrecht	Transition region	Figure C.17
2	Boven-Hardinxveld	River dominated (Rhine)	Figure C.18
3	Hellevoetsluis	Storage dominated	Figure C.19
4	Rotterdam	Sea dominated	Figure C.20
5	Keizersveer	River dominated (Meuse)	Figure C.21

Location 1 through 4 perform as expected and suffice. Deviations are always within 0.2 m, and do not exceed 0.1 m for the normative frequency at that location. Furthermore, as explained in Section 2 the model is adequate for relative databases, meaning that it does not have to reproduce the WBI results within particularly strict margins anyway. Location 5 (Keizersveer) shows an entirely different picture. The model produces results that underestimate the WBI values by as much as +/- 0.5 m across the spectrum. Evidently, considering results in the region dominated by the Meuse would be unwise, or should at least be interpreted carefully. After expanding the boundary conditions to include the discharge stochastically and extend further upstream, the performance may improve massively.

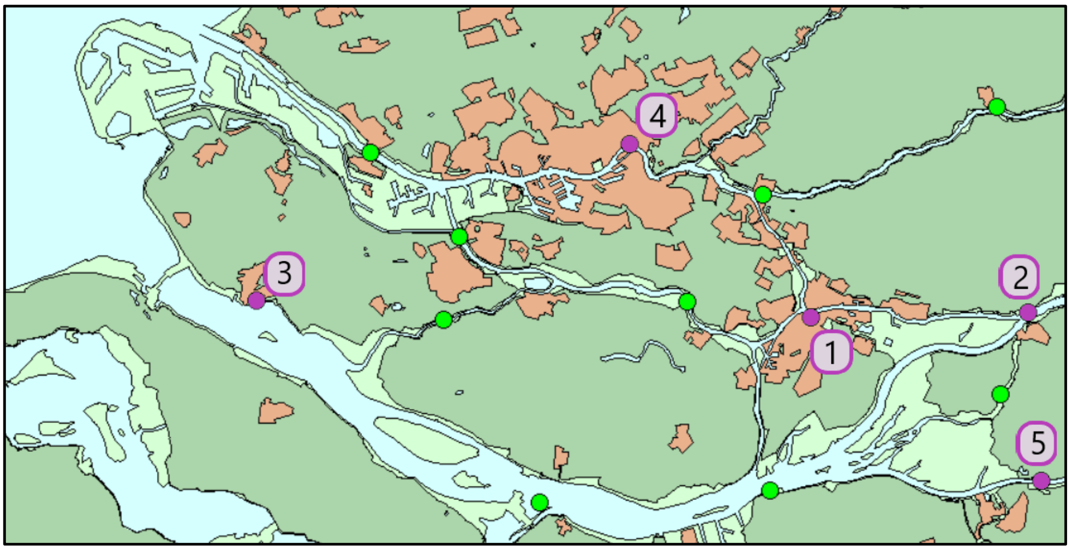


Figure C.16 Map of computation locations with validation locations highlighted

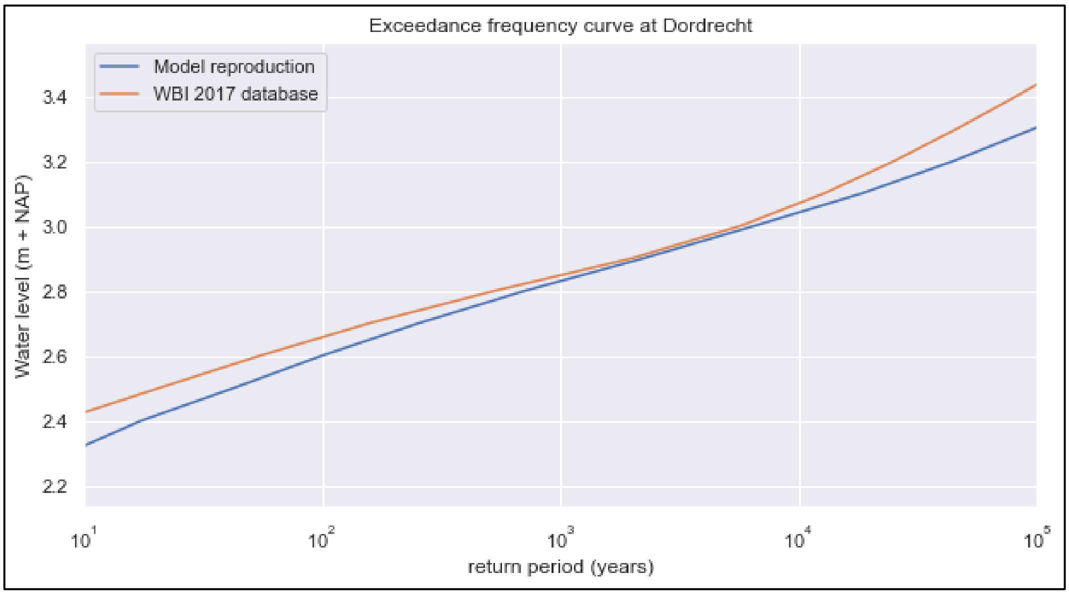


Figure C.17 Validation result at Dordrecht (Transition region)

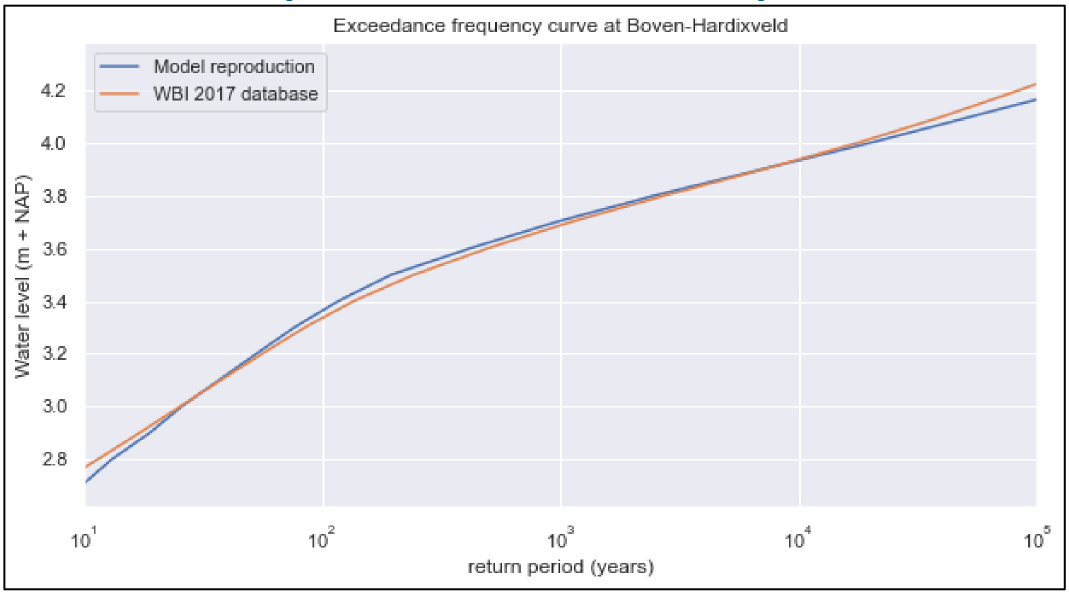


Figure C.18 Validation result at Boven-Hardinxveld (River dominated region)

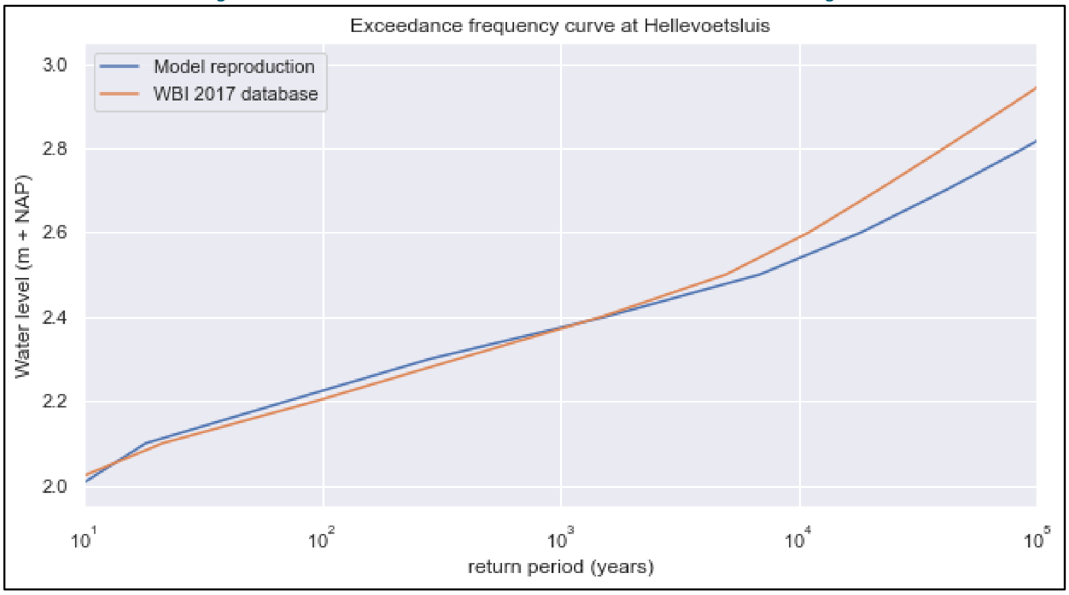


Figure C.19 Validation result at Hellevoetsluis (Storage dominated region)

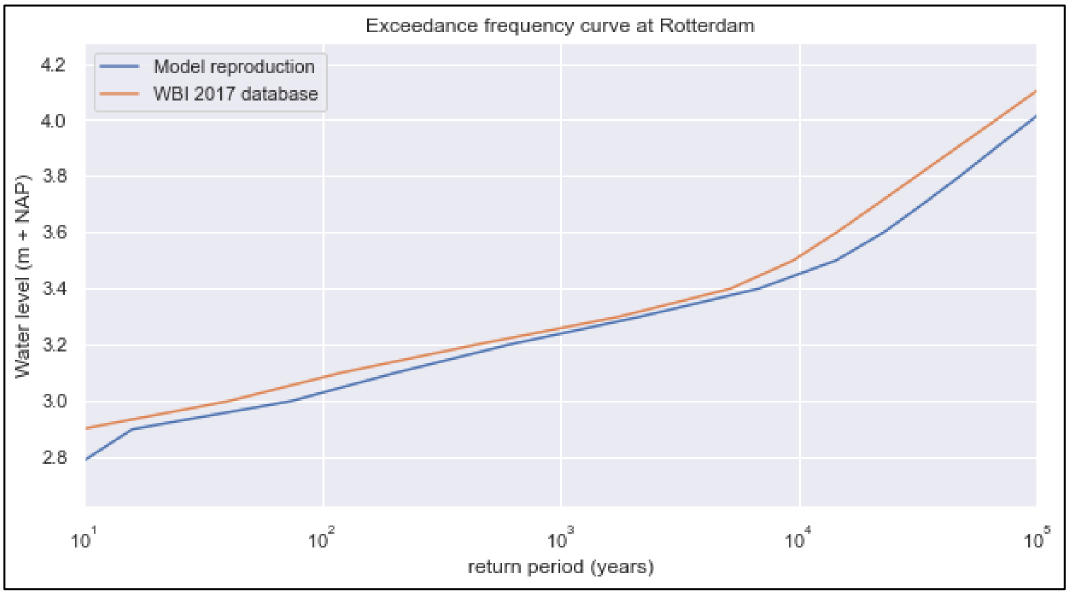


Figure C.20 Validation result at Rotterdam (Sea dominated region)

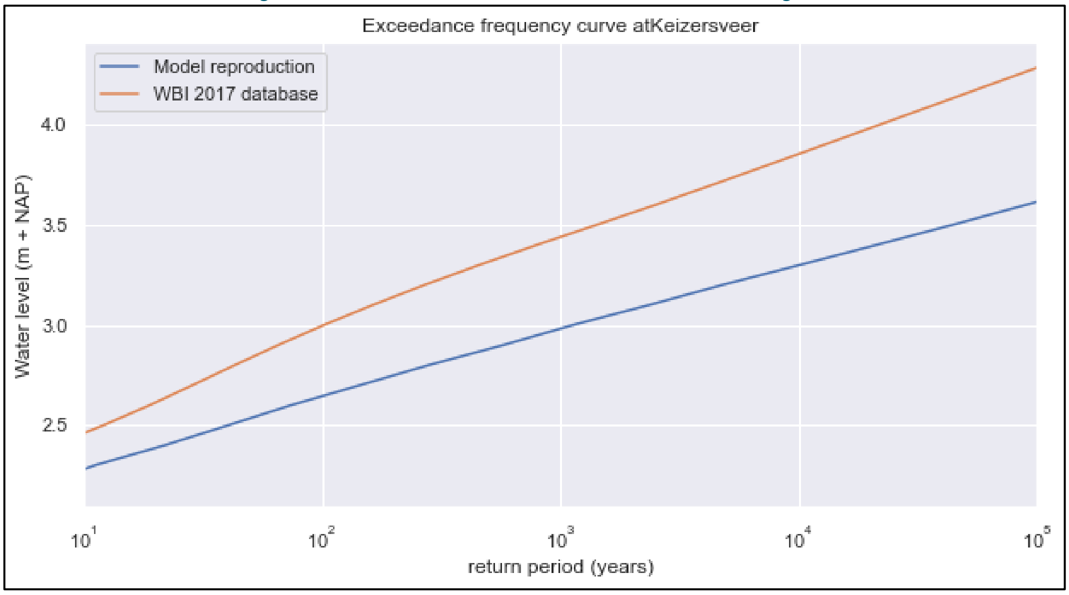


Figure C.21 Validation result at Keizersveer (River (Meuse) dominated region)

Appendix D Estimation error through exclusively statistically included sea level rise

A change in mean relative sea level is processed in two places in the model. The first on is a uniform addition to the downstream boundary condition(s). This means that the equilibrium situation before a storm hits is somewhat higher, depending on how close to the sea a location is. The second and most important place however is in the distribution of extreme sea water levels, which also has to be raised uniformly. Whereas the second method is reasonably fast (it only changes the probabilities of certain levels before sampling), the first requires creating an entirely new database. It is therefore useful to see how large the error becomes for large and small sea level changes, and where they concentrate.

For one location per region the exceedance frequency is computed with both methods (only step 2, or step 1 & 2). The fifth location dominated by the Meuse river (Keizersveer) is excluded, as indicated by Appendix C. A sea level rise of 0.84 m, corresponding with the W= scenario, is included as a large step (0.74 m). A Sea level rise of 0.3 m is included as a small step (0.2 m). Note that the starting value is 0.10 m because tidal signals are from 1991, which is considered the zero value in this research, but reference computations are in performed for 2017.

From Figure D.23 & Figure D.24 it becomes clear that for increasing return periods, the deviation between the two methods becomes larger. Rotterdam, close to the sea, can be modelled particularly well by a simple statistical translation, as the initial conditions matter little there. Deviations are by far the largest for Dordrecht and Hellevoetsluis, because initial conditions are crucial in determining how much storage is available. In a system with Delta21[1], the deviation in Dordrecht becomes smaller - indicating stronger influence of the sea as storage becomes less of an issue with Delta21's capacity. The deviation in Boven-Hardinxveld however becomes larger - indicating a shift of the border between the transition region and river (Rhine) dominated region. A step of just 0.2 m seems to be a sufficiently small change to not need a complete new calculation set, as shown in Figure D.25. Below return periods of about 5000 years, all curves tend to overlap fairly well. As the normative frequencies of Dordrecht and Hellevoetsluis are 3000 and ~300 years respectively, no problems should arise when using shifted statistics exclusively to compute a 0.2 m sea level rise step.

Considered validation locations:

1	Dordrecht	Transition region
2	Boven-Hardinxveld	River dominated (Rhine)
3	Hellevoetsluis	Storage dominated
4	Rotterdam	Sea dominated

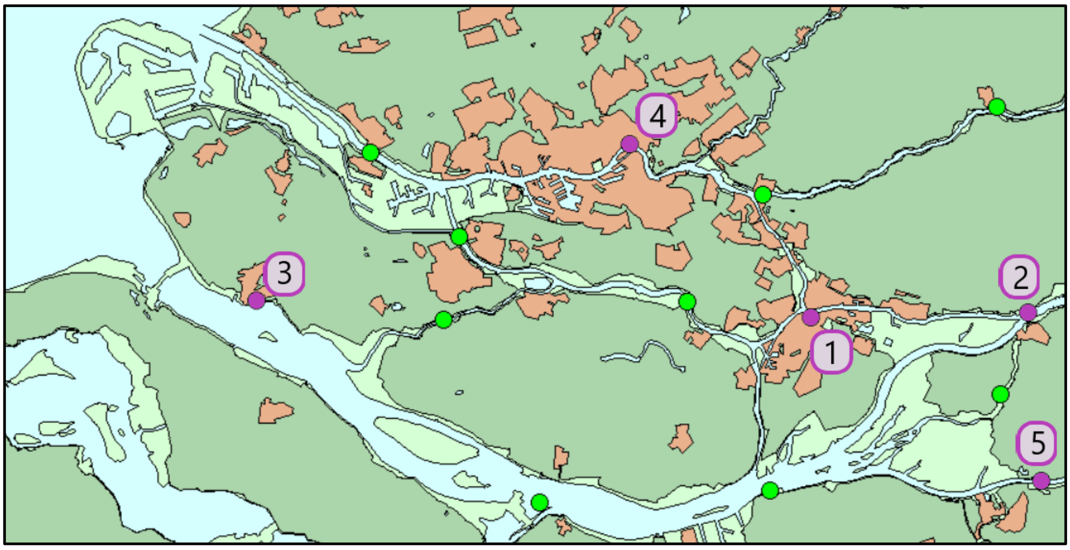


Figure D.22 Map of computation locations with validation locations highlighted

[1] The preliminary configuration

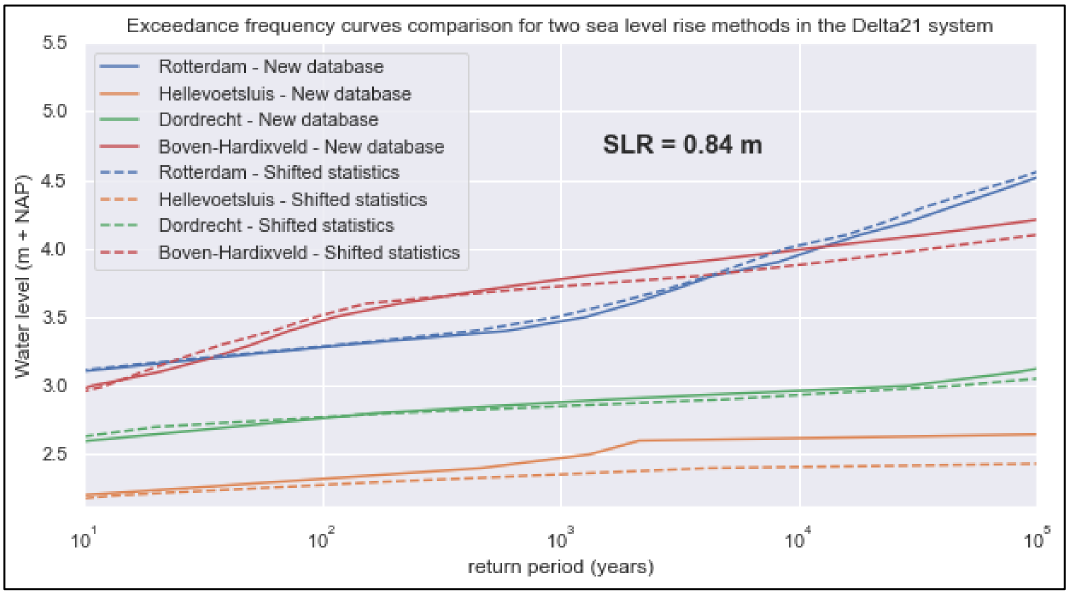


Figure D.23 Indication of error using simple method of computing sea level rise for a system with Delta21 and scenario W+

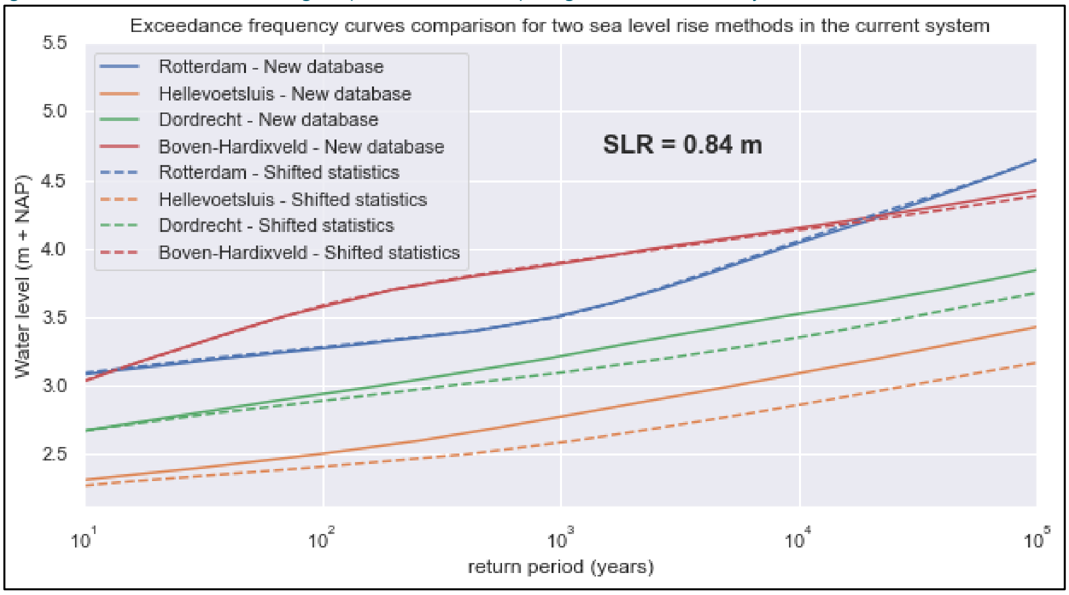


Figure D.24 Indication of error using simple method of computing sea level rise for the current system and scenario W+

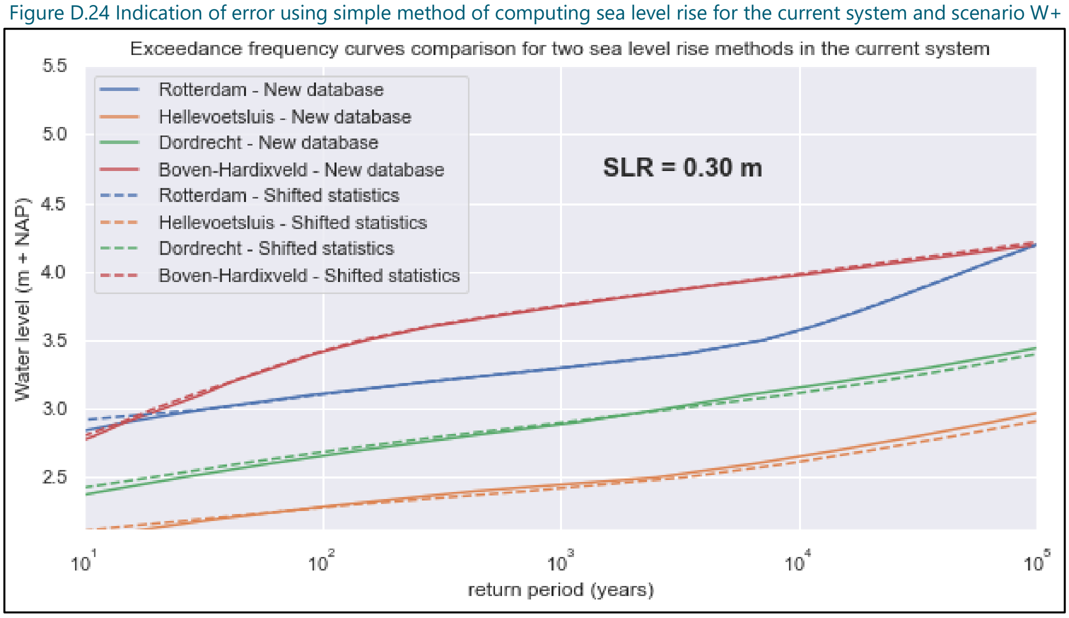


Figure D.25 Indication of error using simple method of computing sea level rise for the current system and a small sea level rise step

Appendix E Historic determination of closure criteria

Ever since the Maeslantkering was constructed its operation is centred around the maximum predicted water levels at Rotterdam and Dordrecht. Specifically NAP + 3.0 m for Rotterdam and NAP + 2.9 m at Dordrecht. The quantitative determination of these levels was not a dry-cut as one might expect. Figure E.26 shows how the levels translate to boundary conditions (system before 10), what criteria determines the closure, and what type of closure. Note that at that time the closure criterion for Rotterdam was still NAP + 3.25 m, it wasn't lowered until 1997 (Besluit gebruik stormvloedkering Nieuwe Waterweg, 2009). In particular after lowering the Rotterdam level to NAP + 3.0 m, a closure of the Maeslantkering is expected to be caused by exceeding this level about 10 times more often than because of exceeding the Dordrecht criterion, which only comes into play once the threshold of 9000 m^3/s is passed.

In choosing a water level criteria, three main considerations came into play:

- The desired and feasible failure probability
- The acceptable closure frequency for port activity
- Uncertainties in water level predictions

Especially the third bullet is relevant for closure criteria variations and bears some historical weight. How exactly the initial choices were made is not particularly well documented, but studies by Rijkswaterstaat that go back until the original 1991 'BEWAKER' reports paint a general picture. The normative high waters for Rotterdam and Dordrecht were in fact set at NAP + 3.6 m and NAP + 3.0 m respectively, meaning that the hysteresis with the current criteria is respectively 0.6 m and a mere 0.1 m. The primary reasoning is that with a given prediction uncertainty for 6 hours in advance the normative water levels could be reached. For the other escalation levels (call-in and preparation level) the idea was that given a certain prediction uncertainty, there would never be an increase in normative water level because the operational team was not present.

Presently, hydrodynamic modelling and uncertainties in predictions are far more advanced. Also, 'normative water level' is no longer the one deciding aspect of hydraulic loading on dikes, rather the entire exceedance curve combined with temporal development and wave conditions. Despite that, the closure criteria haven't changed since 1997, despite the derivation being based on assumptions and uncertainty estimates that may not be sufficiently accurate today.

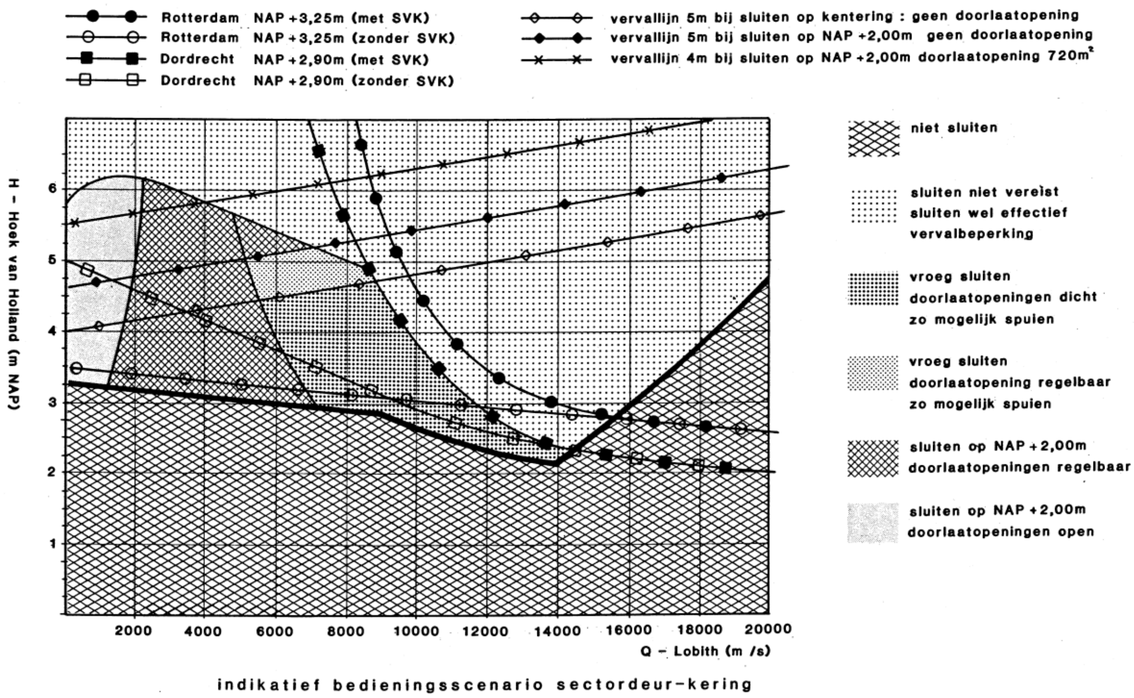


Figure E.26 closure scenarios Maeslantkering (courtesy of Hans Nederend)

Appendix F Justification of simplifications and assumptions in the hydrodynamic model

Several checks and validations are performed to justify preceding assumptions, to which detailed calculations are presented in this.

Operation and schematization of the Haringvlietsluizen

As discussed in Section 2, the Haringvlietsluizen have been simplified quite a bit. Main reasons are a changed function because of Delt21, but also a considerably faster and more stable computation. In principle, the width and maximum allowable height that water can flow through has not changed, but the operation of all separate gates has been omitted in favour of a single decision switch. Water is **always** allowed to flow outwards (towards the sea) and **never** inwards (towards the Haringvliet and Hollandsch Diep).

This change may cause an underestimation of extreme water levels for 2 reasons:

1 For low discharges, in reality the Haringvlietsluizen would remain (partly) closed to prevent salination in the Nieuwe Waterweg. If this coincides with a storm and e.g. Maeslantkering failure, the initial conditions in the transition region may be higher.
2 The simplification allows for instantaneous adaptation, whereas in reality closing and opening the sluice gates takes some time.

To ensure that deviations as a result of this change are not too large, two full computational sets have been calculated for the current system (CS2017) and the very same system but with adapted Haringvlietsluizen (CS2017_HVSL). The resulting exceedance frequency curves for four locations (one per region, see Figure 2.5) have been plotted in Figure F.27. The final results do not appear to deviate from one another particularly much, confirming that the simplified schematization is sufficiently able to model reality. Interestingly, the new results sometimes also exhibit an **overestimation**, albeit still by just a few cm's. What exactly is the cause can't be said for sure, but it has likely to do with random noise caused by oscillations and the time step of 10 minutes.

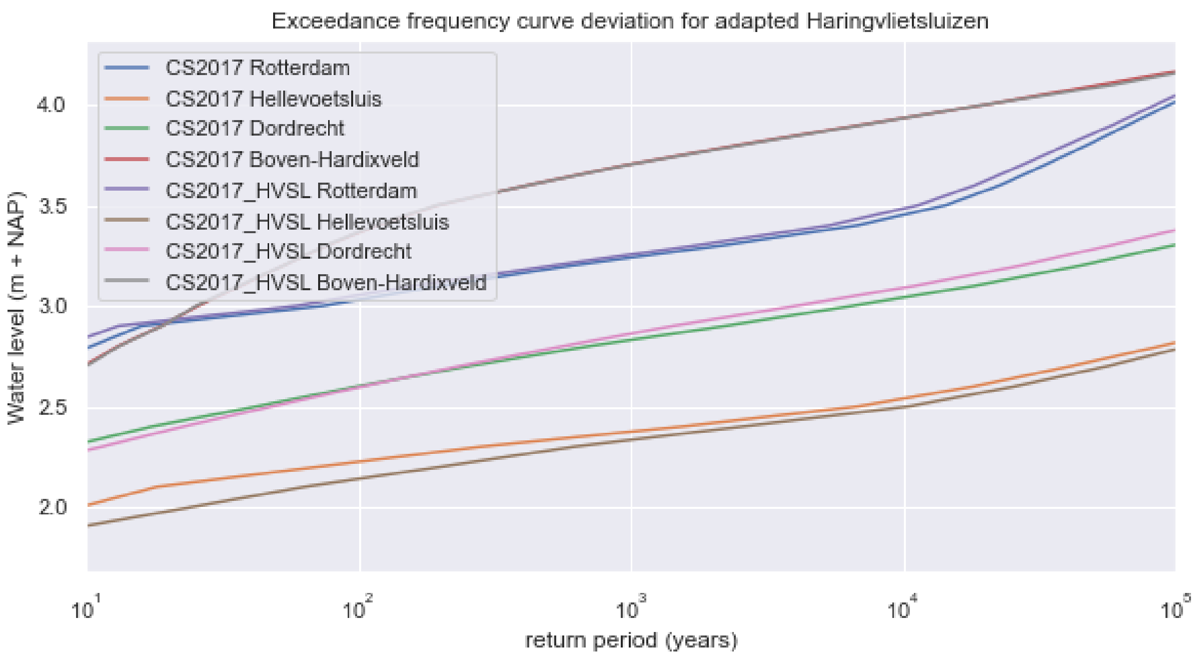


Figure F.27 Change in exceedance frequencies after implementing th adapted Haringvlietsluizen for one location per region

Failure mode Maeslantkering doors do not open

As discussed in Section 2, a failure mode of the Maeslantkering is omitted from the calculations and database generation. This is not uncommon in modelling water level exceedance frequencies in the Rhine-Meuse delta. The other main failure mode of the doors not closing is of far superior importance. Furthermore, a system with Delta21 is much better equipped to deal with discharging water for longer closure times anyway, so any deviation means a conservative estimate of Delta21's effectiveness. Nevertheless, a brief check is performed to see for what locations and conditions the peak of the water level signal is considerably different from the situation where the doors open with no problems. The check is done for the current system, as deviation is expected to be the largest there, and for one location per region (see Figure 2.5). The results are presented in Figure F.28 and Figure F.29.

In Rotterdam, close to the Maeslantkering, deviations are largest and penetrate quite a bit into the transition region as shown by the deviations at Dordrecht. In the worst case scenario an increase of 0.75 m in Rotterdam is obtained for the largest discharge (18000 m^3/s) and a maximum sea water level of NAP + 3.26 m. This is quite considerable, and indicates that for assessments close to the Europoortkering the simplification might not be so easily justified. Nevertheless, the distribution of the failure probability of the Maeslantkering among the modes not opening and not closing is not well understood, and the latter is far more detrimental for obvious reasons. If one assumes an equal chance of occurrence, the failure mode not closing would contribute far more heavily to a rise in exceedance frequencies than the failure mode not opening. Heading further away from the Europoortkering towards the storage or river dominated regions, deviations become much smaller with the exceptional maximum difference of +0.2 m.

Note that for certain conditions (discharge around 6000 m^3/s and max sea level NAP + 3.26) the result of failing Maeslantkering doors actually leads to a **reduction** in maximum water level (up to 0.4 m). The cause is a storm with two peaks (caused by a phase difference as described in Section 2) of which only one is high enough to initiate a closure. Therefore, normally speaking the Europoortkering would open and water levels would rise again by a little. However, because the doors fail to open this second peak is also blocked, and due to the reasonably low discharges the result is a reduced maximum water level.

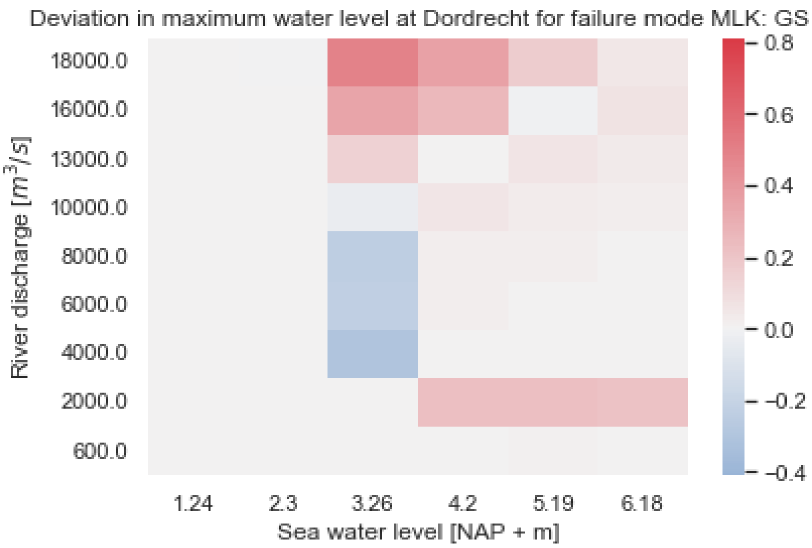


Figure F.28 Difference in maximum water level per boundary condition between Maeslantkering modes CF & GS for Dordrecht

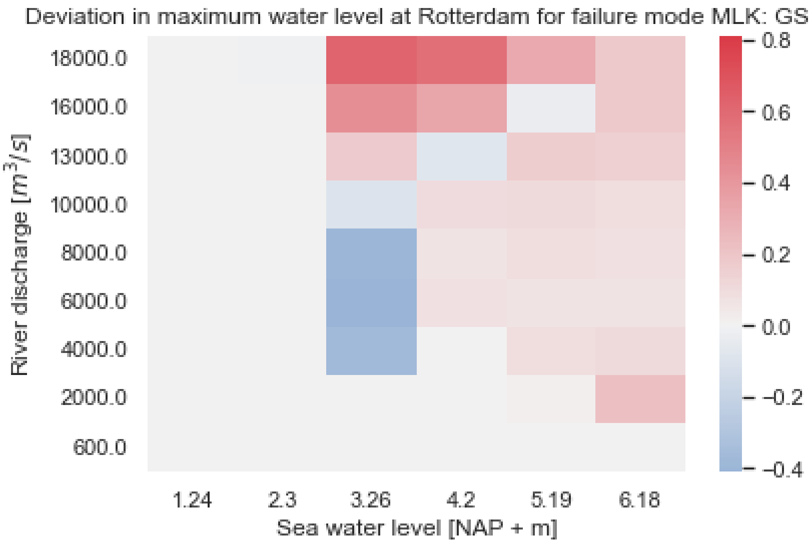
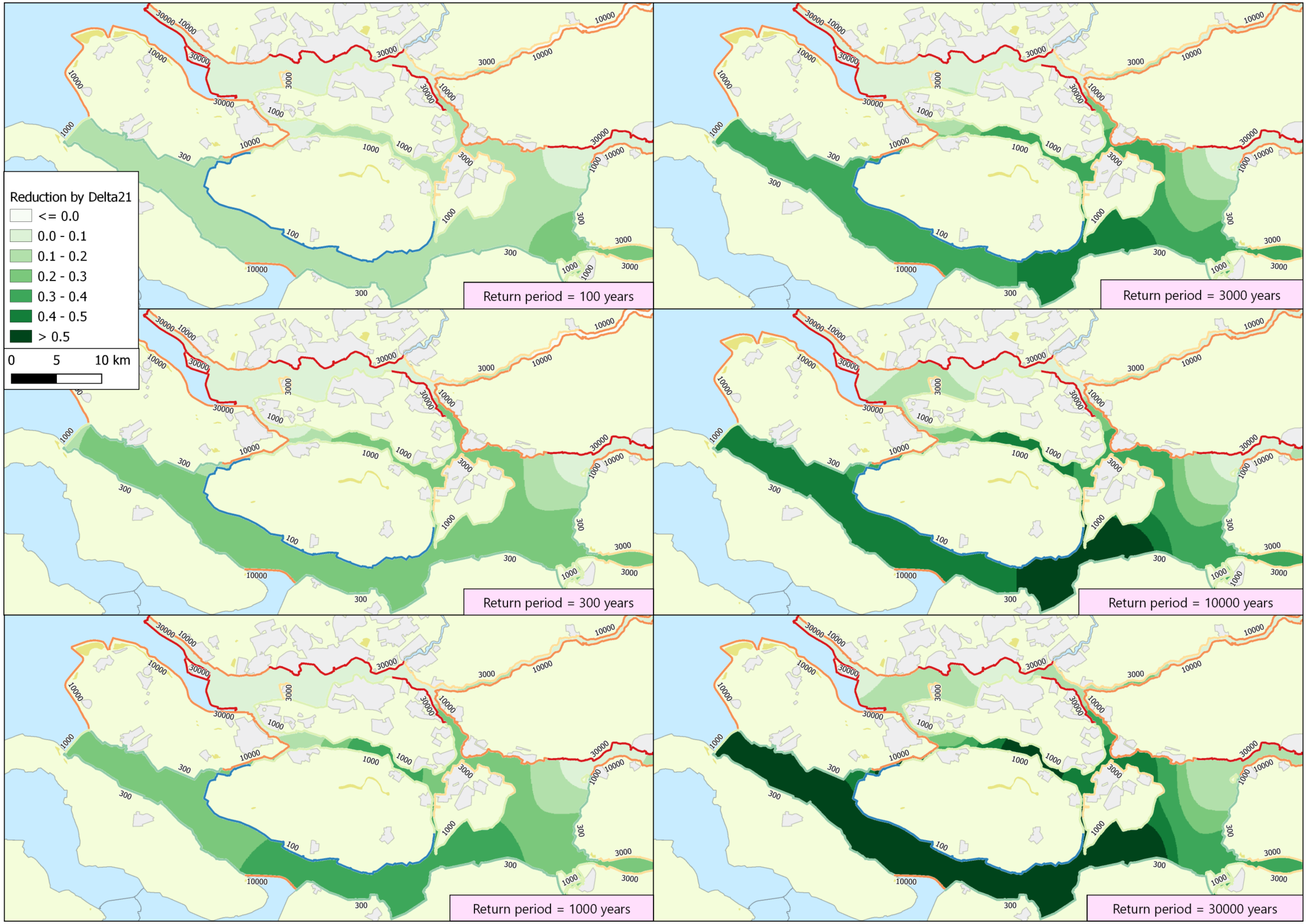


Figure F.29 Difference in maximum water level per boundary condition between Maeslantkering modes CF & GS for Rotterdam

Appendix G Spatial distribution of Delta21 peak water level reductions

The enlarged figure below presents the peak water level reductions for six frequencies. The return periods correspond to all present norms, as mapped too. The preliminary configuration for Delta21 in the current climate is used.



Appendix H Determination of escalation frequencies

To compute the frequency of an event in the boundary condition grid the joint probability distribution of maximum sea-level and discharge is used in combination with the expected amount of storms in a year (season). In compliance with the methods of the WBI2017, a season has 6 storm events of 30 days to make up approximately half a year. An extreme surge setup at sea still only lasts somewhere around 30 hours, of course. The density of this distribution can be integrated with the grid of Figure H.30. Then, the probability density is split into two parts by a line, which is generally some type of function that determines for which conditions that event occurs.

Hydra-NL can use this information per discrete discharge column (in this case: 9 in total) to compute a frequency. The functionality is designed for estimating the closure frequency of the Europoortkering, but works for any closure function. Note that a rise in mean sea level does not change the domains, but **does** influence the joint probability distribution of the boundary conditions.

When the event of interest is not defined by a well-behaved line with only one y-value per x-value, two computations are done where the most extreme is subtracted from the less extreme to represent an upper boundary of that domain.

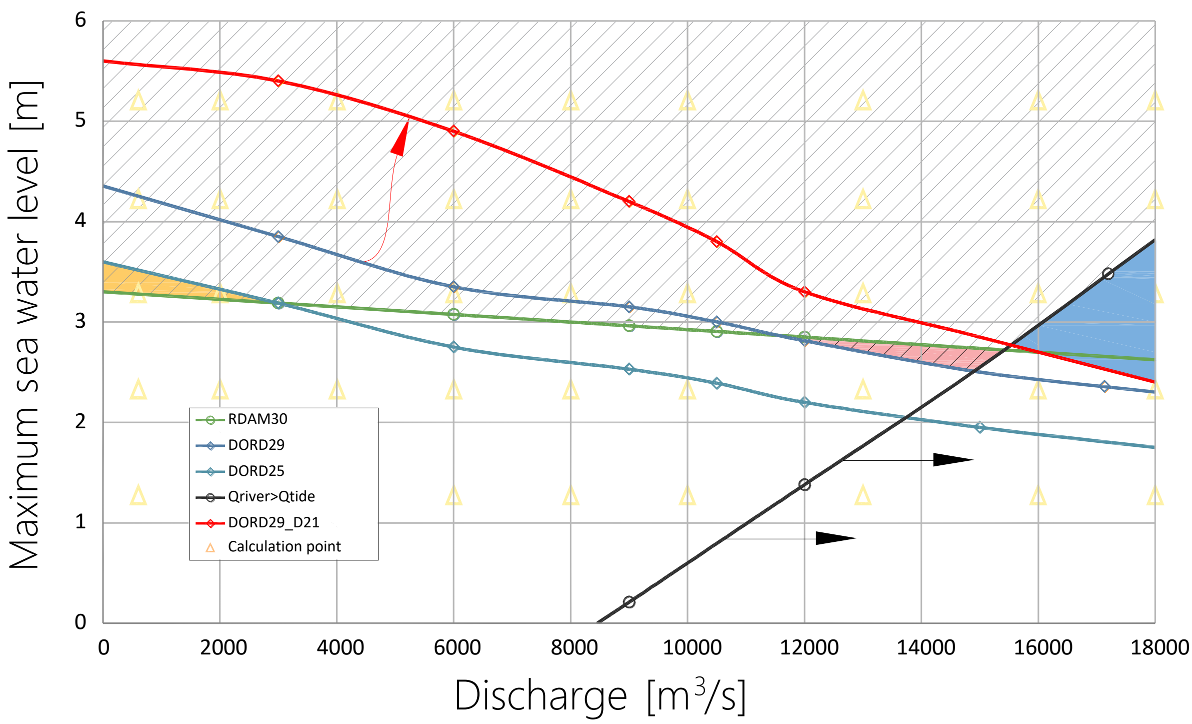


Figure H.30 Escalation domain grid For the Europoortkering and Delta21

For example, the closure function for the Europoortkering in the preliminary Delta21 system is defined as:

X = [600 , 2000, 4000, 6000, 8000, 10000, 13000, 16000, 18000] *in* m^3/s
Y = [3.29, 3.21 , 3.22 , 3.10 , 2.95 , 2.82 , 2.73 , 2.61 , 2.46] *in NAP + m*

Validation with WBI data

The MHWp5 databases tend to underestimate closure frequencies by approximately 20-30% in comparison to WBI2017 databases. The cause is the ex- or inclusion of local setup conditional on wind speed and direction. In the MHWp5 model no local setup is included and the closure function is independent of local wind speed or direction. Note that it is **not** independent of wind speed in general, as the setup at sea is very much correlated with wind speed and direction. Contrarily, in the WBI2017 databases local setup is dependant on wind speed, yet not on direction (which is somewhat peculiar). This underlines the fact that these databases and methods are not particularly well suited to calculate closure frequencies with high accuracy, and that results must be interpreted with care and in a relative sense only.

Table H.2 provides the collected data on Europoortkering closure frequencies in various systems and climate conditions.

Table H.2 Europoortkering closure frequencies in various configurations

System configuration	Europoortkering closure criterion for Dordrecht	D21 closure criterion for Dordrecht	Climate scenario	Closure frequency per year
CS	NAP + 2.9 m		Current climate	3.8E-02
CS	NAP + 2.9 m		Future scenario (W+)	6.0E-01
CS low	NAP + 2.5 m		Current climate	5.9E-02
D21 prelim	NAP + 2.9 m	NAP + 2.5 m	Current climate	4.3E-02
D21 prelim	NAP + 2.9 m	NAP + 2.5 m	Future scenario (W+)	7.0E-01
D21 low	NAP + 2.5 m	NAP + 2.5 m	Future scenario (W+)	8.0E-01
D21 high	NAP + 2.9 m	NAP + 2.9 m	Future scenario (W+)	9.0E-01

Appendix I Reinforcement cost estimation

Every dike reinforcement project requires an individual design and costs per kilometre can vary wildly. The high water protection program uses indicative values as presented in Table 6.1. To obtain a detailed approximation, crude designs and cost analysis for every separate project would be needed, but this falls far outside the scope of this research, which aims to sketch a picture for all the dikes in the Rhine-Meuse delta area. Therefore, a different approach is needed to narrow down the range given in Table 6.1.

Table I.3 HWBP reference values for costs per kilometre (incl. btw, pp 2021) (Haga, et al., 2021)

Project size:	Projects with limited task/complexity	Projects with average task/complexity per km	Projects with large task/complexity per km	Exceptional projects
Total investments cost per km:	€0 - €5 mil./ km	€5 - €10 mil./ km	€10 - €15 mil./ km	> €15 mil./ km
Percentage of dikes in category:	Ca. 30-40%	Ca. 40-50%	Ca.10-20%	Ca. 10%

Fortunately, several reinforcement projects in the Rhine-Meuse delta have already been budgeted in the current High Water Protection Program (HWBP). Table I.4 presents financial details on the projects in *WS Hollandse Delta* and *WS Brabantse Delta*, which are most representative for the Southern and middle branches of the Rhine-Meuse delta. The first six projects are included in the definitive budget for 2024-2035. The last two are registered but not yet fully confirmed, and costs are rough estimations in the year 2029 at the earliest. Their weights towards the average cost per kilometre are therefore correct by a factor of 1/3. The weighted average cost per kilometre of dike reinforcement in these two water boards then becomes **€ 6.7 million/km.**

Table I.4 Dike reinforcement projects in Hollandse Delta and Brabantse Delta in the definitive HWBP program 2024-2035 (HWBP, 2023)

HWBP Project	Total budget (€M)	length (m)	cost/km (€M/km)	weight (-)
Moerdijk Drimmelen	€ 74.4	13953	€ 5.33	24%
Standhazense Dijk	€ 8.8	730	€ 12.00	1%
Zettingsvloeing V3T	€ 49.9	5055	€ 9.88	9%
Geervliet - Hekelingen 20-3	€ 46.0	6000	€ 7.67	10%
17-3 Oostmolendijk Ringdijk	€ 20.0	2000	€ 10.00	3%
20-2 Brielse Maasdijk	€ 76.8	12958	€ 5.93	23%
Geertruidenberg amertak	€ 47.7	7222	€ 6.60	4%*
Willemstad Noordschans	€ 48.9	9476	€ 5.16	6%*
*corrected by factor 1/3			weighted average:	€ 6.7 million/km

Upon further inspection, two projects are highlighted to be particularly representative for the sort of obviation that Delta21 may achieve: Moerdijk & Willemstad. The former dike section has been negatively assessed on both stability (STBI) and piping (STPH). The former being graded as a category IV, and the latter in category V. The reinforcement project is budgeted at a total of €74,4 million with a length of 13,95 km, coming down to €5,3 million/km. With the preliminary configuration of Delta21, the reinforcement for stability is no longer required. Piping is somewhat relieved, but nearly nowhere sufficient to obviate a reinforcement. The Willemstad project has very similar characteristics. STBI is assessed in category IV, and piping in V. Costs: a total of €48,9 for 9,5 km, meaning €5.1 million/km. A small overestimation of the former method is therefore possible.

To consider a larger dataset, the entirety of the definitive HWBP budget can be analysed in similar fashion. Table I.5 provides the data of all budgeted dike reinforcement projects in the Netherlands. The resulting weighted average becomes €7.8 Million/km, which means that the previous estimate might be somewhat on the low side. It is not uncommon for water boards to program those reinforcements projects that are needed the most first. Those also tend to be among the more expensive. Simultaneously it is also not uncommon that the 'simple' projects appear on the budgets first, because the more complex instances are still being worked on. These simple reinforcements tend to be among the less expensive ones. Taking all these considerations into account, no correction of the initially proposed €6.7 million/km is made.

Figure I.31 presents a brief statistical analysis of the budgeted HWBP dike reinforcement projects, where a general extreme value distribution is fitted to the data. The 90% confidence interval of the reinforcement costs per kilometre becomes approximately €2 mil./km - €25 mil./km.

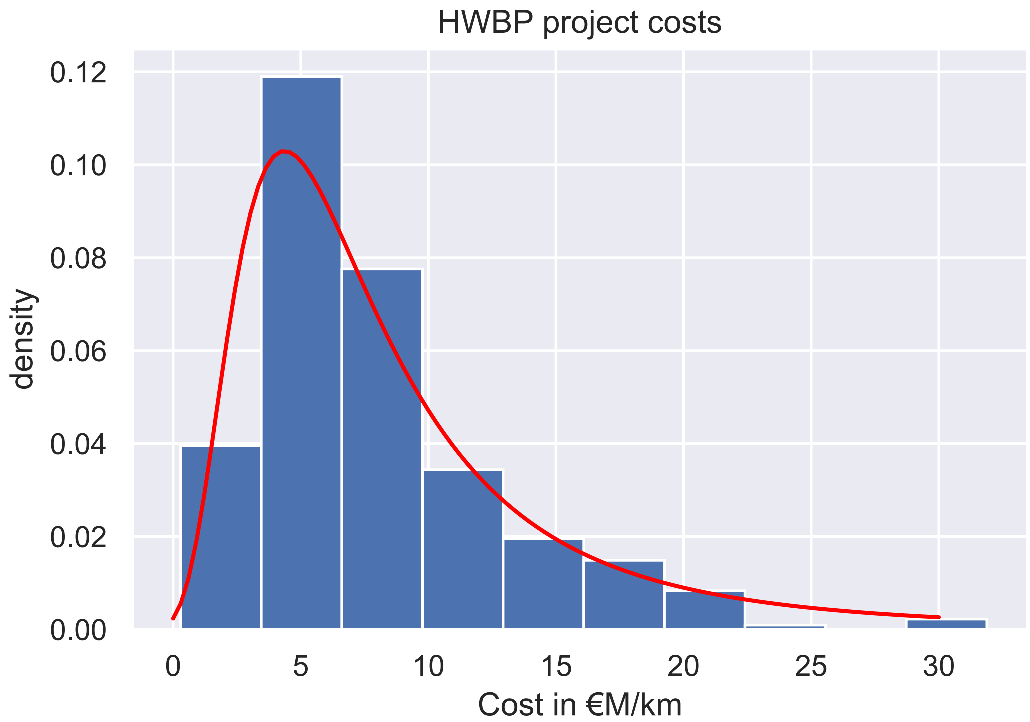


Figure I.31 Histogram and fitted GEV distribution on HWBP project budget reinforcement costs

Table I.5 overview of dike reinforcement projects in the definitive HWBP program 2024-2035 (HWBP, 2023)

Beheerder	Projectnaam	Length (m)	total costs (€M)	costs/km (€M/km)	weights
HH De Stichtse Rijnlanden	Versterking voormaligt C-kering HDSR (SHU)	10800	43.5	€ 4.0	1.72%
HH De Stichtse Rijnlanden	Wilk bi Dourstede Amerangen (WAM)	9799	39.4	€ 4.0	1.56%
HH De Stichtse Rijnlanden	Salmsteke	1951	20.1	€ 10.3	0.31%
HH De Stichtse Rijnlanden	Culemborgie Veer-Beatrix Slub (CUB)	6370	64.0	€ 10.1	1.01%
HH De Stichtse Rijnlanden	Salmsteke Schoonhover (SAS)	7128	62.5	€ 8.8	1.13%
HH De Stichtse Rijnlanden		11348	84.8	€ 7.5	1.80%
HH De Stichtse Rijnlanden	Irenesluis Culemborgse Veer	9535	71.5	€ 7.5	1.51%
HH Hollands Noorderkwartier	Der Oever Der Heider DOOH	12989	37.7	€ 2.9	2.06%
HH Hollands Noorderkwartier	Kopoelstuk Durgerdam	659	13.6	€ 20.6	0.10%
HH Hollands Noorderkwartier	Helderse Zeewering	1235	8.2	€ 6.6	0.20%
HH Hollands Noorderkwartier	Neuwe Dep	1900	46.2	€ 24.3	0.30%
HH van Rijnland	Usseldijk Goude (VUG) spoor (GHU)	919	5.4	€ 5.9	0.15%

Beheerder	Projectnaam	Length (m)	total costs (€M)	costs/km (€M/km)	weights
HH van Schieland en de Krimpenerwaard	Krachtige Usseldiker Krimpenerwaard (KUK)	10472	171.3	€ 16.4	1.66%
HH van Schieland en de Krimpenerwaard	Capelle-Zuidpla	11400	230.1	€ 20.2	1.81%
WS Aa en Maas	Ravenstein Let	26552	136.5	€ 5.1	4.22%
WS Aa en Maas	Cuit Revenstein	20724	118.6	€ 5.7	3.29%
WS Aa en Maas	Doeveren	4099	27.1	€ 6.6	0.65%
WS Brabantse Delta	Muerdijk Drimmeten	13953	74.4	€ 5.3	2.22%
WS Brabantse Delta	Standharense OR	730	8.8	€ 12.0	0.12%
WS Drents Overijsselse Delta	Stadsdijken Zwolle (15E)	7641	92.3	€ 12.1	1.21%
WS Drents Overijsselse Delta	Generuulden-Hassel	7191	42.5	€ 5.9	1.14%
WS Drents Overijsselse Delta	Mastenbrock Ussel	14623	78.0	€ 5.3	2.32%
WS Drents Overijsselse Delta	Zwelle Dist	28880	265.6	€ 9.2	4.59%
WS Drents Overijsselse Delta	Vecht-Stenendiji Hasselt	1284	10.7	€ 8.3	0.20%
WS Drents Overijsselse Delta	Vecht Dather Zwork Mastenbrook Zwarte Meet	32000	133.0	€ 4.2	5.08%
WS Drents Overijsselse Delta	Keershis Zwelle	283	2.1	€ 7.5	0.04%
WS Drents Overijsselse Delta	Vecht-Cost	10900	5.1	€ 0.5	1.73%
WS Drents Overijsselse Delta	Vecht Zwartewaterland	9800	2.9	€ 0.3	1.56%
WS Fryslan	Koehook Louwersmee	35900	331.2	€ 9.2	5.70%
WS Fryslan	Zurich Koehool	22300	199.6	€ 9.0	3.54%
WS Fryslan	DIR en duinversterking Schlermonni-kong	9895	61.1	€ 6.2	1.57%
WS Hollandse Delta	Zettingsvloeing V31	5055	49.9	€ 9.9	0.80%
WS Hollandse Delta	17-3 Oostmolendik Ringdilk	2000	20.0	€ 10.0	0.32%
WS Hollandse Delta	20-2 Brieise Meascije	12958	76.8	€ 5.9	2.06%
WS Hunze en Aa's	Kerkhowanpolder Dultsland LRT3	7144	57.1	€ 8.0	1.13%
WS Limburg	Roermand Traject 76 deeltraject Zuid	1712	19.1	€ 11.2	0.27%
WS Rijn en IJssel	Tolkamer Pannerdense Woard	9425	130.6	€ 13.9	1.50%
WS Rijn en IJssel	Den (termeg-Zutphen	4713	96.2	€ 20.4	0.75%
WS Rijn en IJssel	Westerwort-Daesburg	6407	29.5	€ 4.6	1.02%
WS Rijn en IJssel	Bingerden Doesburg	3131	26.6	€ 8.5	0.50%
WS Rijn en IJssel	Lathumsedik	2555	16.3	€ 6.4	0.41%
WS Rijn en IJssel	Dee/project Doesburg Rts	13160	59.6	€ 4.5	2.09%
WS Rivierenland	Welferen Sarak incl DTO	13175	128.6	€ 9.8	2.09%
WS Rivierenland	Gorinchem Waardenburg (GoWa)	23485	230.0	€ 9.8	3.73%
WS Rivierenland	Tel Waardenburg (TMa)	19457	330.1	€ 17.0	3.09%
WS Rivierenland	Neder-Betuwe	20147	225.8	€ 11.2	3.20%

Beheerder	Projectnaam	Length (m)	total costs (€M)	costs/km (€M/km)	weights
WS Rivierenland	Sprok Sterreschars Heteren	38313	36.4	€ 1.0	6.08%
WS Rivierenland	Streetkerk Ameide Fort Everdingen (SAFE)	9654	138.2	€ 14.3	1.53%
WS Rivierenland	Stad Tiel excl Fluvia	2709	38.2	€ 14.1	0.43%
WS Scheldestromen	Buid-Beveland West, Westerschelde Hansweert	4507	143.7	€ 31.9	0.72%
WS Scheldestromen	Zuid Beysland West, Wasterschelder S2	25200	90.0	€ 3.6	4.00%
WS Scheldestromen	Zuid Beveland Cost, Westerscheide	14400	52.0	€ 3.6	2.29%
WS Valei en Veluwe	Noordeleke Randmeerdjk find WOOD]	977	6.0	€ 6.1	0.16%
WS Valei en Veluwe	Apeldooms Kanzal	2810	0.3	€ 0.1	0.45%
WS Valei en Veluwe	Grebbedijk	4813	46.2	€ 9.6	0.76%
WS Zuiderzeeland	Zuidermeerdijk-MSNF	1200	1.2	€ 1.0	0.19%
WS Zuiderzeeland	Ijsselmeerdijk	17600	230.7	€ 13.1	2.80%
WS Zuiderzeeland	Oostvaardersdijk	4976	33.6	€ 6.8	0.79%
			weighted average cost/km:	**€7.80 million/km**	

Appendix J Obviated project km's within HWBP

Firstly, data from the *Wettelijk Toets Instrumentarium* (WBI) that is readily available at the *Nationaal Georegister* (NGR) is used to map the dikes in the Rhine-Meuse estuary, see Figure J.32 below. Included in WBI data are the assessments per track for dike sections (*dijkvakken).* Three tracks are considered, in which reductions as a result of Delta21 are expected to play a role:

1. Piping (STPH)
2. Macro-stability (STBI)
3. Crest/inner slope erosion or 'height' (GEKB)

For every 100 m long stretch of dike, the following information is compiled:

- The Dike section ID with accompanying **trajectory ID** and **norm (minimal, not signal value)**
- For all three tracks: The section assessment **category** and **failure probability** P_{fail}

Note that this information is not (yet) publicly available for trajectories adjacent to the sea (208, 209, 19-1) , 18-1, and the Volkerakdam (215), and they are therefore not included in the assessment (referred to as NO DATA). Trajectory 20-3 is also missing, but is rather essential considering its location. Therefore, it is added to the data manually using the assessment reports by Waterschap Hollandse Delta (Bossenbroek J. , 2017).

Figure J.32 Map of dike trajectories in the Rhine Meuse delta in the NGR

The failure probability of a dike section determines the category in which it is classified. The classification margins are a product of the trajectory's norm and defined as follows in Table 2-3 of WBI protecols:

Table J.6 Categorization of dike sections per track (Dutch) (Ministerie van Infrastructuur en Milieu, 2019)

Cat.	Aanduiding categorie toetsoordeel per vak per toetsspoor	Begrenzing categorie $P_{f;dsn}$ Faalkans per vak (doorsnede of kunstwerk) [1/jaar]. $P_{eis;sig}$ Signaleringswaarde van het dijktraject [1/jaar]. $P_{eis;ond}$ Ondergrens van het dijktraject [1/jaar]. $P_{eis;sig;dsn}$ Faalkanseis per doorsnede of kunstwerk [1/ jaar]
I_v	voldoet ruim aan de signaleringswaarde	$P_{f;dsn} < \frac{1}{30} P_{eis;sig;dsn}$
II_v	voldoet aan de signaleringswaarde	$\frac{1}{30} P_{eis;sig;dsn} < P_{f;dsn} < P_{eis;sig;dsn}$
III_v	voldoet aan de ondergrens en mogelijk aan de signaleringswaarde	$P_{eis;sig;dsn} < P_{f;dsn} < P_{eis;ond;dsn}$
IV_v	voldoet mogelijk aan de ondergrens of aan de signaleringswaarde	$P_{eis;ond;dsn} < P_{f;dsn} < P_{eis;ond}$
V_v	voldoet niet aan de ondergrens	$P_{eis;ond} < P_{f;dsn} < 30 P_{eis;ond}$
VI_v	voldoet ruim niet aan de ondergrens	$P_{f;dsn} > 30 P_{eis;ond}$
VII_v	nog geen oordeel	

The *Doorsnede-eis* or cross-sectional requirement is calculated for every dike section using its norm and length effect factor N calculated as follows according to guidelines in the WBI (Ministerie van Infrastructuur en Milieu, 2019):

$$P_{cs,requirement} = \frac{1}{P_{norm}} * \frac{\omega}{N} \; ; \qquad N = 1 + \frac{a}{b} * length$$

The WBI schematization guidelines present values for the constants per track, or simply specify N per trajectory.

Table J.7 Length-effect factor N constants (Ministerie van Infrastructuur en Waterstaat (2022) (2021a) (2021b)

	ω	a	b
STPH	24%	0.4 for the Rhine-Meuse delta	300 m
STBI	4%	0.033	50 m
GEKB	24%	$N = 2$ in entire area with data, except trajectories starting with 24-, which have $N = 1$	

Both the sections computed failure probability, and the probability requirement[1] are now known. The logarithm of the difference between the two can be used to express how many decimations[2] are needed for that particular section to meet its norm:

$$Required\ decimation = \log\left(\frac{P_{fail}}{P_{cs,requirement}}\right)$$

Next, the required decimation needs to be translated to a required height to assess whether Delta21 can meet this demand. For the tracks STPH and STBI one can employ the fragility curves being developed within the Knowledge Program Sea Level Rise (KPZSS). These describe 'typologies' for dike sections that have a distribution describing failure probability conditional on the water level. The distribution is a normal one, and the variance describes in a way the 'sensitivity' to a lower water level. Figure J.33 presents an example fragility curve, and Figure J.34 displays how one would extract a decimation height from it.

[1] When the cross-sectional requirement seems to be met, but the official categorization is still IV, a required decimation of 0.5 is assigned. Assumed is that an improved failure probability by approximately 0.33 is sufficient in these cases.

[2] Division by 10

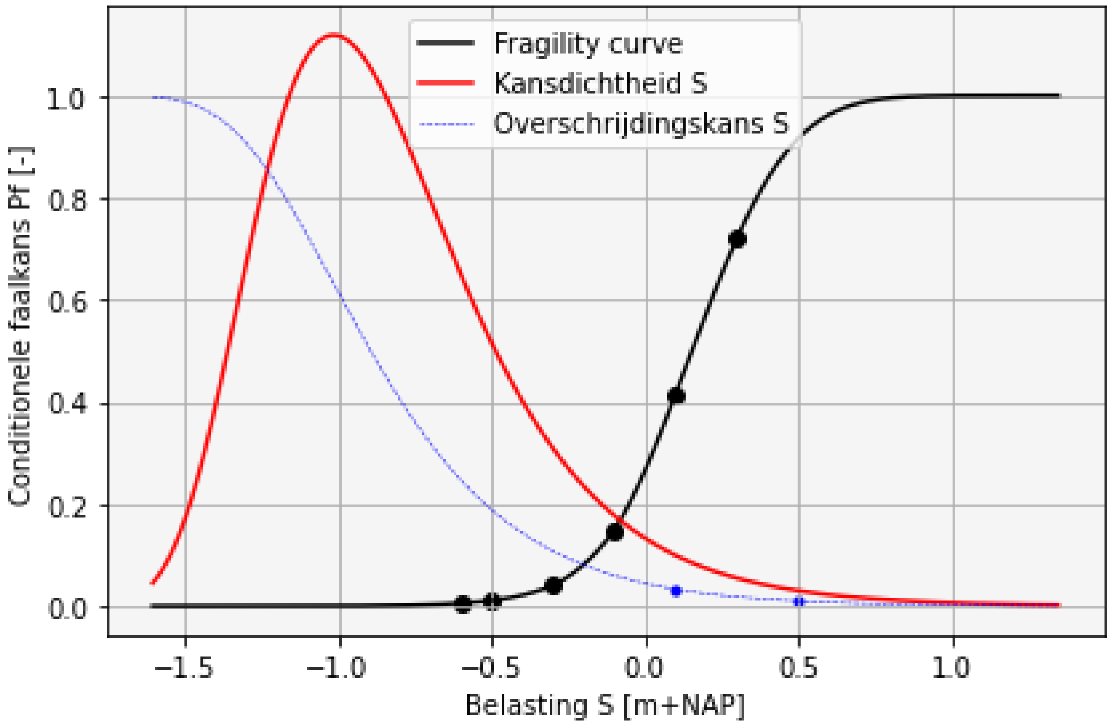


Figure J.33 Example Fragility curve (KPZSS)

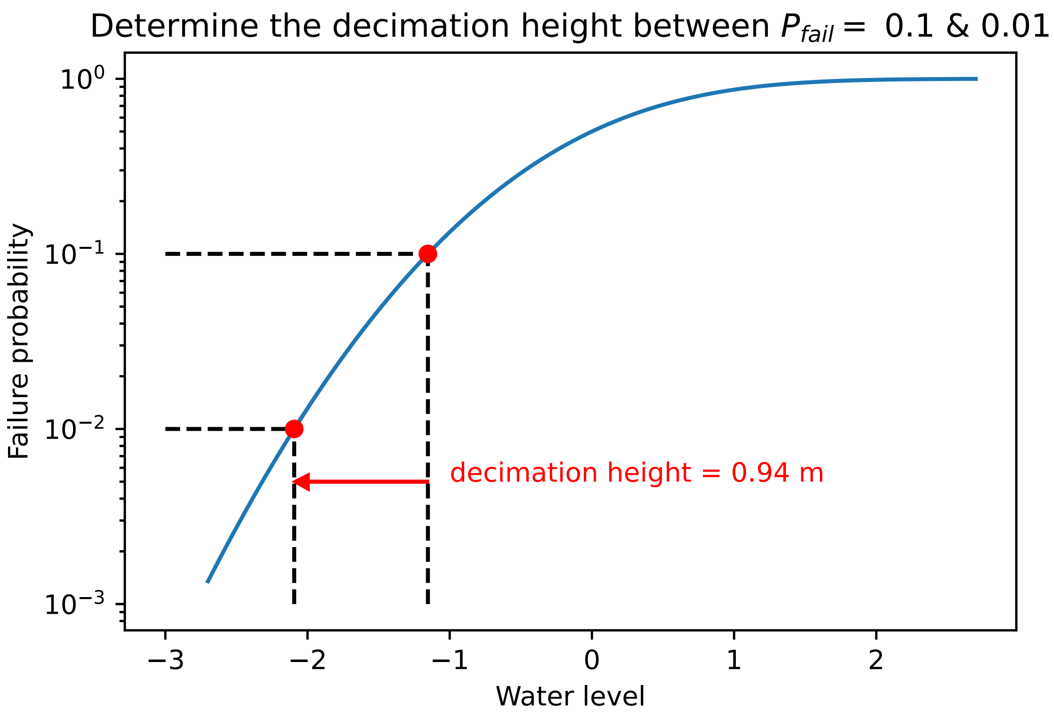


Figure J.34 Example Fragility curve with decimation height calculation

The goal is to have a basic idea of potential savings due to Delta21, so the dikes with no typology are assigned one based on its closest neighbours and proximity to urban areas. The result is presented in Figure J.35. Because the failure probability of each dike section is known, the decimation height is taken from the corresponding normal distribution between P_{fail} and $\frac{P_{fail}}{10}$.

Typologies KPZSS												
STPH	**Type nr.**	**1**	**2**	**4**	**5**	**6**	**7**	**8**	**9**	**11**	**12**		
	Standard deviation	0.37	0.39	1.08	0.72	0.45	0.65	0.55	0.47	0.9	0.5		
STBI	**Type nr.**	**2**	**3**	**4**	**6**	**7**	**8**	**9**	**10**	**11**	**13**	**14**	**15**
	Standard deviation	1.8	0.6	0.8	3.2	2.5	1.4	1.4	0.9	0.9	3.3	1.9	1.1

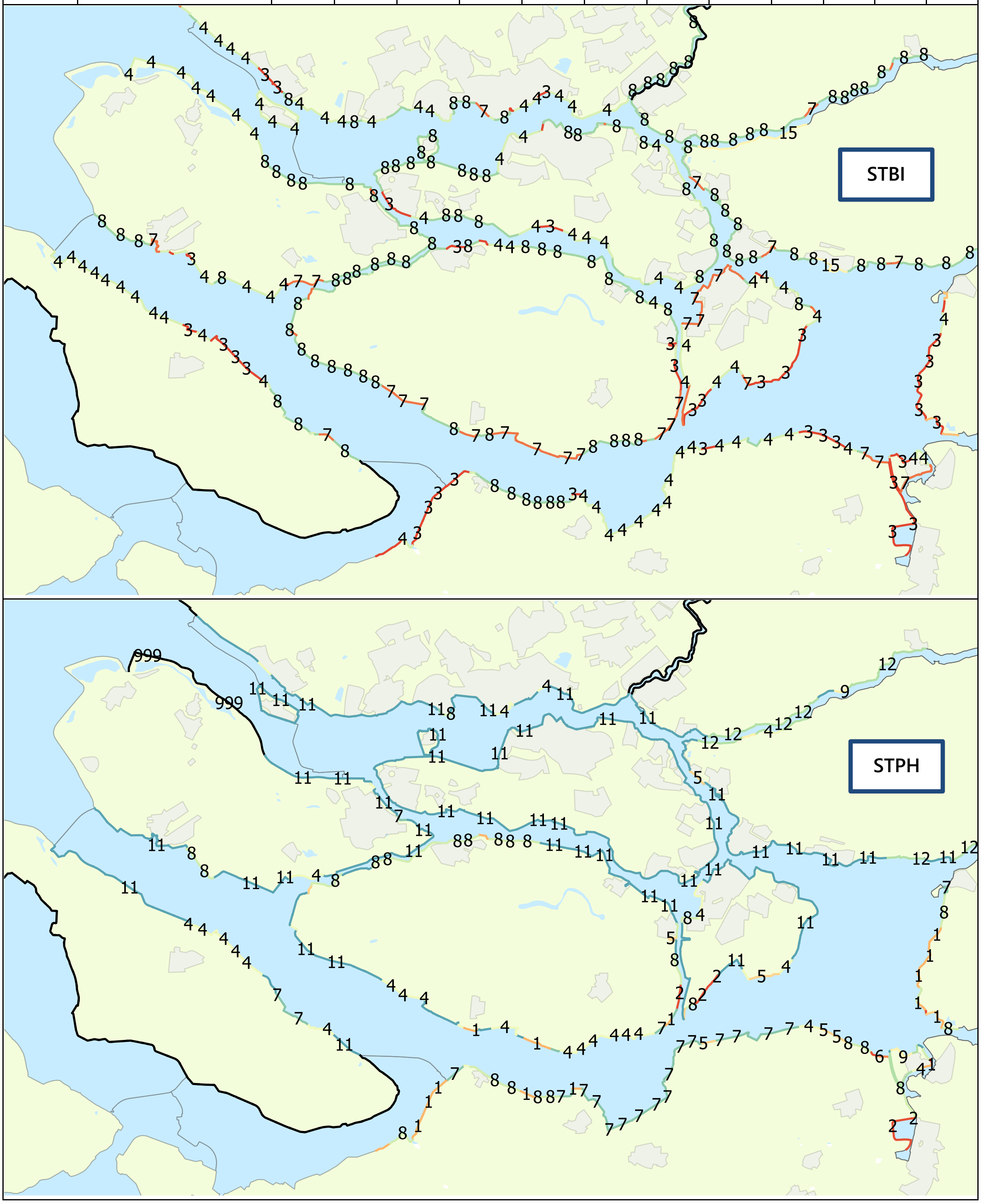


Figure J.35 Typology maps from the KPZSS

The decimation height for the track GEKB is not described within the KPZSS. The failure mode also does not lend itself particularly well for a conditional description with a normal distribution, because the standard deviation would in all cases be very small. In the context of Delta21, the decimation height for this track can be taken from the slope of the exceedance frequency curve itself. After all, when the dike fails at a certain approximate water level, making sure that water level occurs 10 times less often yields approximately a single decimation.
The exceedance frequency curve slope for the preliminary configuration of Delta21 are computed for six frequencies corresponding to the norms. These slopes are than interpolated for the entire area using a straightforward TIN interpolation. For each section the decimation height is taken as the interpolated slope at the normative frequency of that section.

Note that the cross-sectional probability requirement is significantly lower than the trajectory norm. Therefore, the decimation height of GEKB could be evaluated at a larger return period. However, this effect is approximately counteracted by the fact that the wind / wave climate is also a very determining factor for GEKB. This means that the still water level for illustrative conditions is lowered to, fortunately, more or less the same level as is exceeded at the overall normative frequency. A full inclusion of all these effects could yield better fragility estimates for GEKB, but is not within the scope of this research.

Decimation heights are very useful to get a good feeling of how much reduction is needed because their unit is also in metres. Nevertheless, for example in the future scenario, it is useful to consider the full distribution again, because decimation height is a function of the probability where it is evaluated. Only the standard deviations are once again important. To acquire an estimate for the standard deviation of the track GEKB, the calculation is reversed using:

$$\sigma = \frac{Decimation\ height}{P(Z < P_{evaluate}) - P(Z < \frac{1}{10} P_{evaluate})}$$

Where:

σ = The standard deviation of the fragility curve
Z = standard normal distribution
$P_{evaluate}$ = the probability where the decimation height was evaluated (the norm of that trajectory)

Note that the decimation height is estimated at the frequency that corresponds to the failure probability in the data for that segment, but required reduction is expressed at the trajectory norm. Because Delta21 has the greatest potential amongst dikes with failure probabilities that are not extremely much higher than the limit, these two frequencies are not significantly different.

The final steps concern the comparison with Delta21. Using Delta21, exceedance frequency curves are obtained that are compared to the current system to yield reductions (see for example Section 5 or Appendix G). For each 100 m stretch of dike, the reduction at the normative frequency is sampled. Then, a check for all three tracks (STPH, STBI, GEKB) is performed to see whether the reduction by Delta21 is sufficient to meet the required decimation:

$$\frac{Reduction}{Decimation\ height * required\ decimation} > 1$$

The result is subsequently a map which shows per track where a potential saving of Delta21 within the HWBP can be obtained. 'Potential' is used because these maps give estimates, and for a true assessment one would need to use the hydraulic database to perform a detailed stability analysis per section. Figure J.36 presents the final result for the example of the preliminary configuration. Naturally, the HWBP is already ongoing, meaning that certain reinforcements are already being carried out or will be soon. Checking where these trajectories are located and comparing that with potential obviations due to Delta21 indicates very little to no overlapping at the time of writing. Therefore, the numbers in Figure J.36 are not reduced.

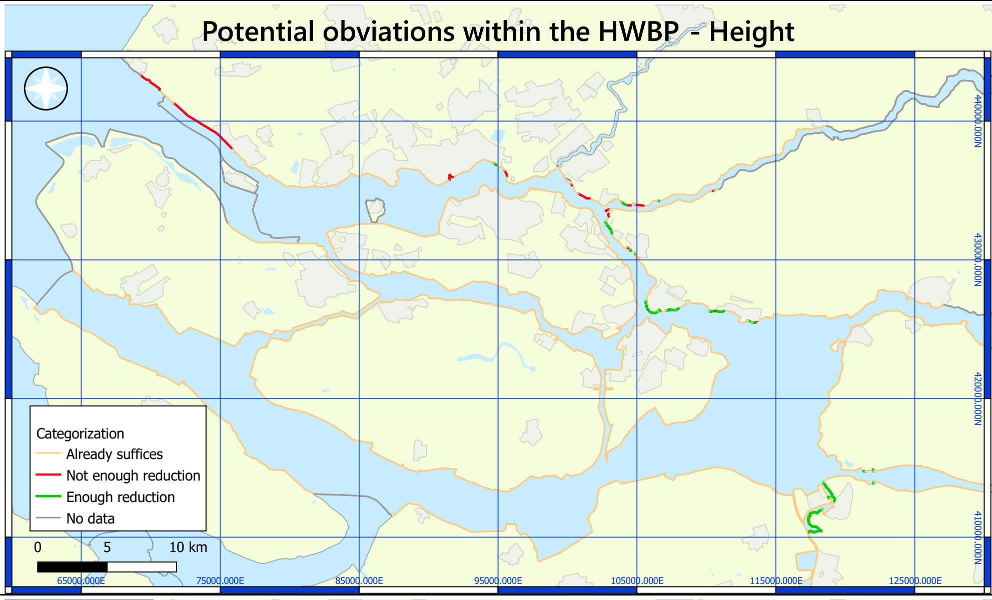
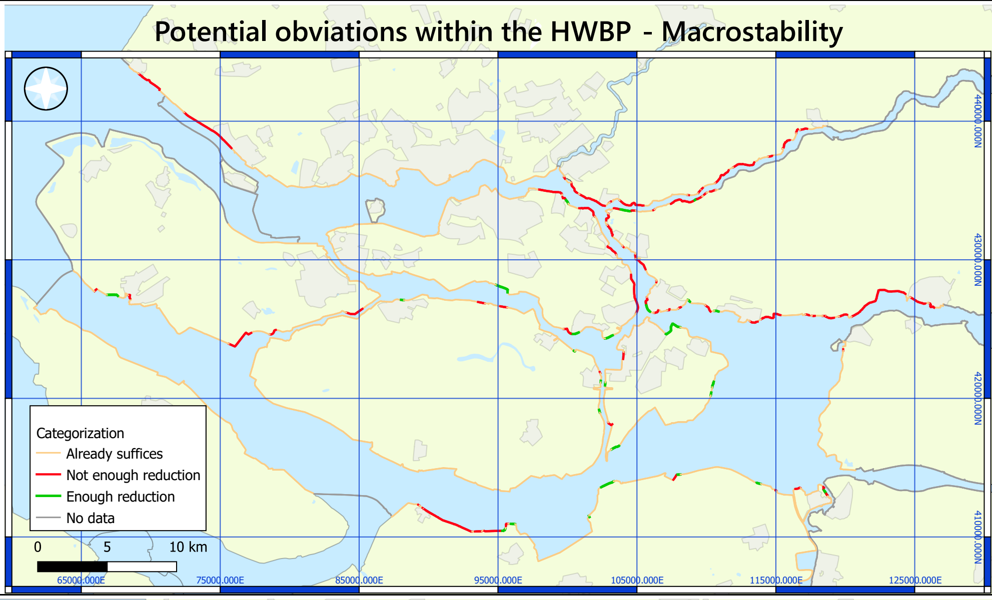
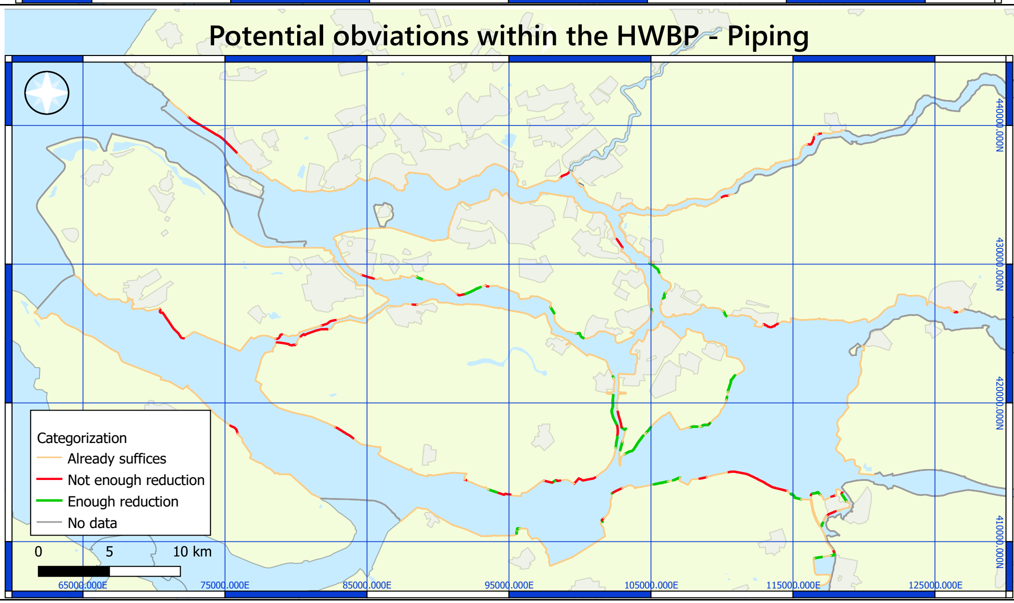
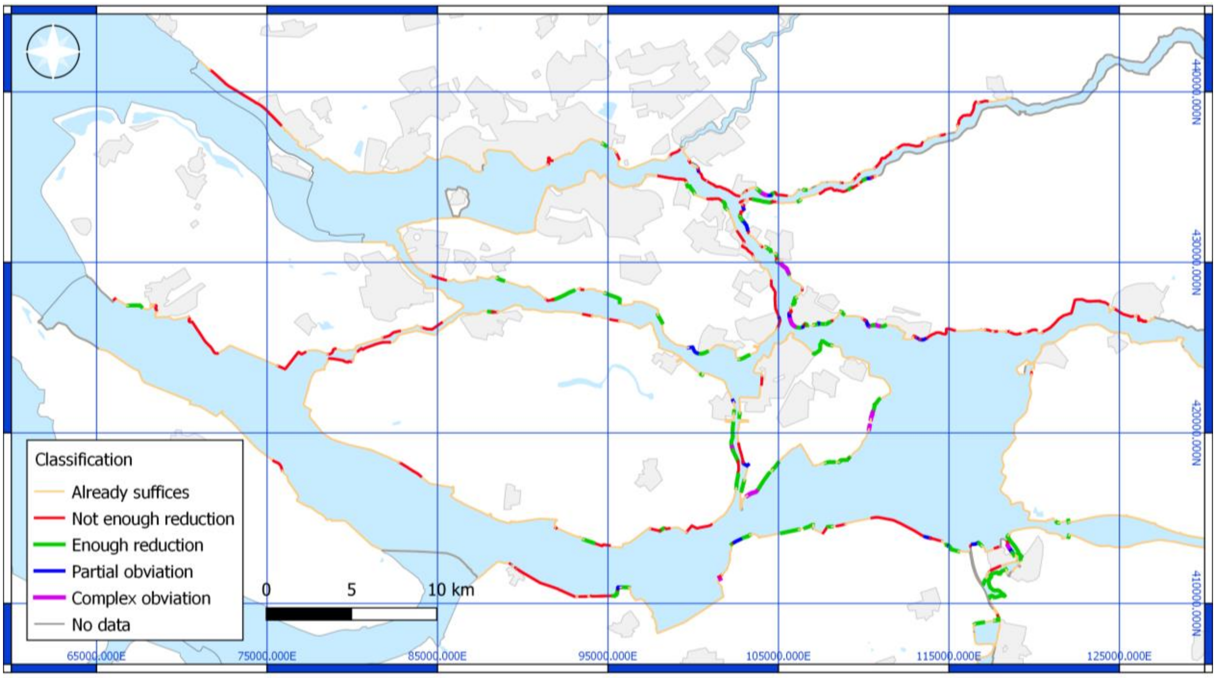
<table>
<tr>
<td>12.1 km obviation
49 % of total disapproved km’s (excluding nodata)</td>
<td>
</td>
</tr>
<tr>
<td>11.7 km obviation
16 % of total disapproved km’s (excluding nodata)</td>
<td>
</td>
</tr>
<tr>
<td>20.3 km obviation
37 % of total disapproved km’s (excluding nodata)</td>
<td>
</td>
</tr>
</table>

Figure J.36 HWBP savings of the preliminary Delta21 configuration

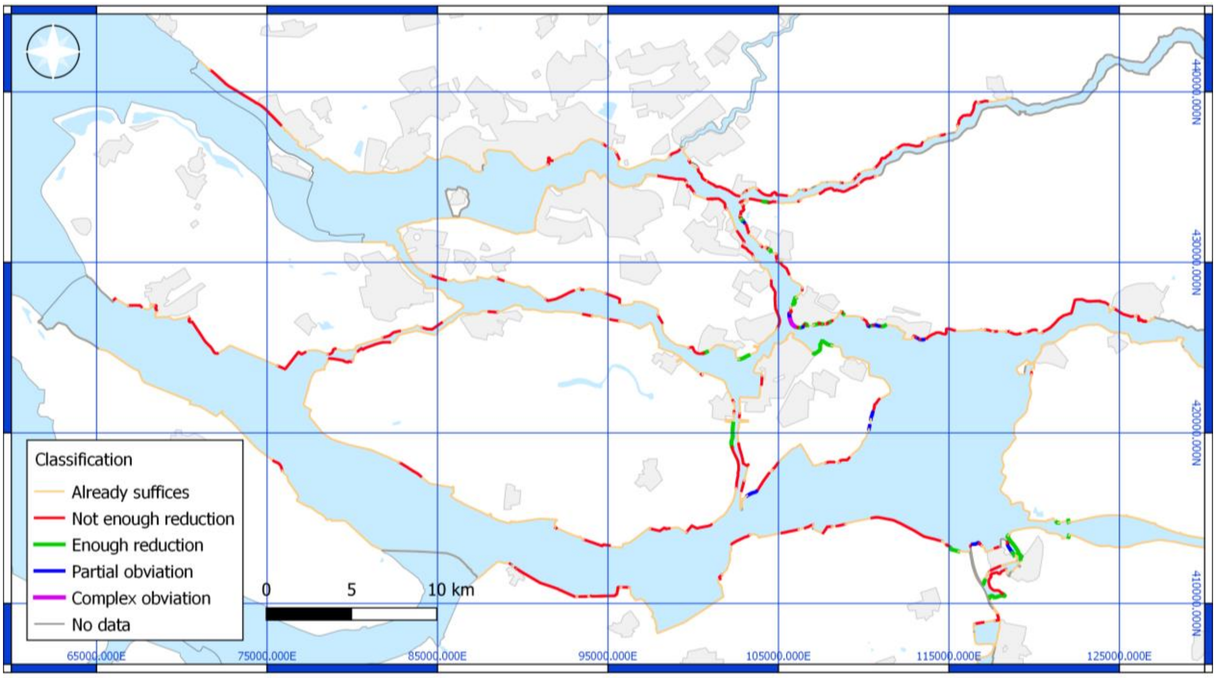
Obviation overviews for adapted closure criteria in the current climate

Delta21 and the Europoortkering have criterion Dordrecht NAP + 2.5 m



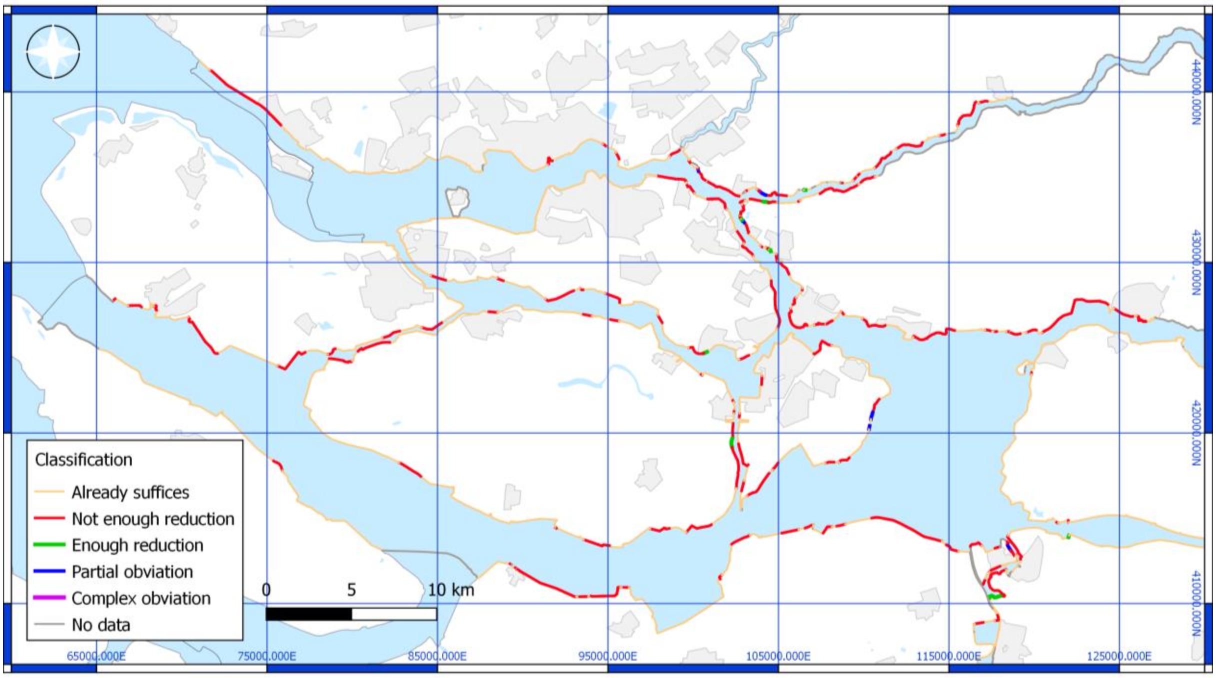
Delta21 and the Europoortkering have criterion Dordrecht NAP + 2.5 m	Already suffices	Not enough to obviate	Enough to obviate - average	Enough to obviate - complex	Enough to obviate - partial	No Data
STPH	324 km	33.9 km	20.8 km	-	-	-
STBI	312 km	54.2 km	15.2 km	-	-	-
GEKB	469 km	10.3 km	12.7 km	-	-	-
combined	**383 km**	**82.6 km**	**34.2 km**	**4.3 km**	**6.0 km**	**364 km**

Delta21 and the Europoortkering have criterion Dordrecht NAP + 2.9 m



Delta21 and the Europoortkering have criterion Dordrecht NAP + 2.9 m	Already suffices	Not enough to obviate	Enough to obviate - average	Enough to obviate - complex	Enough to obviate - partial	No Data
STPH	324 km	50.4 km	4.3 km	-	-	-
STBI	312 km	65.0 km	4.4 km	-	-	-
GEKB	469 km	16.3 km	6.7 km	-	-	-
combined	**383 km**	**112 km**	**10.6 km**	**0.7 km**	**3.4 km**	**364 km**

No Delta21, but the Europoortkering has criterion Dordrecht NAP + 2.5 m



No Delta21, but the Europoortkering has criterion Dordrecht NAP + 2.5 m	Already suffices	Not enough to obviate	Enough to obviate - average	Enough to obviate - complex	Enough to obviate - partial	No Data
STPH	324 km	53.3 km	1.4 km	-	-	-
STBI	312 km	58.9 km	0.5 km	-	-	-
GEKB	469 km	20.8 km	2.2 km	-	-	-
combined	**383 km**	**123 km**	**2.5 km**	**0 km**	**1.6 km**	**364 km**

Appendix K Risk calculations for unprotected areas on the island of Dordrecht

To calculate the average annual expected damage for the Island of Dordrecht Equation 3-1 is used, repeated below.

$$R = \int_{f_{min}}^{f_{max}} D(f)df \qquad \text{Equation 3-1}$$

Where:

R = the average annual expected damage [€ / year]
f = the annual frequency of an event [year^{-1}]
D(f) = damage as a function of annual frequency

The bounds f_{min} and f_{max} are determined by the range of frequencies in which water level exceedance is described. Because Hydra-NL is not able to give sufficiently reliable data for frequencies lower than 10^{-5}, this is taken as the upper bound.

In his research, Buijs (2021) computes damage profiles as a function of water level for three distinct areas on the island of Dordrecht: the historical harbour, flanks, and Biesbosch (see Figure K.37). The damage profiles are presented in Figure K.38 and contain values up to approximately €5.0 * 10^7. Because of a change in among others land use and economic development, an adapted curve is included for the year 2100. The water level exceedance frequency curve for Dordrecht is computed at the marked location in Figure K.37.

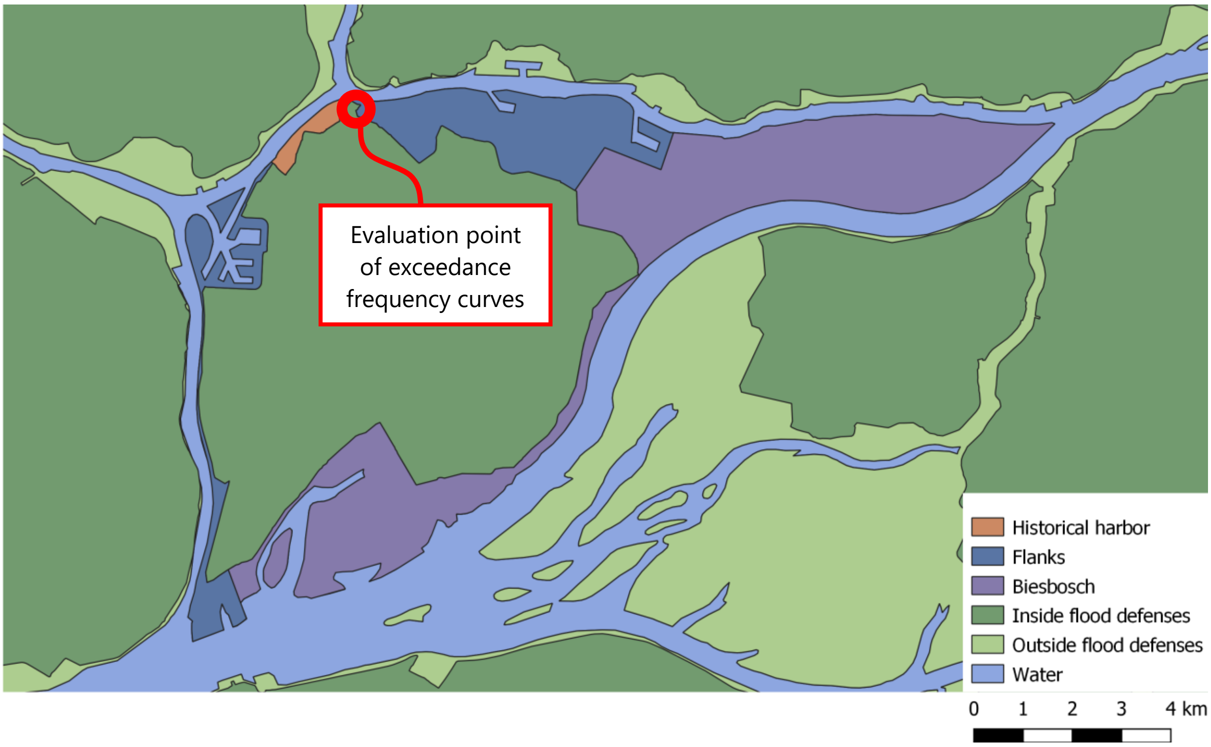
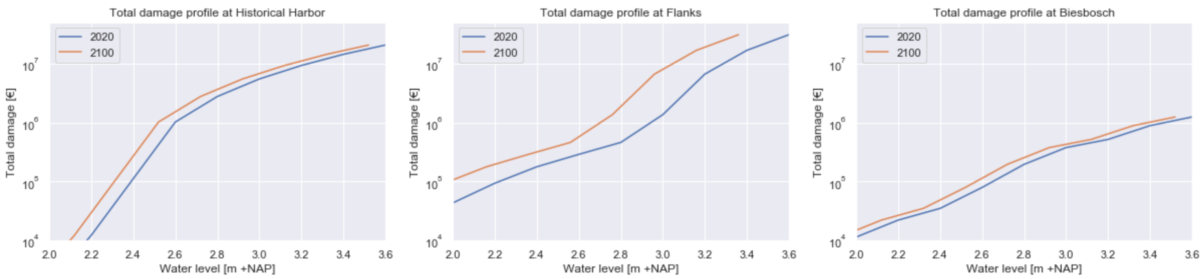


Figure K.37 Map of unprotected areas on the island of Dordrecht with three classifications . (Buijs, 2021)

A majority of the potential damages lie around the historical harbour, with also the flanks having a concentrated value close to the harbour. Furthermore, at that location a full probabilistic evaluation of exceedance frequencies is available from model computations in various variations and scenarios. Therefore, the Biesbosch area is excluded from this basic risk estimation. The historical harbour and flanks border the Oude Maas, Beneden Merwede, and Dordtsche Kil. The exceedance frequencies at these branches are fairly well described by the marked evaluation point, assuming concentrated value around this location. Additional saving in the Biesbosch area is possible and recommended for more detailed estimates, but requires separate evaluation of exceedance frequencies, as the behaviour of the Nieuwe Merwede is significantly different.



a. b. c.

Figure K.38 Damage profiles for every flood prone region not protected by flood defenses for the year 2020 and 2100 (Buijs, 2021)

By summing the damage profiles from Figure K.38 a and b, a total damage profile is produced that will be used in subsequent calculations. Figure K.39 presents the profiles for the years 2020 and 2100.

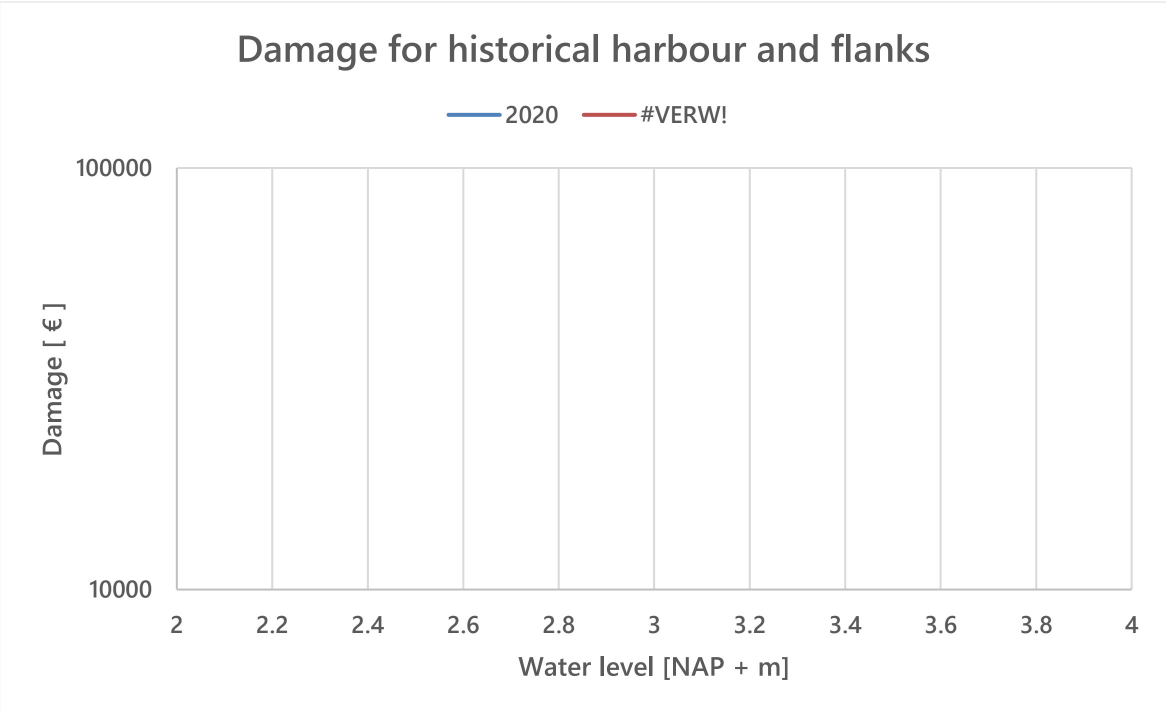


Figure K.39 Damage estimates for Dordrecht for extreme water levels.

Next, the damage profile is combined with a water level exceedance frequency curve for Dordrecht. Two such curves are presented in Figure K.40a for the current climate in the current system, and preliminary Delta21 system. For the future climate scenario, these curves are presented in Figure K.40b. Note that this is a configuration of Delta21 with adapted closure criteria and therefore not exactly the same as the preliminary configuration. Section 5.3 details on this choice, which is required to prevent Delta21 from closing and opening every high and low tide respectively. The result is the function $D(f)$ in Equation 3-1, as presented in Figure K.41.

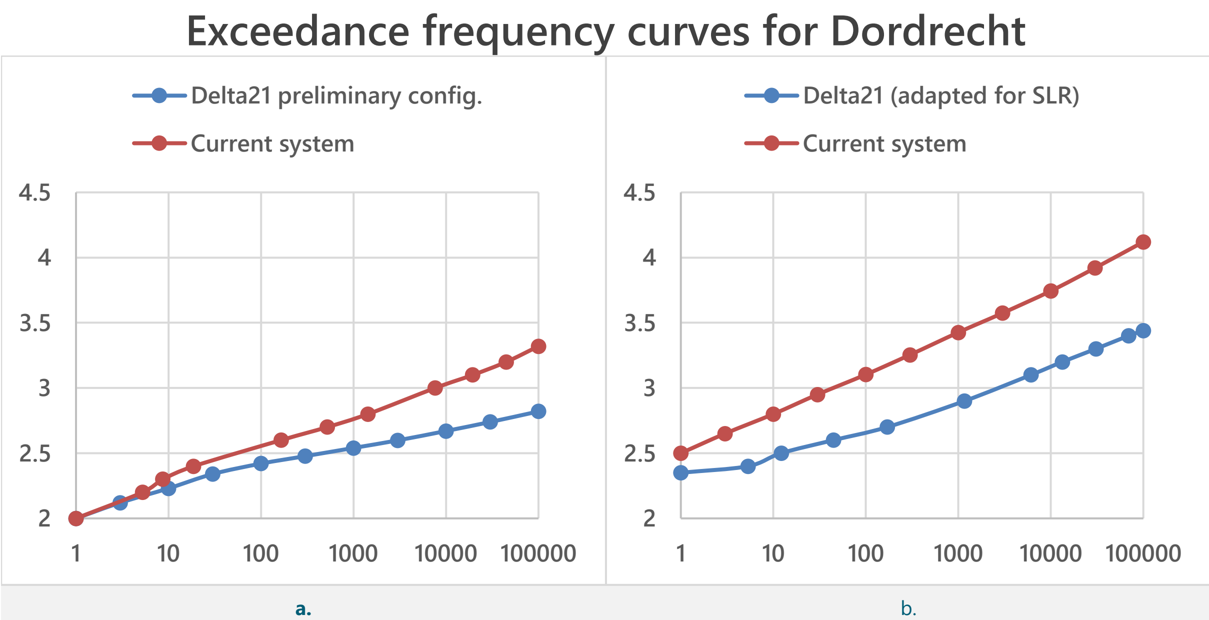


Figure K.40 Water level exceedance frequency curves for Dordrecht in the current (a) and future (b) climate, for the current (reference) system, and a system with Delta21

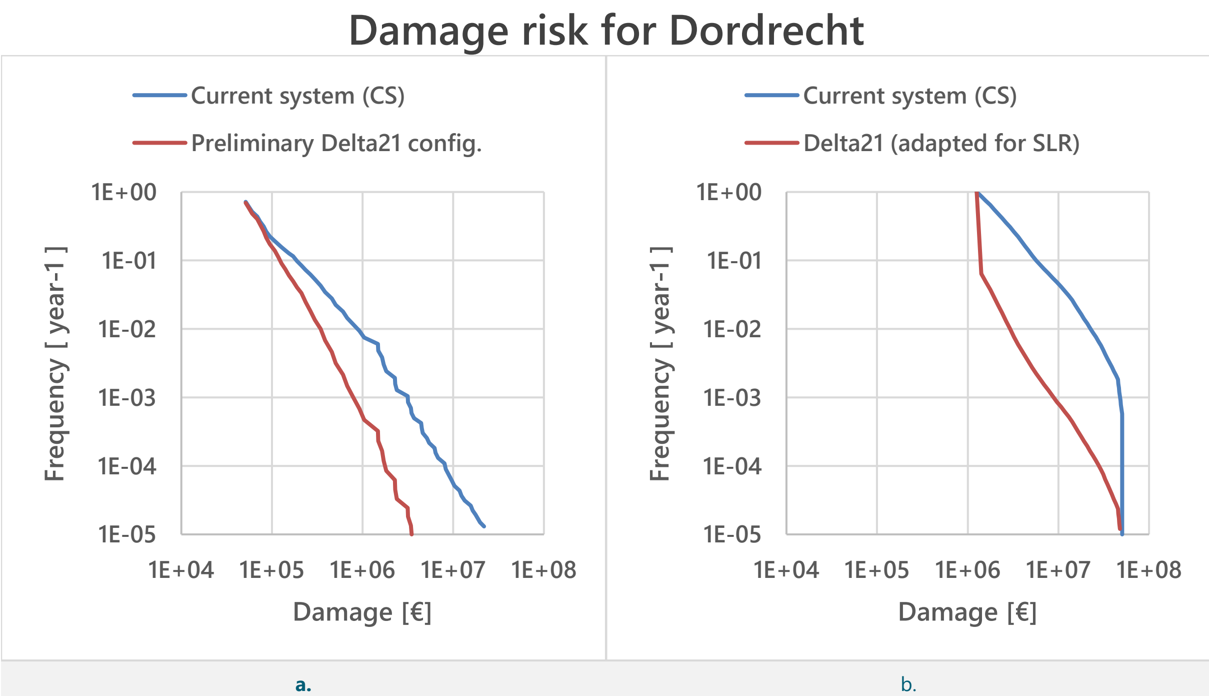


Figure K.41 Damage risk function for Dordrecht in the current (a) and future (b) climate for the current (reference) system, and a system with Delta21

Finally, taking the integral of damage risk function (D(f)) yields the average annual expected damage for the Island of Dordrecht. Note that the exceedance frequencies are **derived without model uncertainty**. Therefore, these results are best interpreted in a relative sense. Table K.8 presents the calculated risk and saving potential.

Table K.8 calculated expected yearly damages for Dordrecht's historical harbour and flanks

Climate scenario	System	Expected yearly damage	Reduction
Current climate	Current system	€ 115,483	-
	Delta21	€ 68,501	€ 46,982 (40.7%)

Climate scenario	System	Expected yearly damage	Reduction
Future climate scenario	Current system	€ 3,346,251	
	Delta21	€ 1,981,947	€ 1,364,303 (40.8%)

Appendix L Time of closure of the Europoortkering

An additional to the models Real-Time-Control code is made to recalculate a different closing time for the Europoortkering when Delta21 escalates. After all, the Maeslantkering should close during a tidal low water with low or zero flow speeds. Then, a small script checks for each calculation point if the closing time has changed. It does this by comparing the original closing time as calculated by the control of the Europoortkering, with the updated one calculated by Delta21. If after that, the Europoortkering actually closes it is added to the inventory of calculation points below. The Europoortkering does not always close when calculating a best closing time, because sometimes predictions do not reach the final closure criteria at Rotterdam or Dordrecht. The new predictions when Delta21 escalates yield a preponed closing time for the Europoortkering in the boundary condition combinations as shown in the figure below. The amount of hours that the closure time can be preponed ranges from 0.5 to 3 hours, and tends to be larger for smaller storm surges. See also Table L.9.

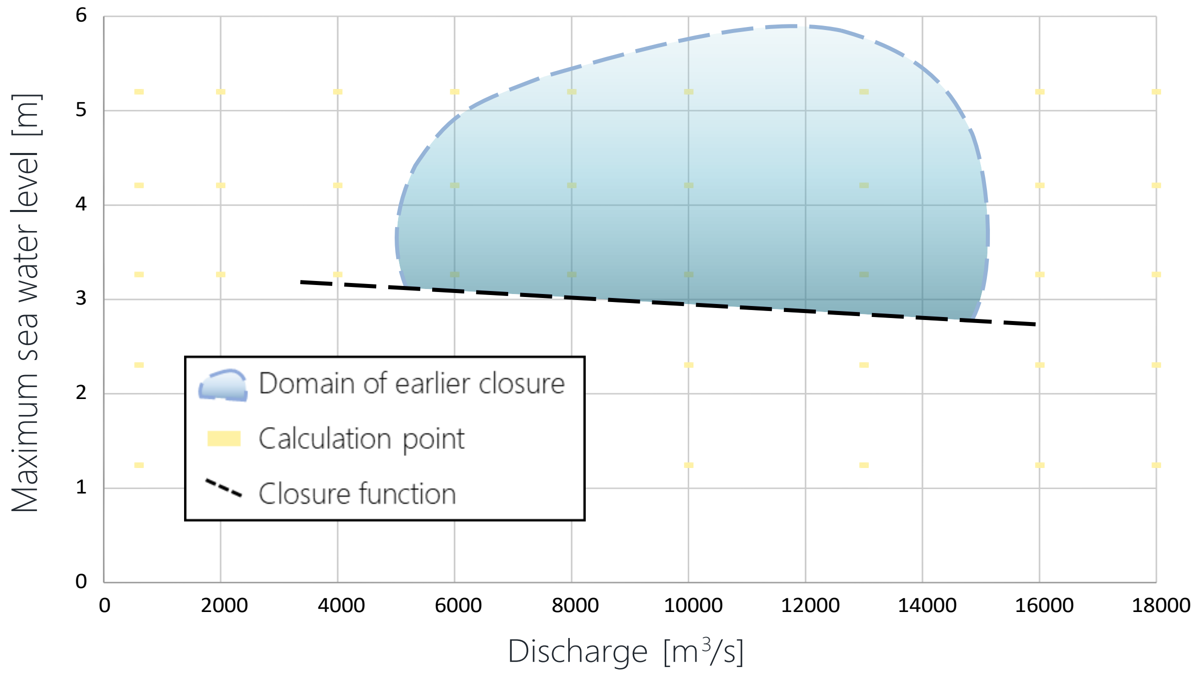


Figure L.42 Boundary condition domain of earlier closure due to Delta21

Table L.9 boundary conditions and preponed Europoortkering closing times

Discharge at Lobith [m^3/s]	Sea water level (Maasmond) [NAP + m]	Time that the Europoortkering closes earlier [hours:minutes]
10000 m^3/s	3.3	3:00
10000 m^3/s	4.2	1:30
10000 m^3/s	5.2	0:50
13000 m^3/s	3.3	2:30
13000 m^3/s	4.2	2:40
13000 m^3/s	5.2	1:10
6000 m^3/s	3.3	1:50
6000 m^3/s	4.2	0:40
8000 m^3/s	3.3	3:00
8000 m^3/s	4.2	1:00
8000 m^3/s	5.2	0:40

Appendix M Influence of an Europoortkering failure probability decimation

Similar to how reductions across several frequencies can be calculated for Delta21, so can it be done for the Europoortkering. The reduction this time however, is a smaller failure probability result relative to the current failure probability results. For the Europoortkering, larger return periods are exceedingly more sensitive to changes in the failure probability. Take for example the exceedance frequency curves for Rotterdam before and after two decimations (divide by 10) of the Europoortkering's failure probability, presented in Figure M.43.

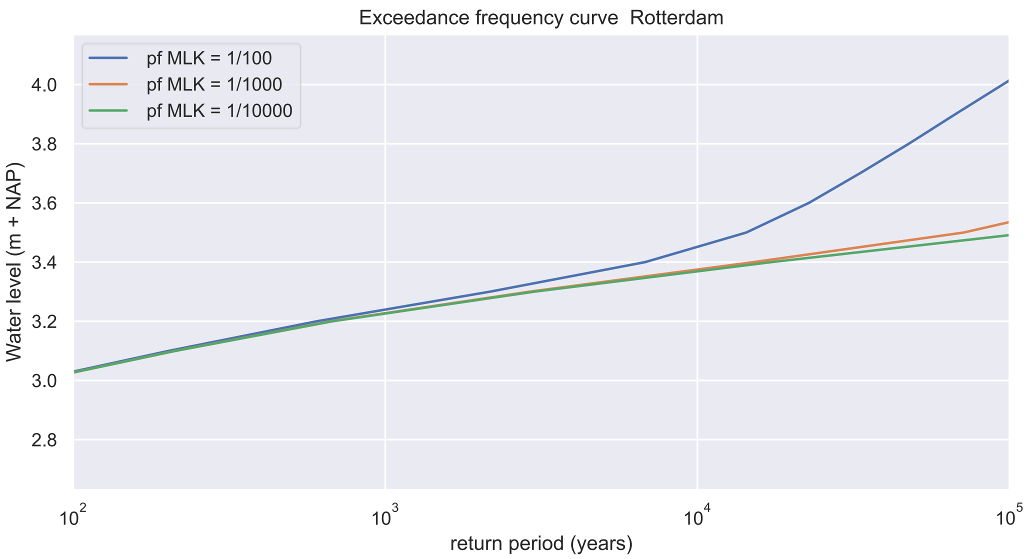


Figure M.43 Exceedance frequency curves for Rotterdam in the current system and climate, with decimated P_f for the Europoortkering

By looking at return periods of 30,000 years, one can get a sense of the failure-dominated area and how its borders may shift in various configurations. Figures Figure M.45 through Figure M.48 present the reduction maps for a decimated Europoortkering failure probability. The borders of the area with certain reductions are drawn and composed in Figure M.44.

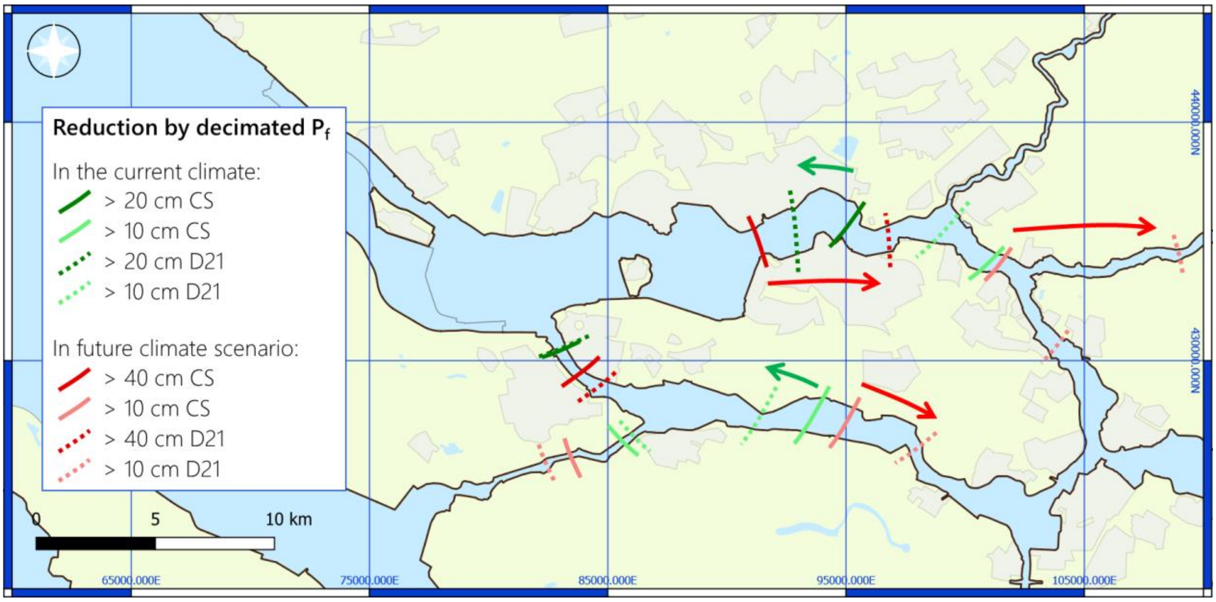


Figure M.44 Borders of reductions on water levels with return period 30,000 years by decimating the Europoortkering failure probability

Finally, a detailed analysis of illustrative conditions at Spijkenisse was done. Table provides the results of various combinations. Crucially, the dominance of the Europoortkering in this location **only** wavers when the failure probability is decimated at least once, and the future climate scenario is considered. Therefore, these are the scenarios where synergetic effects of reduced Europoortkering failure probability, and yields from Delta21 can be expected. Note that the column "% of illustration based on open Europoortkering" does not necessarily imply a **failure**. The condition might be such that the barrier does not need or attempt to close. However, a low percentage **does** imply that the influence of river discharge and storage characteristics is larger.

Table M.10 Water levels with return period 30,000 years at Spijkenisse for various configurations

System	Climate scenario	Europoortkering failure P_f	Water level (30,000 years)	reduction from smaller P_{f_EPK}	Reduction in Delta21 system	% of illustration based on open Europoortkering
CS	Current	1:100	3.69	-	-	99.9%
CS	Current	1:1000	3.47	0.22 m	-	98.1%
CS	Future	1:100	4.37	-	-	99.2%
CS	Future	1:1000	3.85	0.52 m	-	68.6%
CS	Future	1:10000	3.72	0.65 m	-	13.1%
Delta21	Current	1:100	3.57	-	0.12	100.0%
Delta21	Current	1:1000	3.35	0.22 m	0.12	100.0%
Delta21	Future	1:100	4.25	-	0.12	100.0%
Delta21	Future	1:1000	3.70	0.55 m	0.15	99.8%
Delta21	Future	1:10000	3.49	0.76 m	0.23	99.4%
Delta21	*Future*	*1:1000000*	*3.48*	*0.77 m*	-	*99.8%*

Reduction in maximum water level for return period = 30000 years for a decimation of the Europoortkering's failure probability with Delta21 in the W+Climate scenario

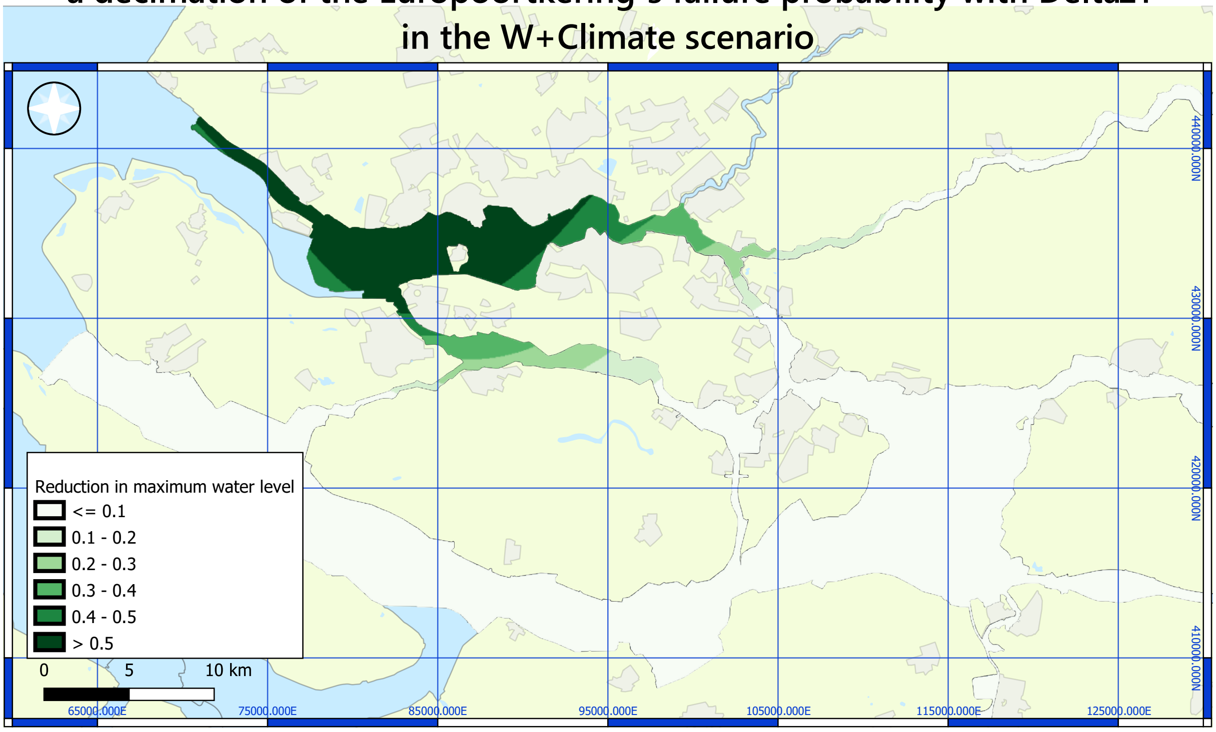


Figure M.45 Reduction map 1 for decimated Europoortkering failure probability

Reduction in maximum water level for return period = 30000 years for a decimation of the Europoortkering's failure probability with Delta21

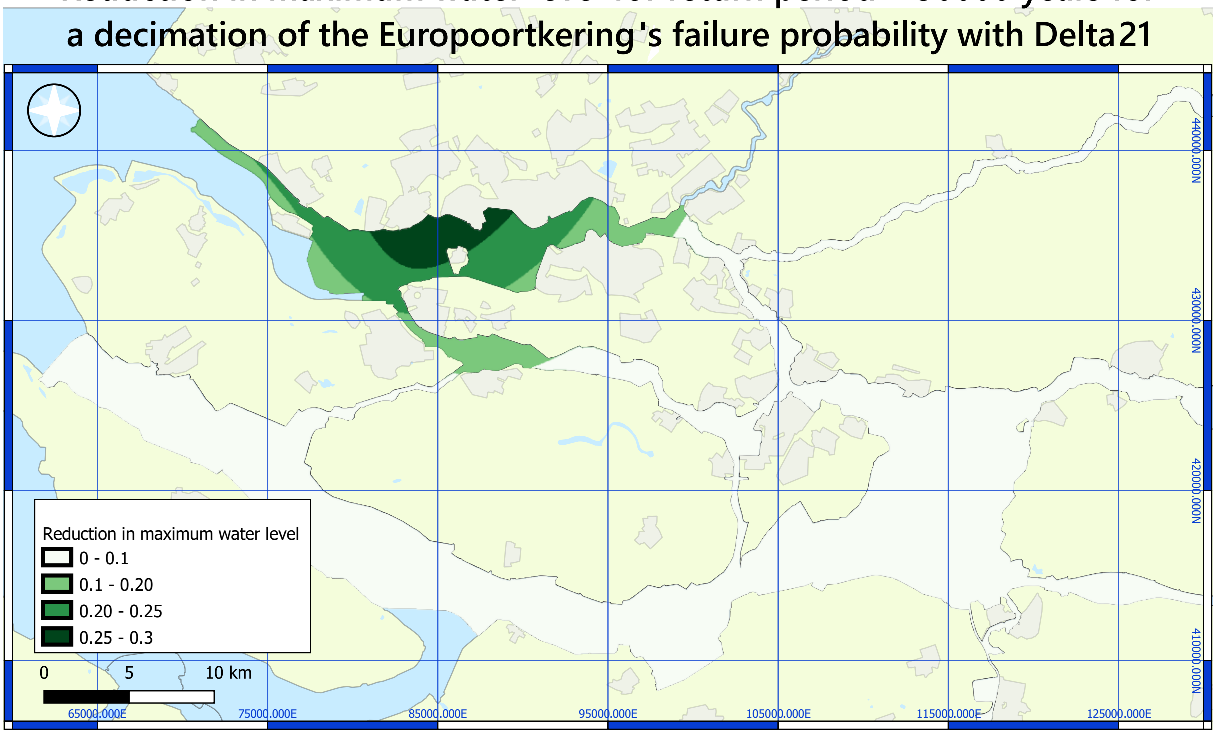


Figure M.46 Reduction map 2 for decimated Europoortkering failure probability

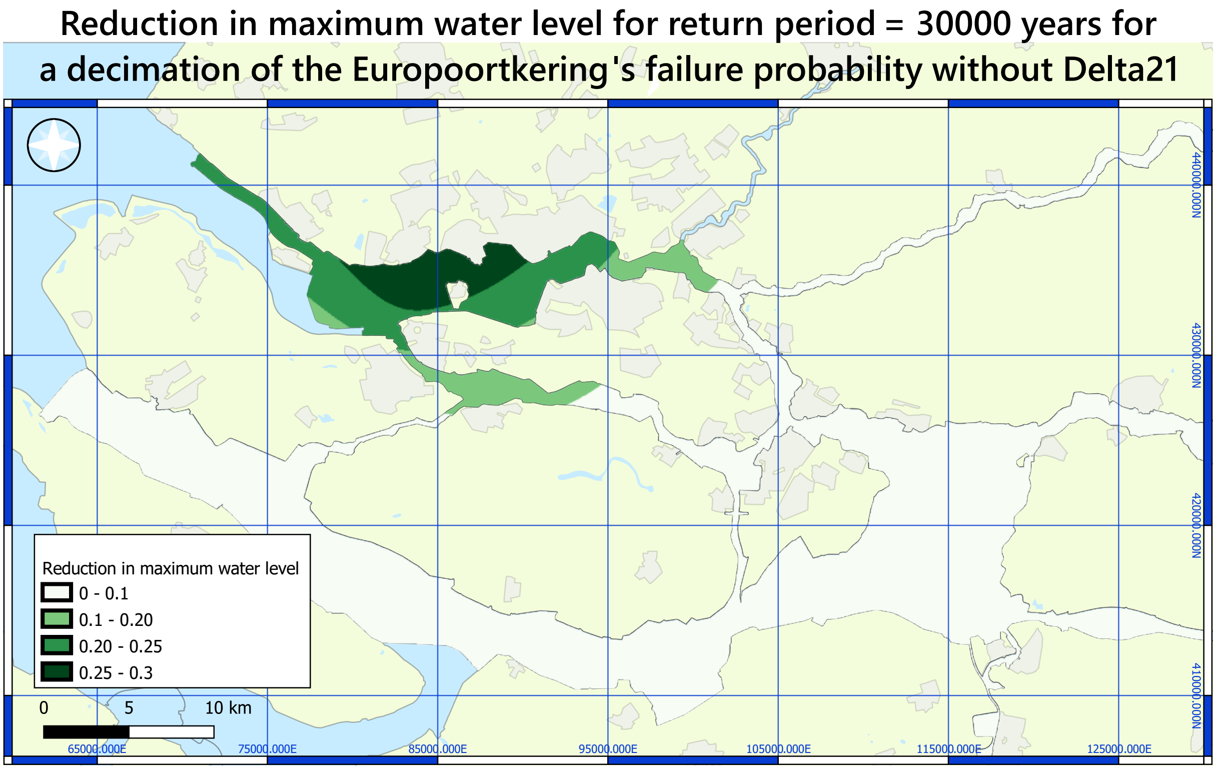


Figure M.47 Reduction map 3 for decimated Europoortkering failure probability

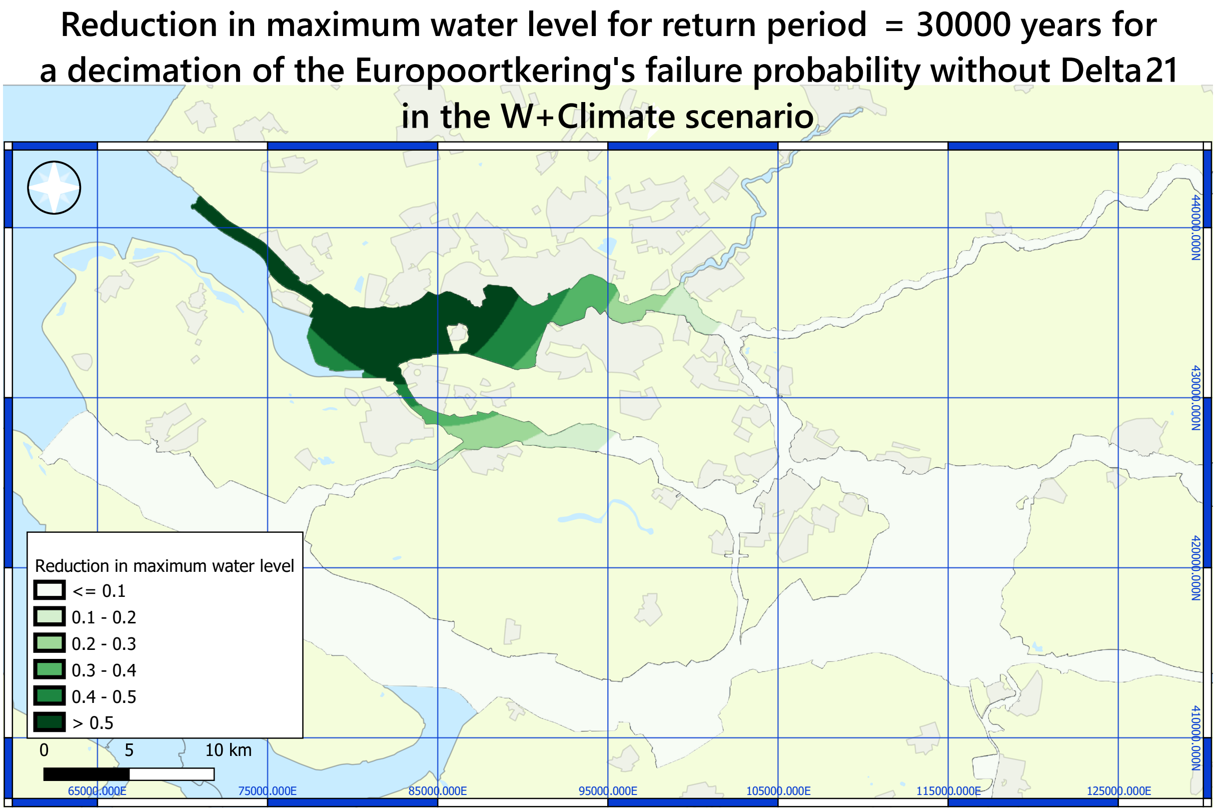


Figure M.48 Reduction map 4 for decimated Europoortkering failure probability

Appendix N Water level exceedance reductions in variations of Chapter 5 for all frequencies

Below is a collection of maps presenting the reduction in water level that is exceeded for six given frequencies. The six frequencies are chosen such that all the present normative frequencies are represented.

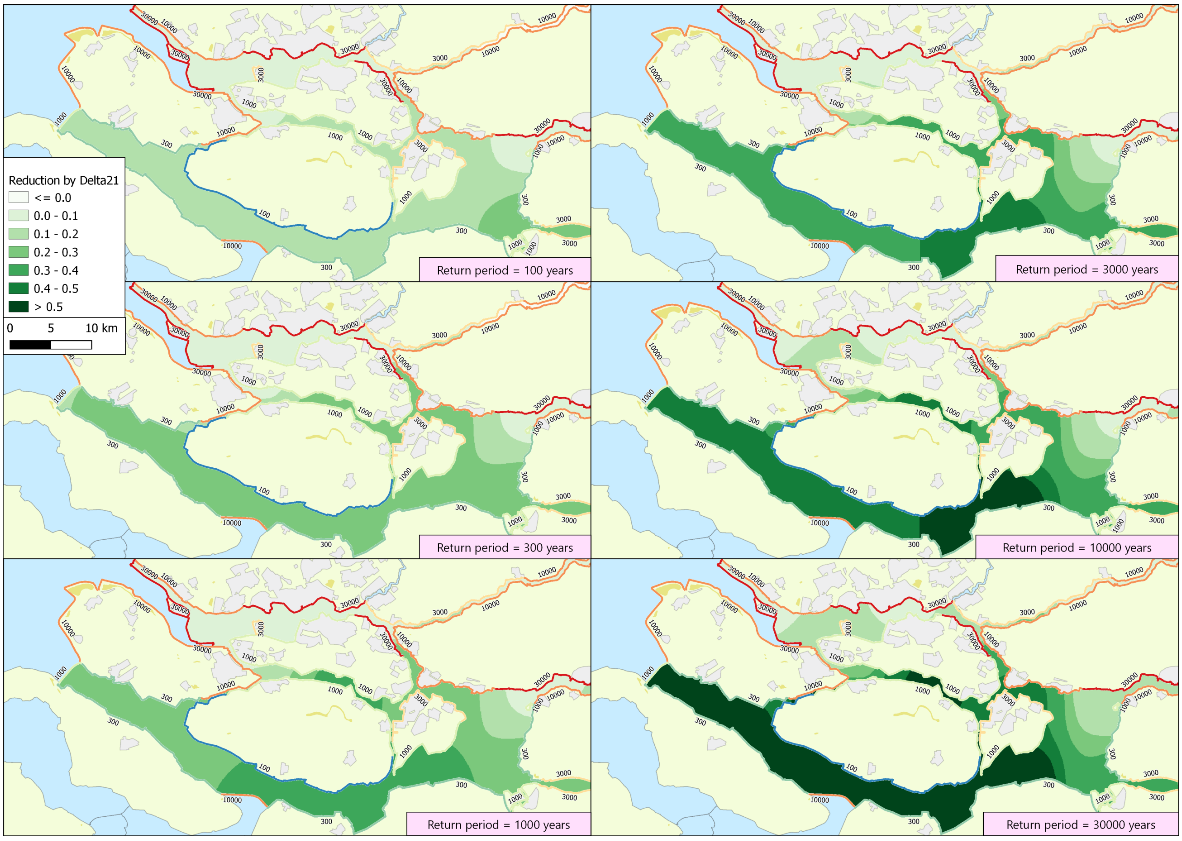


Figure N.49 Changes to the exceeded water level [m] per frequency for: The preliminary configuration of Delta21 (reference: current system)

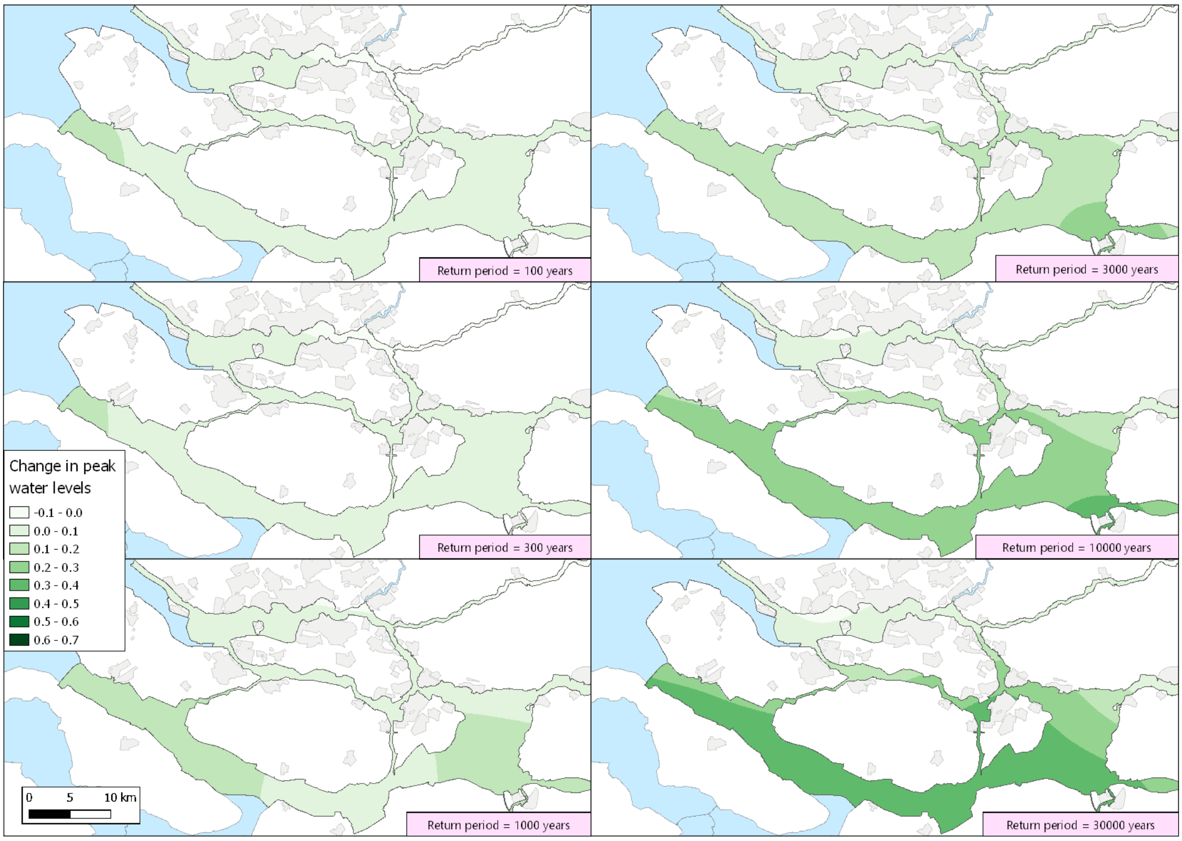


Figure N.50 Changes to the exceeded water level [m] per frequency for: Delta21 with closure criterion Dordrecht NAP + 2.9 m (reference: current system)

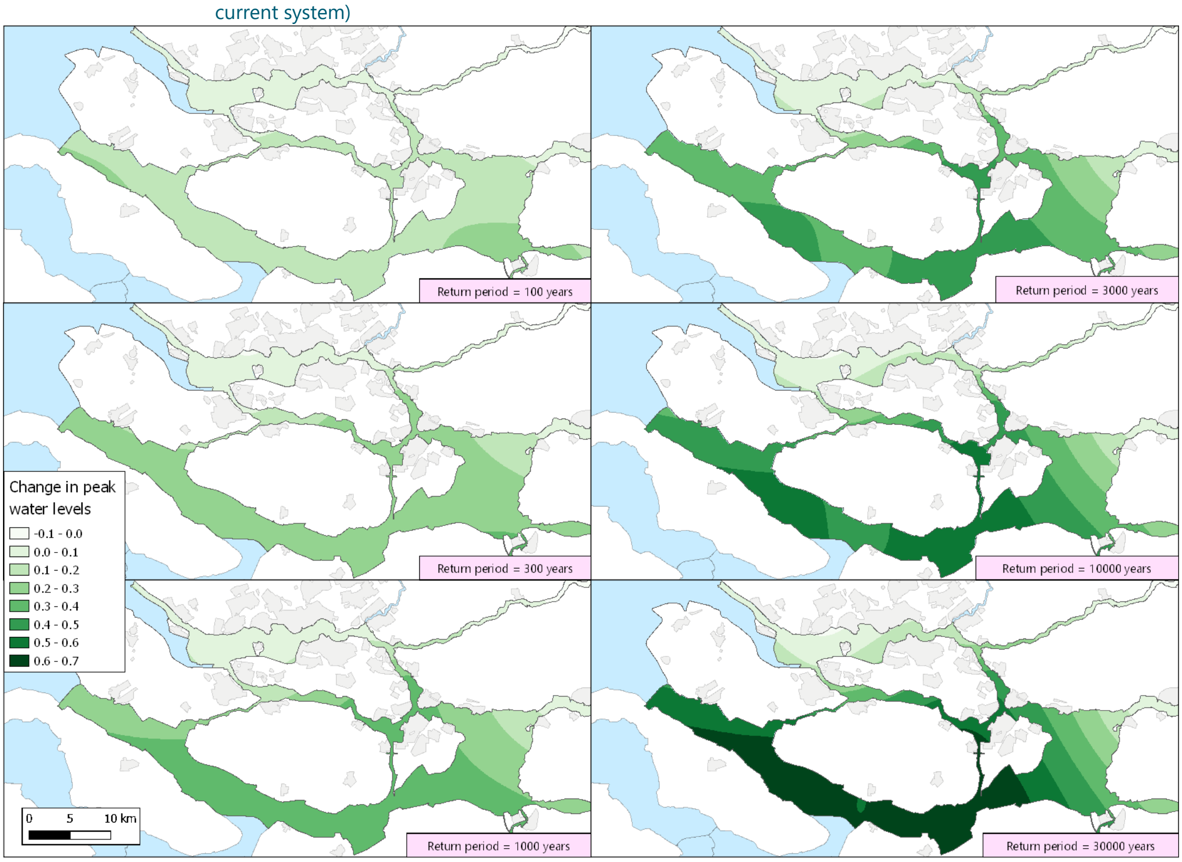


Figure N.51 Changes to the exceeded water level [m] per frequency for: The preliminary configuration of Delta21 with Delta21 with an Europoortkering closure criterion Dordrecht NAP + 2.5 m (reference: current system)

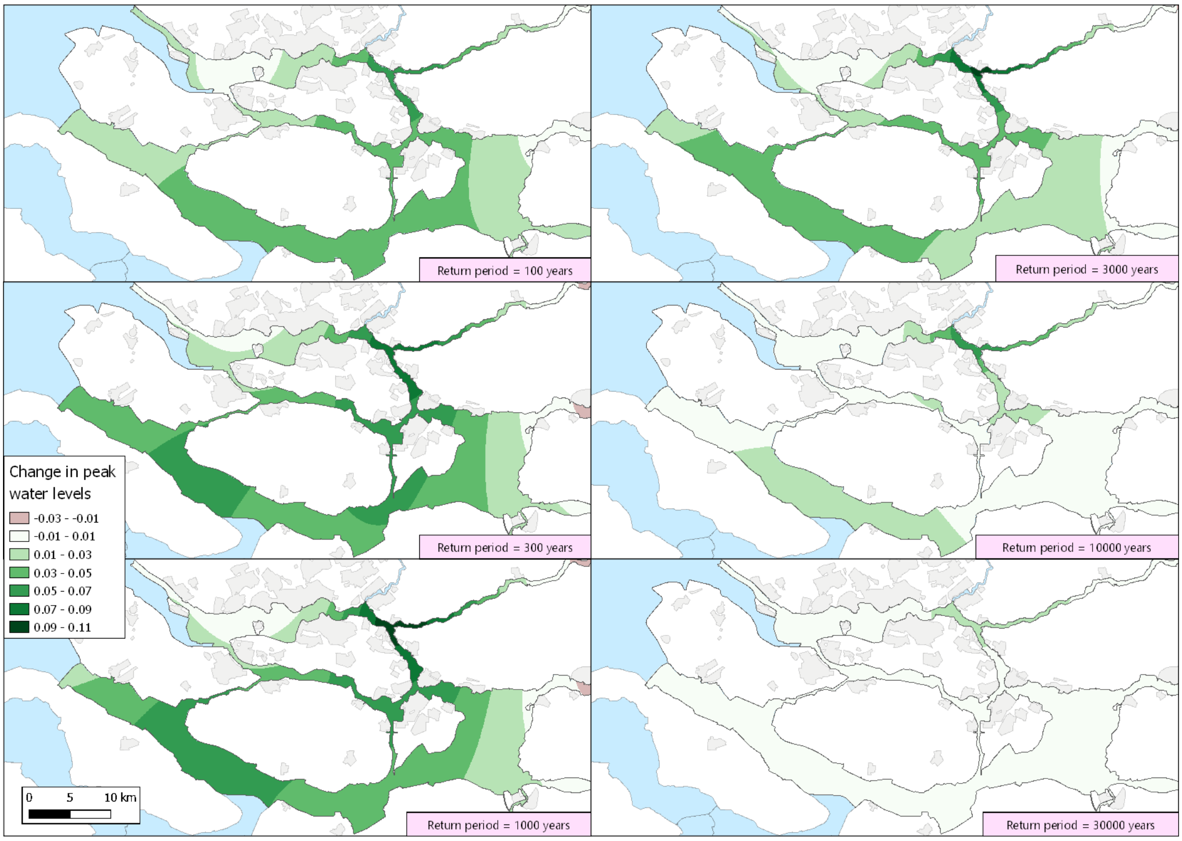


Figure N.52 Changes to the exceeded water level [m] per frequency for: No Delta21 + an Europoortkering closure criterion Dordrecht NAP + 2.5 m (reference: current system)

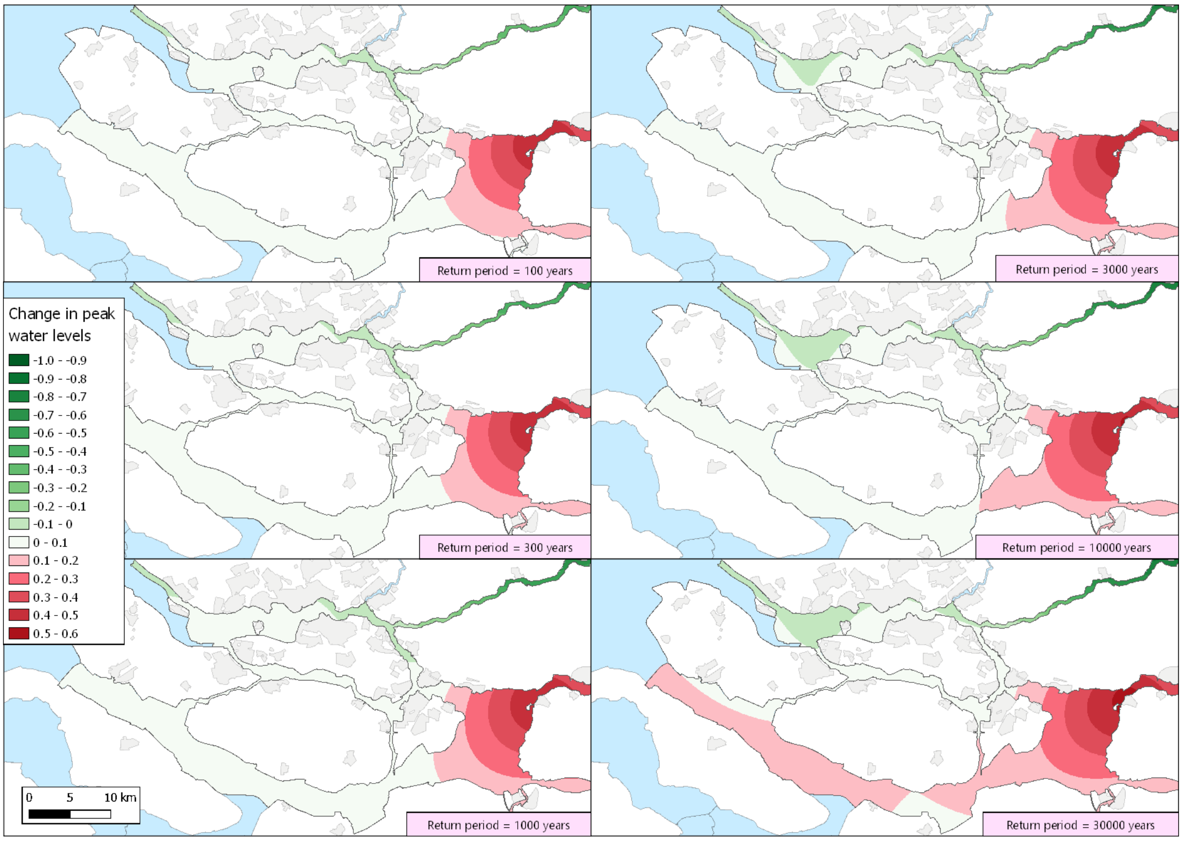


Figure N.53 Changes to the exceeded water level [m] per frequency for: Current system with a changed Pannerden division (reference: current system)

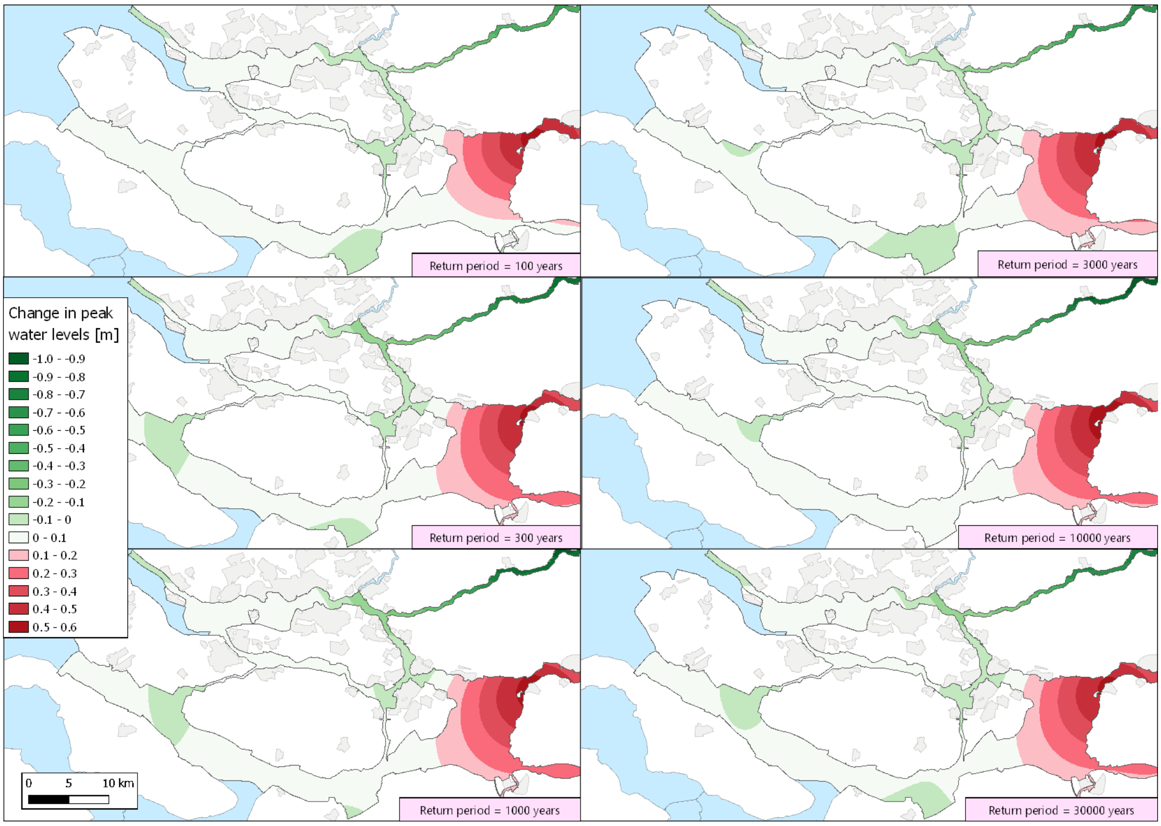


Figure N.54 Changes to the exceeded water level [m] per frequency for: The preliminary configuration of Delta21 with a changed Pannerden division (reference: Preliminary configuration of Delta21)

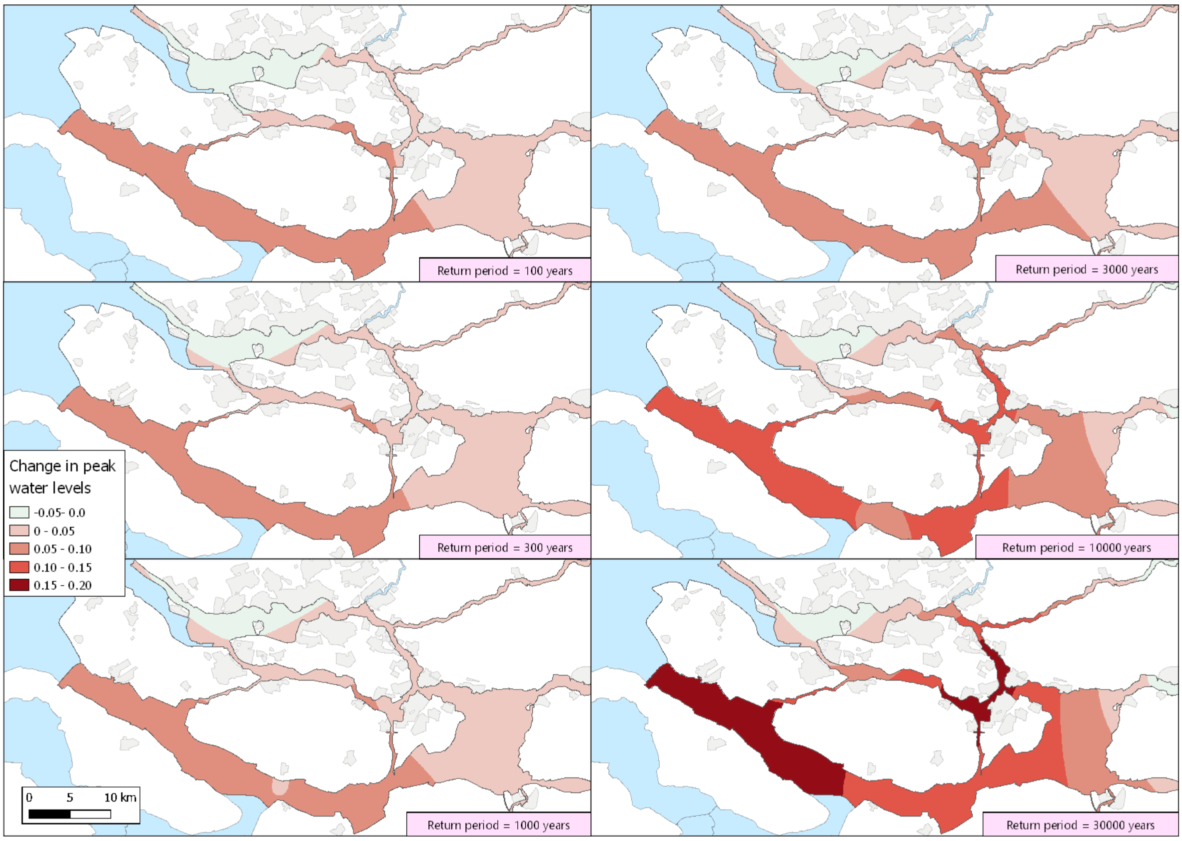


Figure N.55 Changes to the exceeded water level [m] per frequency for: Current system in longer storm (reference: current system)

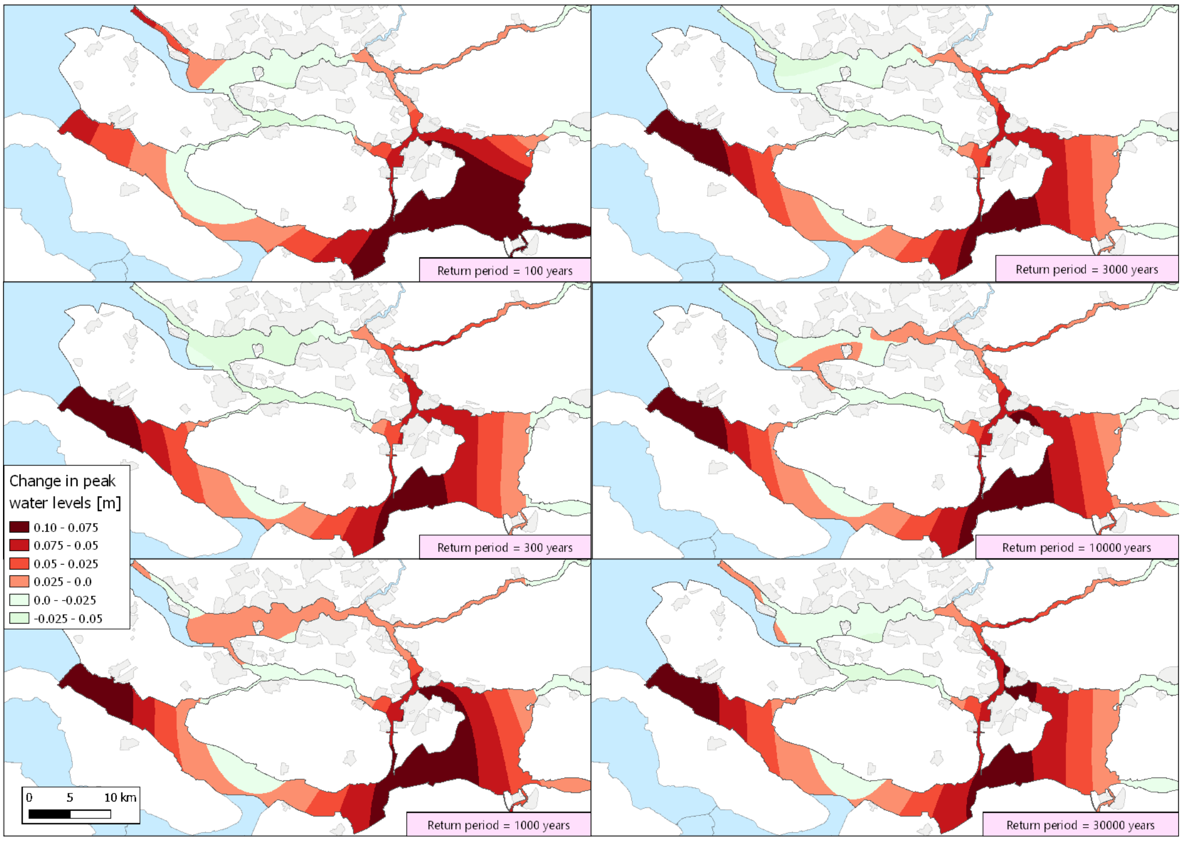


Figure N.56 Changes to the exceeded water level [m] per frequency for: Preliminary Delta21 in longer storm (reference: Preliminary configuration of Delta21)

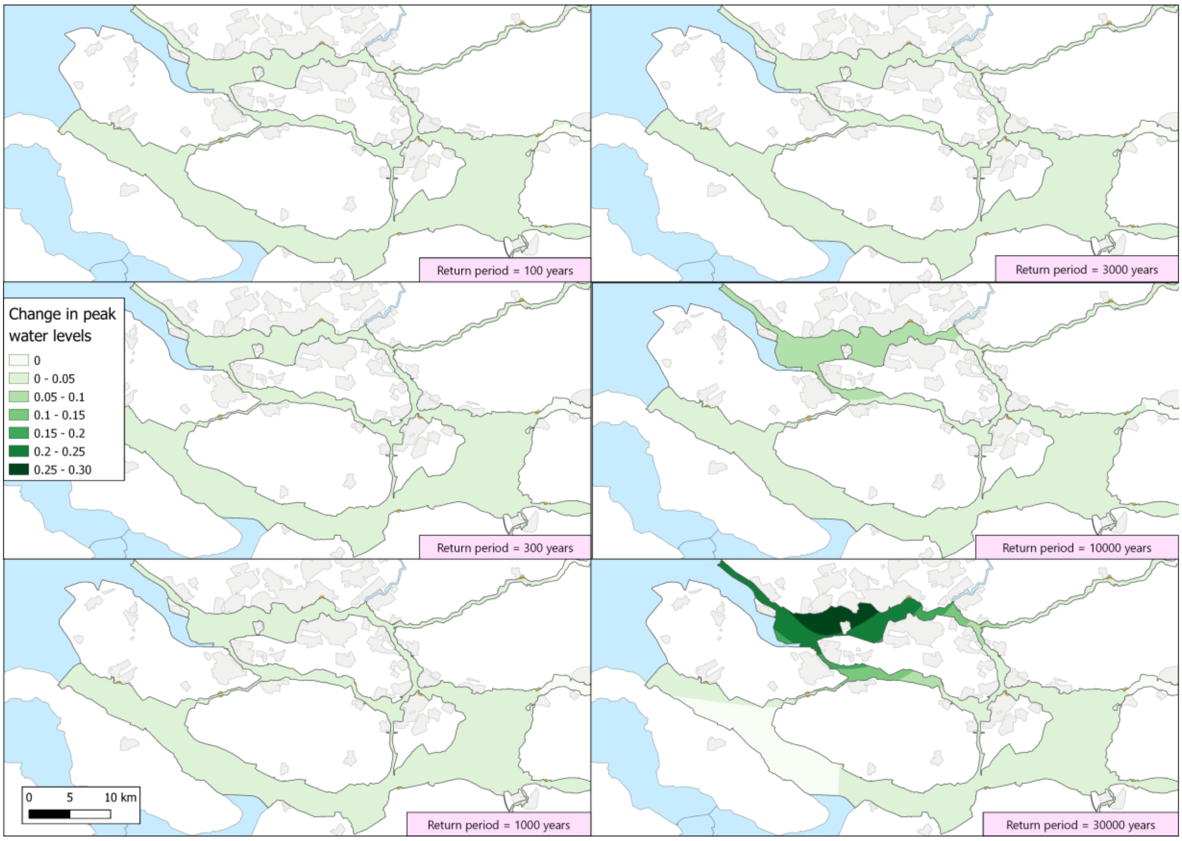


Figure N.57 Changes to the exceeded water level [m] per frequency for: Current system with decimated Europoortkering failure probability (reference: current system)

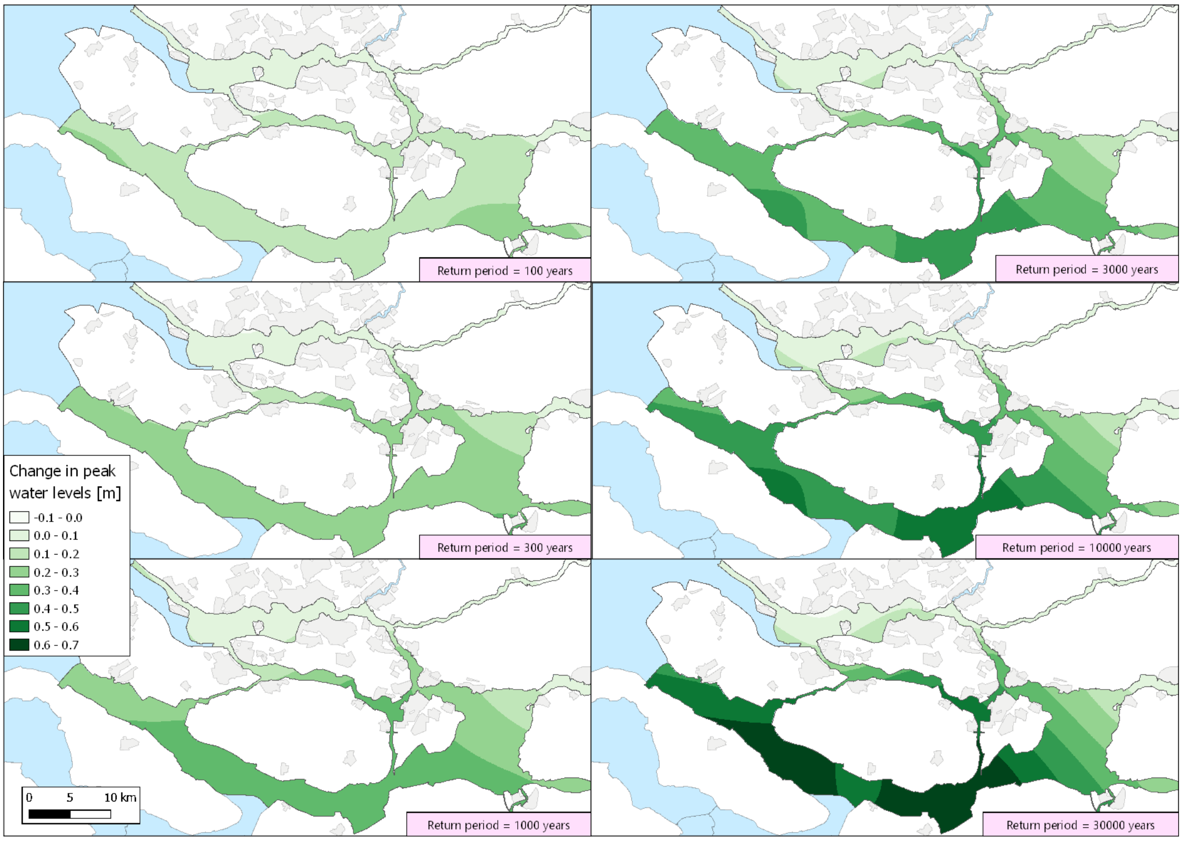


Figure N.58 Changes to the exceeded water level [m] per frequency for: Preliminary Delta21 with decimated Europoortkering failure probability (reference: Current system with also a decimated Europoortkering failure probability)

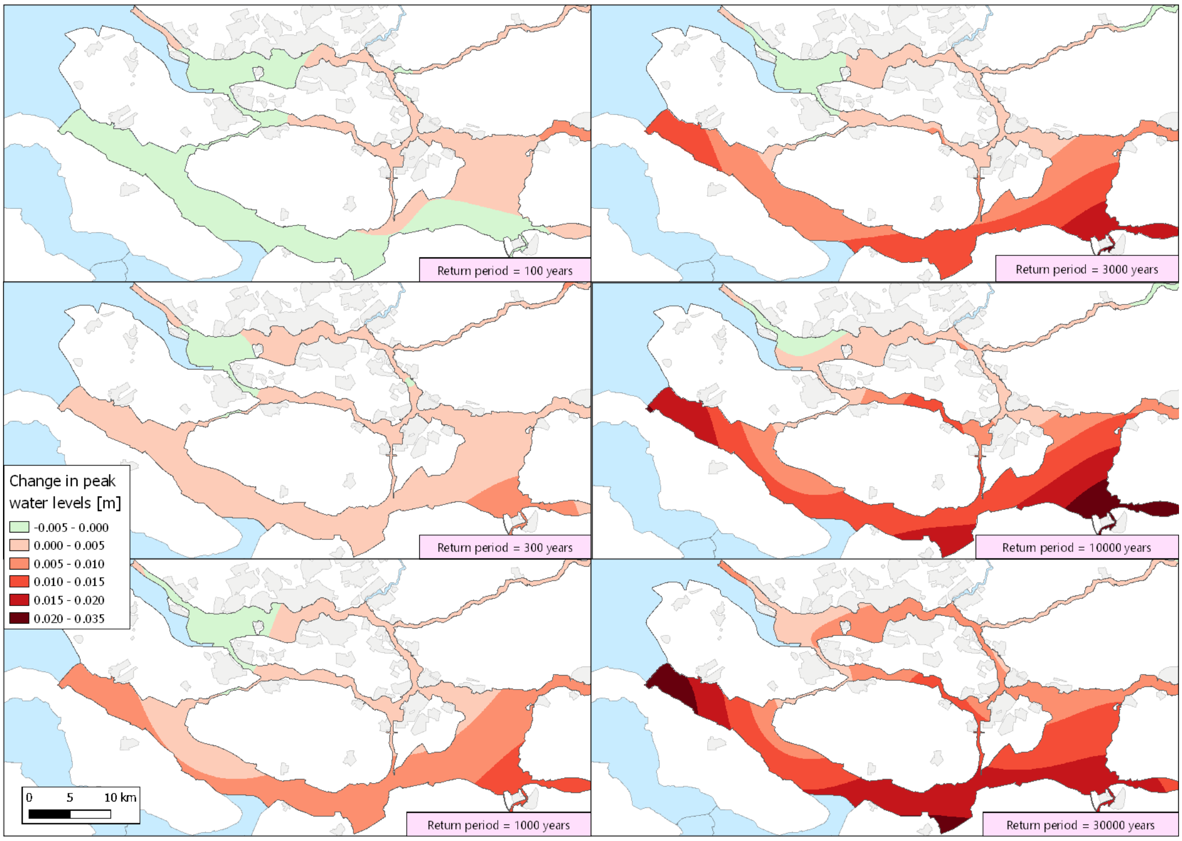


Figure N.59 Changes to the exceeded water level [m] per frequency for: Delta21 with reduced storage and pump capacity (reference: Preliminary configuration of Delta21)

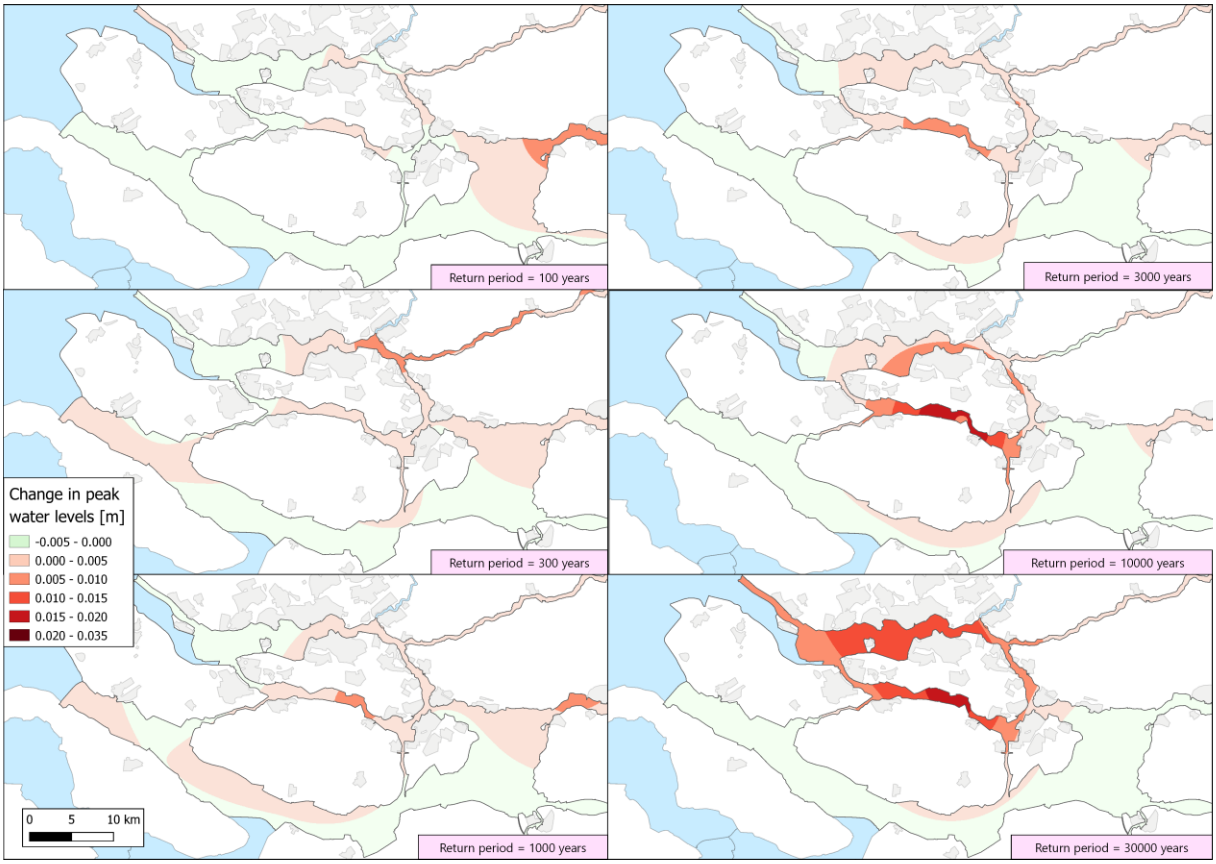


Figure N.60 Changes to the exceeded water level [m] per frequency for: Delta21 with reduced spillway width and raised sill height (reference: Preliminary configuration of Delta21)

Several calculation point examples of the reduced spillway width and raised height, used in Chapter 5.1.

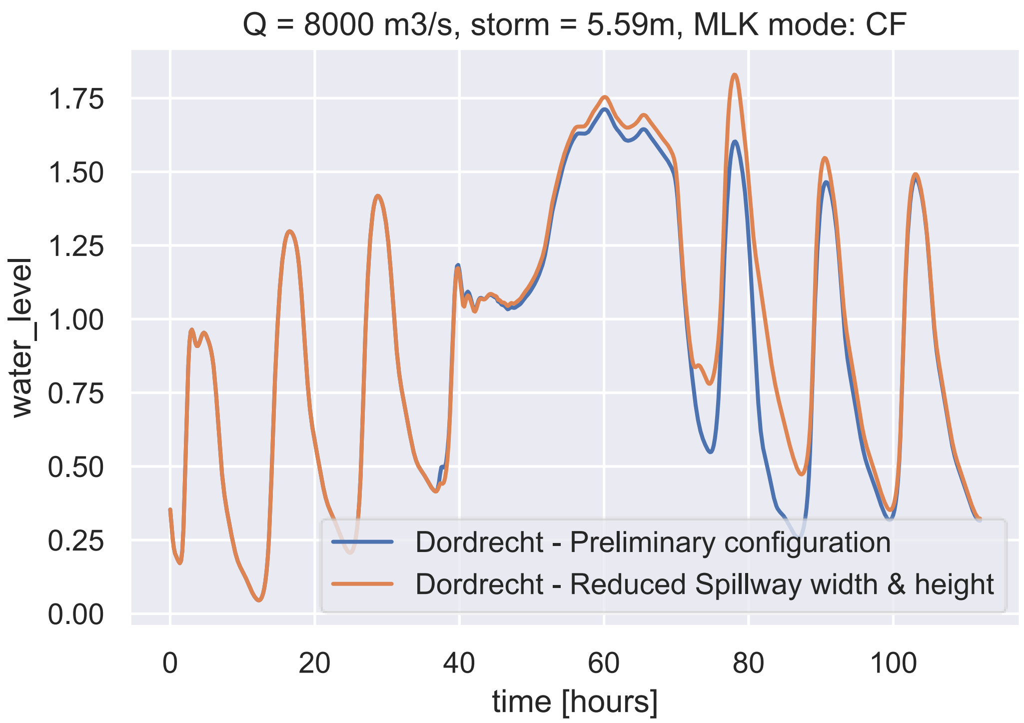


Figure N.61 Water level signals for Dordrecht when the spillways capacity is reduced example 1

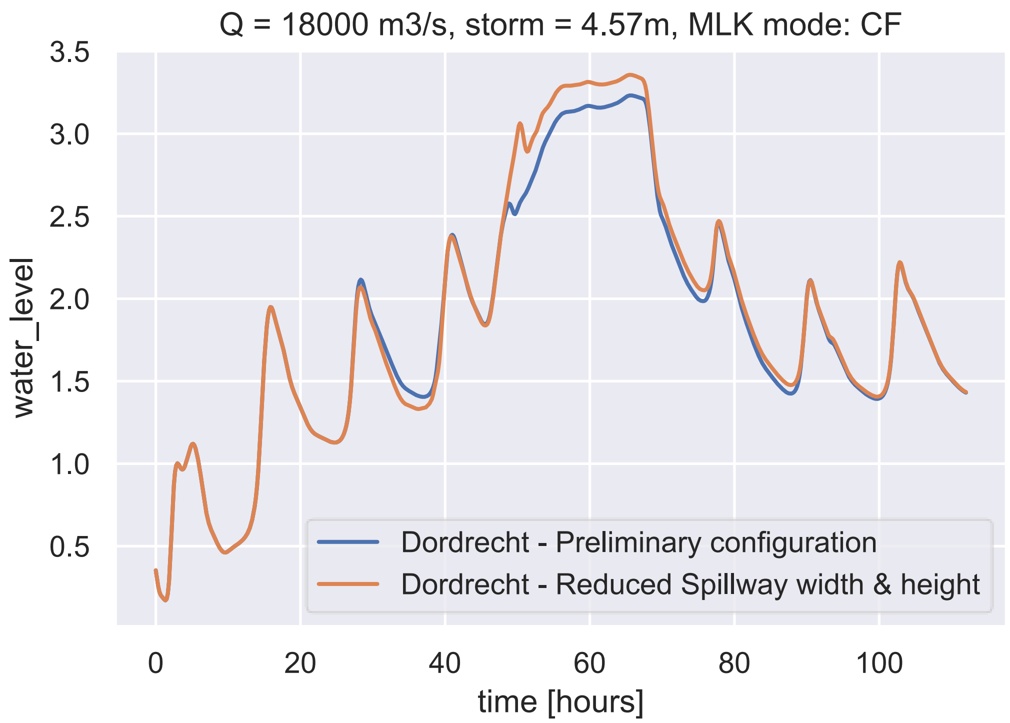


Figure N.62 Water level signals for Dordrecht when the spillways capacity is reduced example 2

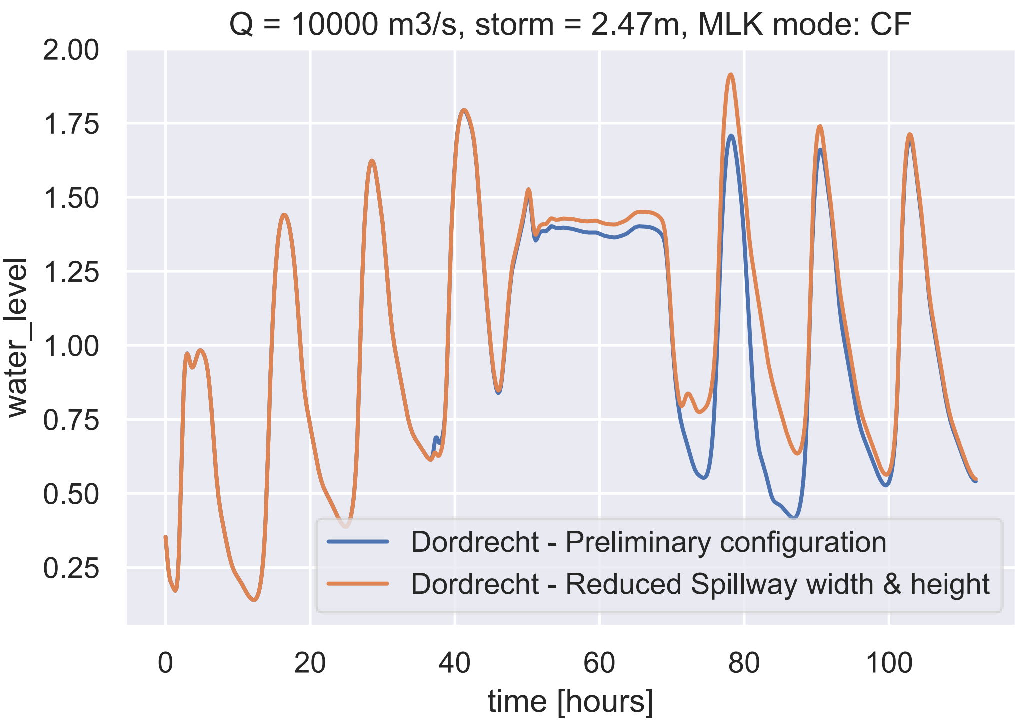
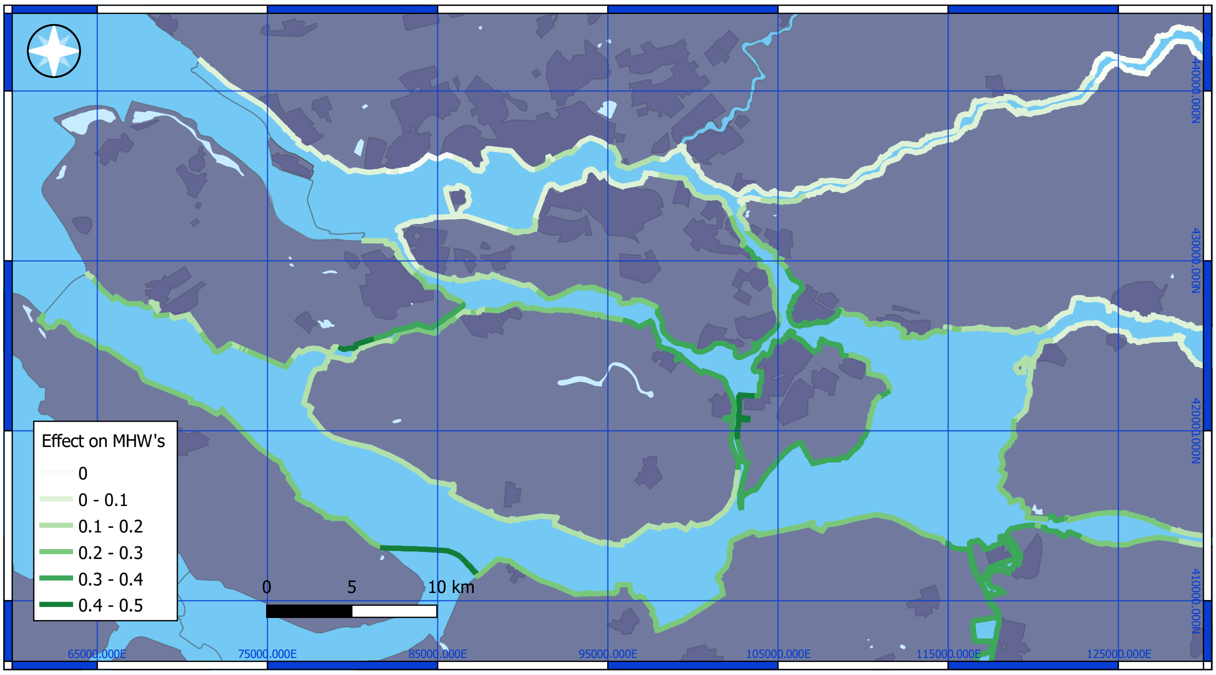
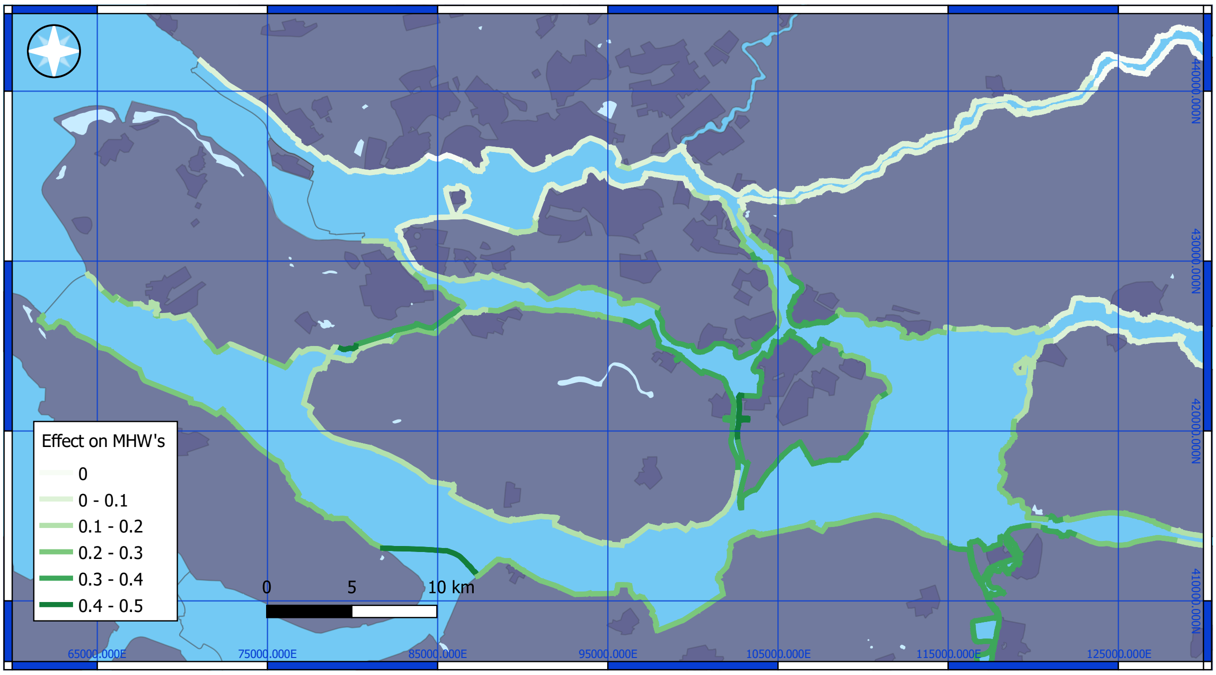


Figure N.63 Water level signals for Dordrecht when the spillways capacity is reduced example 1

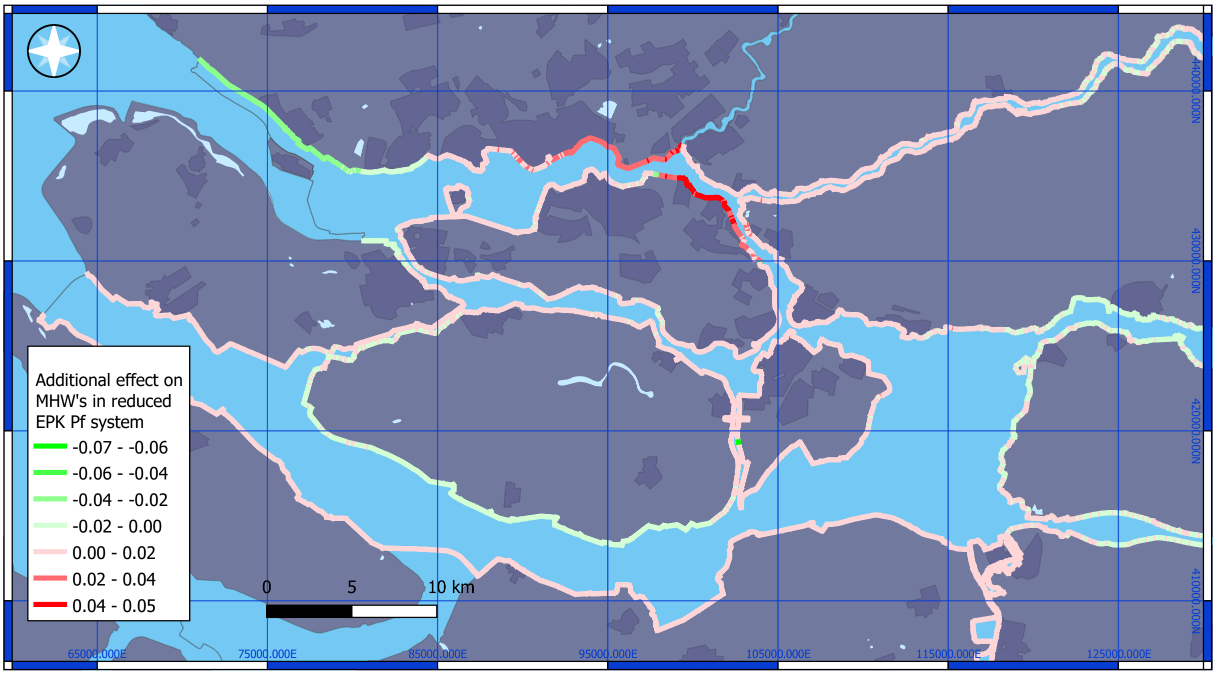
MHW effects in [m] for a system with and without a decimated Europoortkering failure probability, in current and future climate.



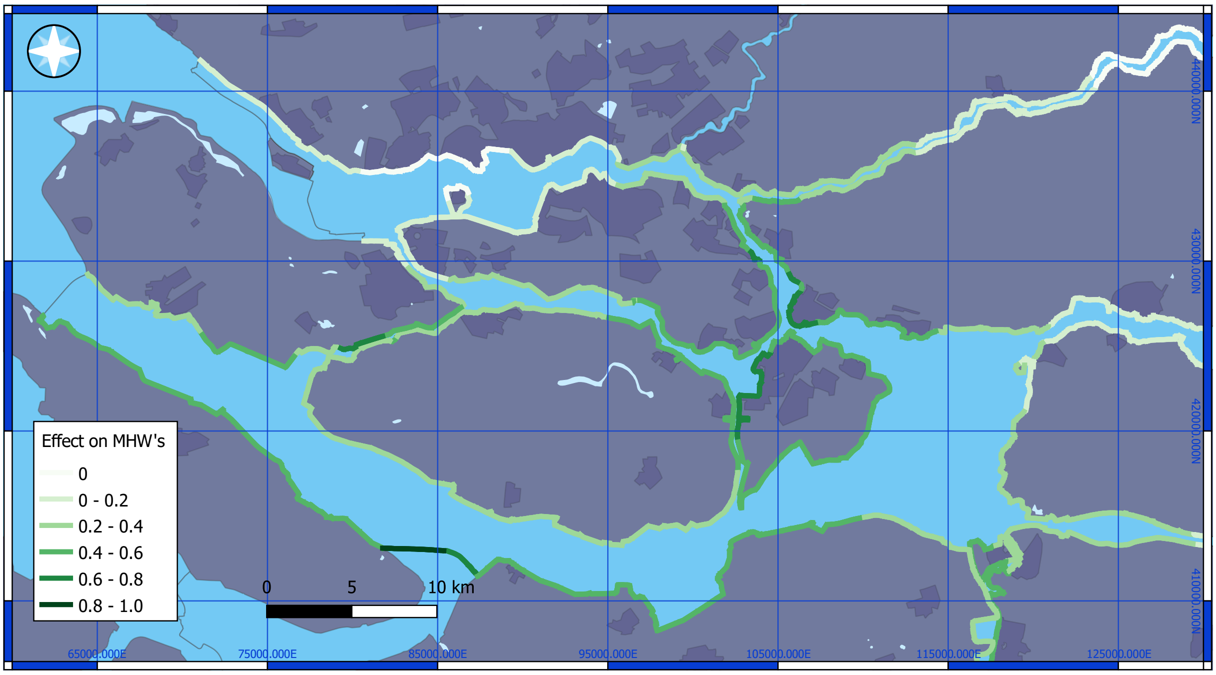
Europoortkering failure probability = 1:100, current climate



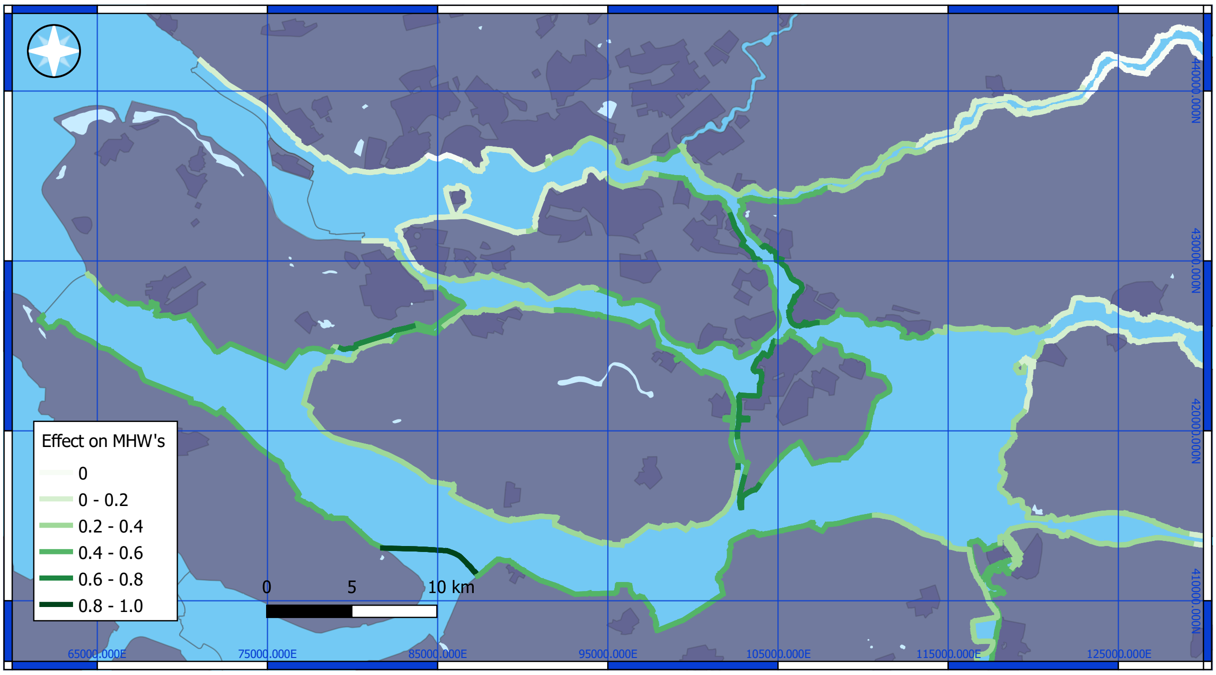
Europoortkering failure probability = 1:1000, current climate



Difference for current climate in Delta21 MHW reduction for a decimated Europoortkering failure probability



Europoortkering failure probability = 1:100, future climate



Europoortkering failure probability = 1:1000, future climate

MHW and reduction maps in the future climate scenario

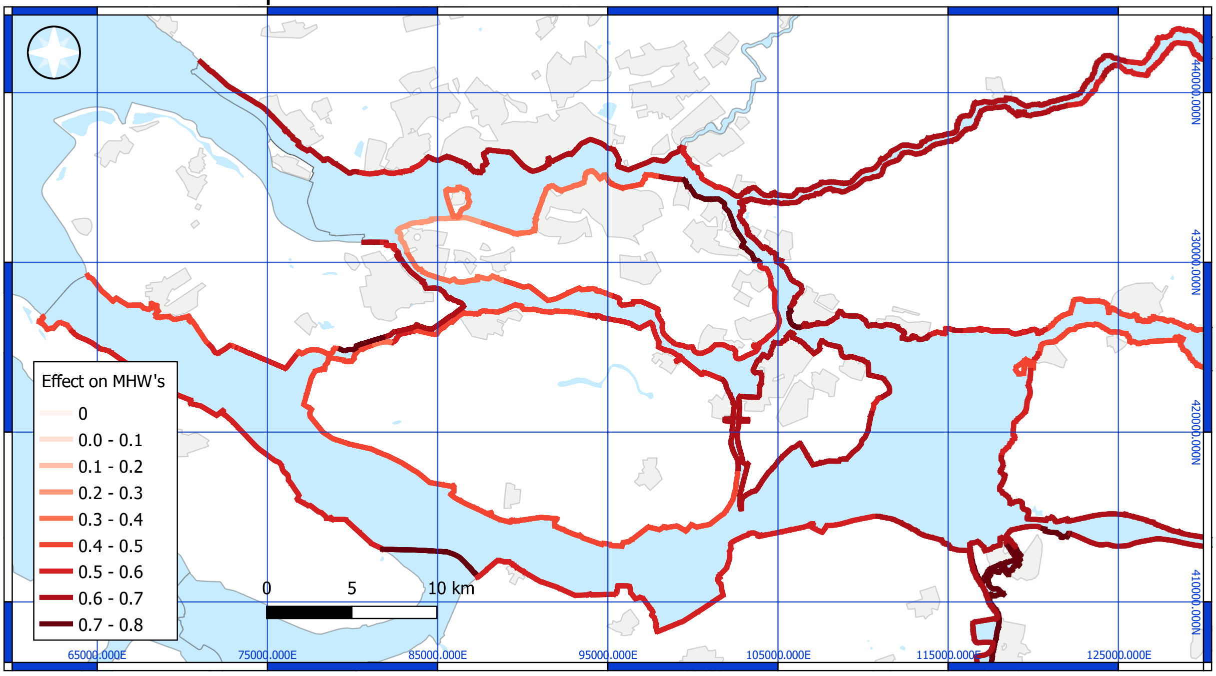


Figure N.64 Change in MHW [m] of the current system (CS) in the future climate scenario (relative to CS in current climate)

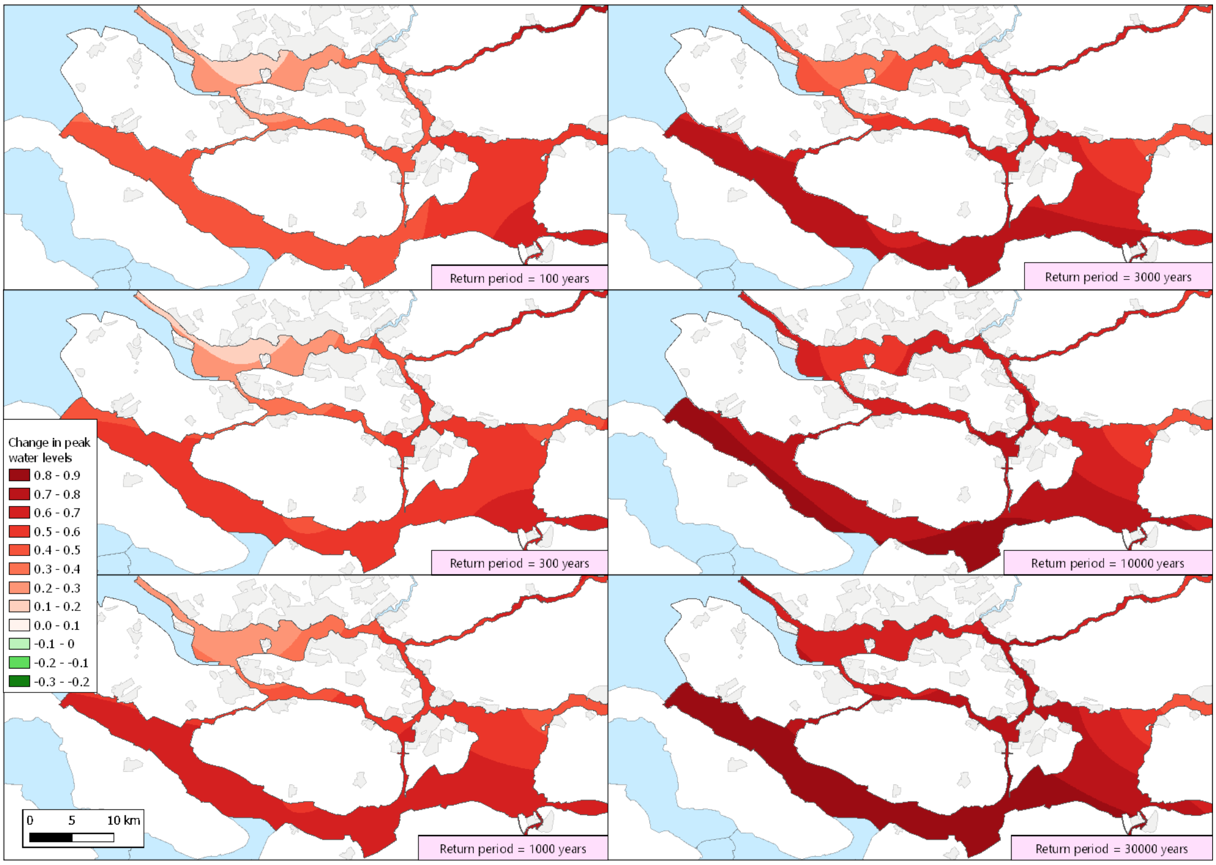


Figure N.65 Increase in peak water levels [m] in the current system (CS) in the future climate scenario (relative to CS in current climate)

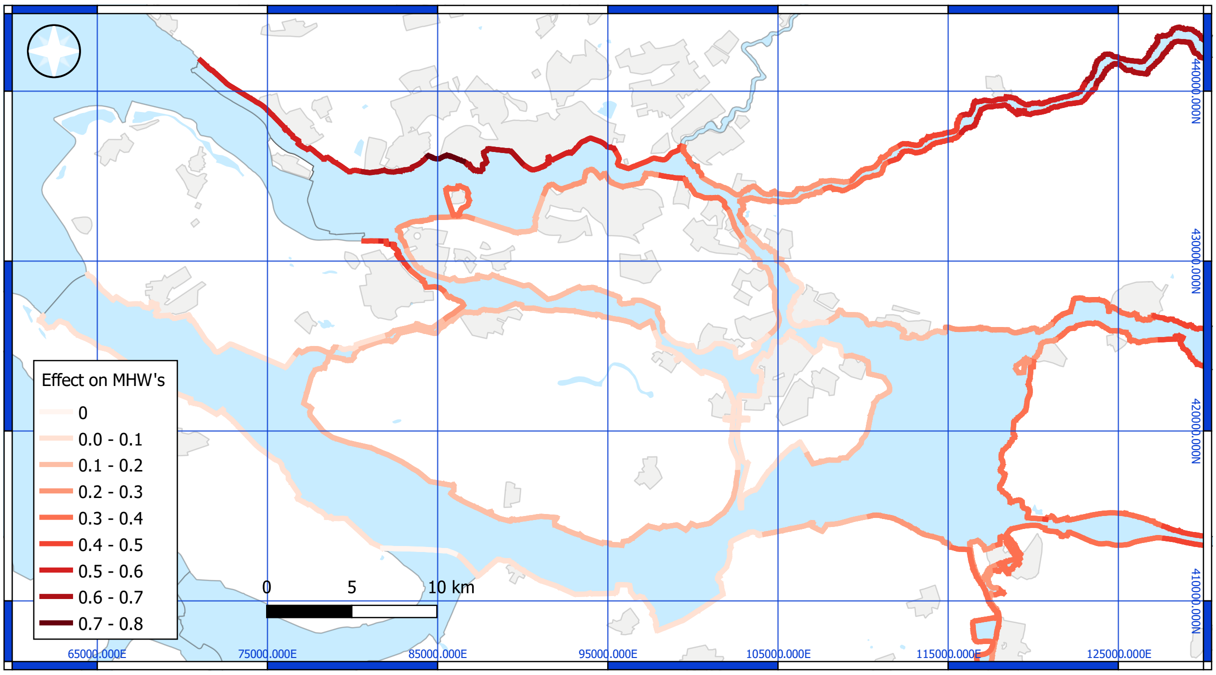


Figure N.66 Change in MHW [m] of the Delta21 system[1] in the future climate scenario (relative to CS in current climate)

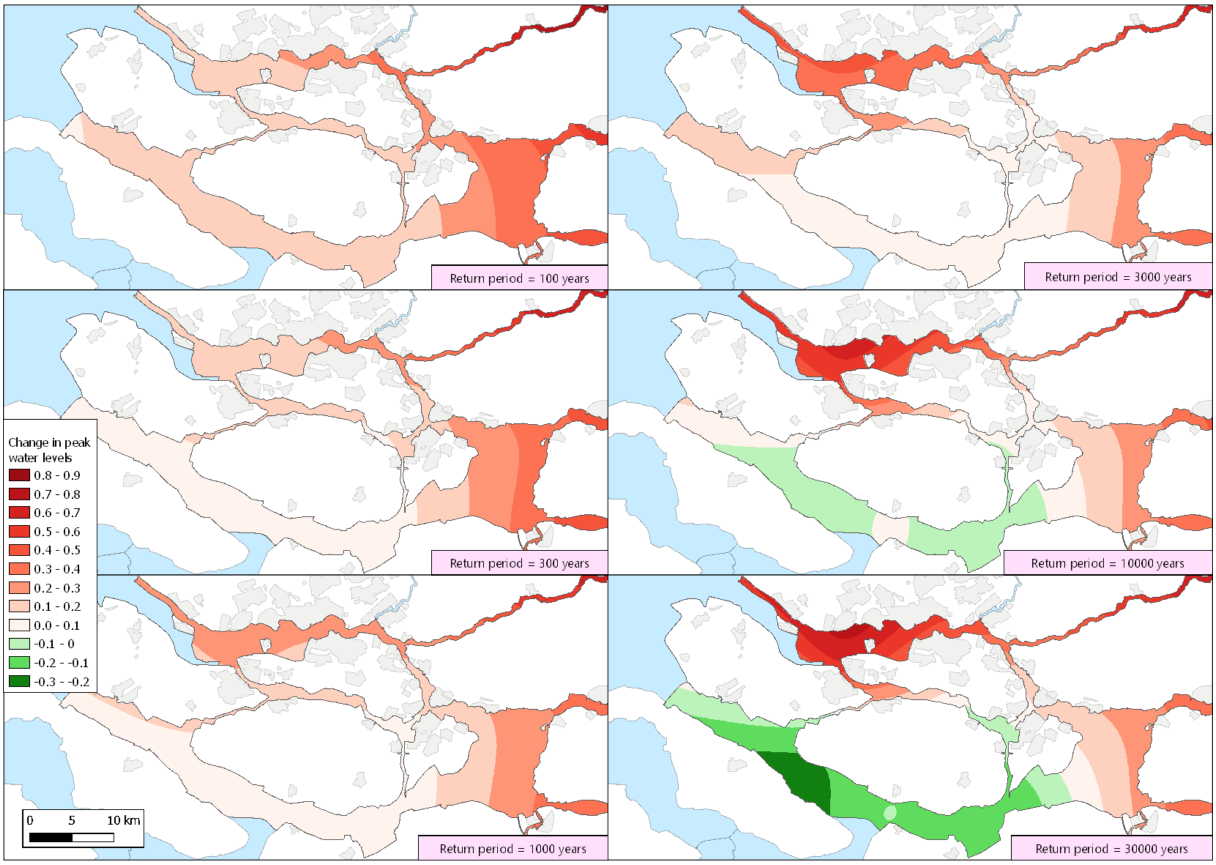
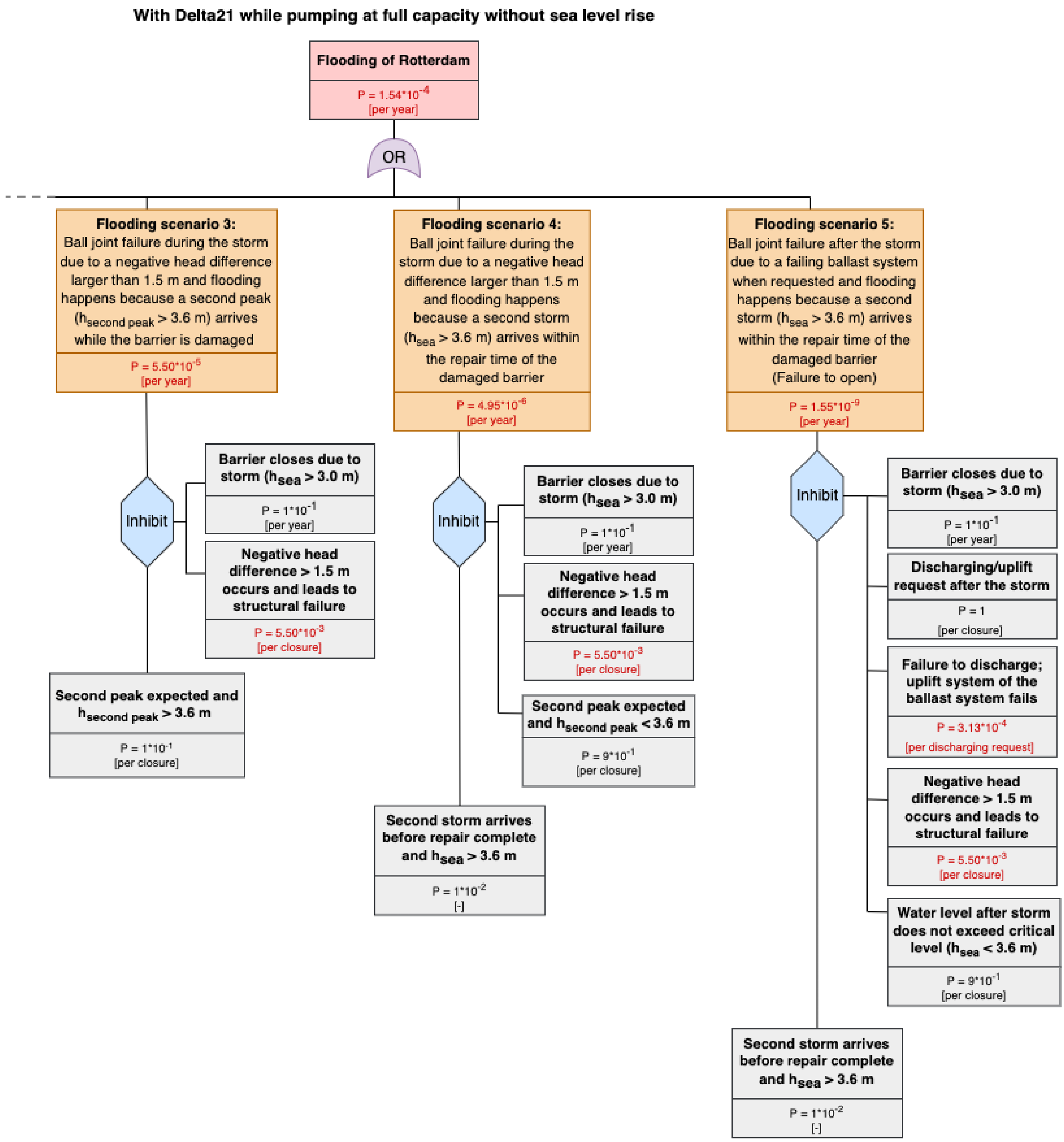


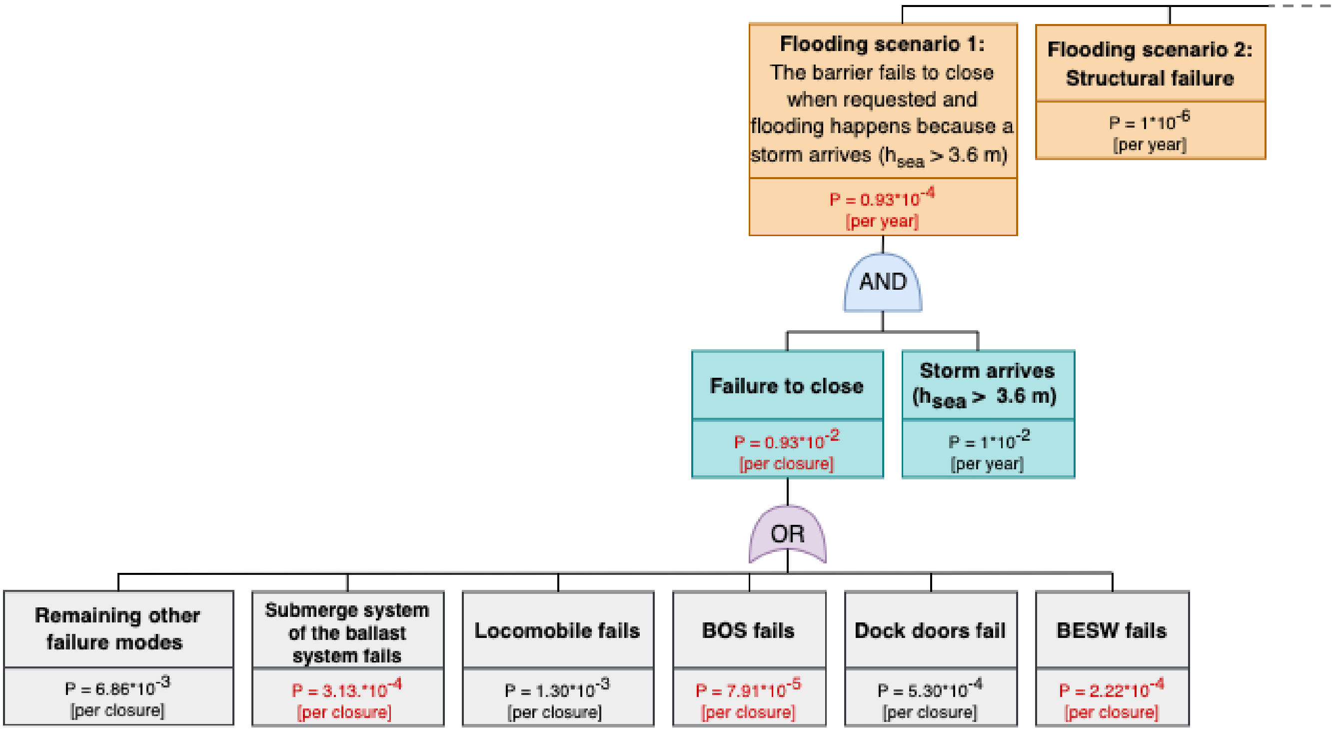
Figure N.67 Increase in peak water levels [m] in the Delta21[1] system in the future climate scenario (relative to CS in current climate)

[1] With adapted closure criterion of DORDrecht +2.9 m, see Section 5.3

Appendix O Fault tree of the Europoortkering failure probability

The figure below shows the fault tree for the Europoortkering as determined by Sewberath-Misser (2022). For more details on the origin of these numbers, the reader is refereed to his report.





Flooding scenario 1:
The barrier fails to close when requested and flooding happens because a storm arrives (h_{sea} > 3.6 m)
P = 0.93*10^-4
[per year]
Flooding scenario 2:
Structural failure
P = 1*10^-6
[per year]
AND
Failure to close
P = 0.93*10^-2
[per closure]
Storm arrives (h_{sea} > 3.6 m)
P = 1*10^-2
[per year]
OR
Remaining other failure modes
P = 6.86*10^-3
[per closure]
Submerge system of the ballast system fails
P = 3.13.*10^-4
[per closure]
Locomobile fails
P = 1.30*10^-3
[per closure]
BOS fails
P = 7.91*10^-5
[per closure]
Dock doors fail
P = 5.30*10^-4
[per closure]
BESW fails
P = 2.22*10^-4
[per closure]

Appendix P Net present value (NPV) calculations

All described savings and initial investments do not occur at once. To properly account for the time dependency of money flows, the net present value of the expected savings must be calculated to correctly appreciate the nominal quantities. Only then can a comparison be made with e.g. the costs of Delta21, in light of a costs-benefits analysis. Net present value (NPV) is calculated using the following equation:

$$NPV = \frac{V_{nominal}}{(1+i)^p} \quad \text{Equation P-1}$$

Where:

$V_{nominal}$ = the nominal value of a(n obviated) cost in a given year
i = the discount rate
p = the period that has passed since the reference year

The discount rate (i) is predetermined by the Dutch government for a variety of societal projects and analyses. Since 2017 the government and water bodies agreed that the 'obviated costs' (*vermeden kosten*) for dike reinforcements as a result of interventions that reduce the hydraulic loading can be interchanged. Artikel 7.24 of the Waterwet (2009) contains the juridical foundation for this. The High Water Protection Program (HWBP) has since then advised to employ the low discount rates for infrastructural costs to projects that save on reinforcement costs elsewhere. (Werkgroep Financiële uitwisseling tussen dijkversterking en rivierverruiming, 2019). The HWBP guidelines therefore indicate a discount rate of 1.6%, corresponding to 'sunken costs', among which dike reinforcement projects belong (Ministerie van Financiën, 2020). Furthermore, current policies dictate that no correction for inflation is performed on i for societal cost-benefit analyses of a project such as Delta21. Note that risk free interest and inflation rates, which determine in part the height of the discount rate, are currently quite different from the time at which the centre of economic expertise (SEE) determined them. Between the current values and previous one was merely a period of 6 years. It is therefore not unthinkable that they will change again, requiring an actualization of these calculations in due time. For now however, the guidelines and examples of the HWBP are followed.

Given that Delta21 is accredited an estimated obviation of costs in every year from construction onwards, the total NPV of all savings can be appreciated with equation Equation P-1 rewritten as:

$$NPV = \sum_{t=T_R}^{T_Z} \frac{V_{n,t}}{(1.016)^{t-T_R}} \quad \text{Equation P-2}$$

Where:

$V_{n,t}$ = the nominal value of a(n obviated) cost in year t
T_R = the reference year (year of construction)
T_Z = the final considered year (2100)

For the following calculation it is assumed that Delta21 is finalized in 2030, which serves as the reference year. The current High water protection program (HWBP) ends in 2050. The short term obviated costs as calculated in Section 6.2 are therefore assumed to be spread out evenly over the period 2030-2050. After that, a similar distribution is assumed for the obviated costs between 2050 and 2100, where the results of Section 6.2 are assumed to have an approximately steady contribution each year. In addition to this, the savings from reduced average expected yearly damage at the unembanked areas of Dordrecht are expected to grow linearly from the lower and upper bound as calculated in Section 6.3.

Several important assumptions are made to allow for this calculation. First of all, a calculated cost of €6.7 mil./km of dike reinforcement is used as a representative value for the Rhine-Meuse delta. Furthermore, the W+ KNMI scenario is assumed, based on the IPCC's high emission SSP5-8.5 scenario. This means that the obviated costs by Delta21 in the future scenario, are indeed all included by 2100. If climate change and in particular sea level rise occurs faster, the NPV grows, whereas a slower progression leads to a lower NPV due to the stronger discount. Table P.11 presents the results of the NPV calculation. A total of €783 mil. in savings are attributed to Delta21 in the reference year 2030, with a 90% confidence interval of [€251 million, €2,852 million].

The uncertainty of reinforcement costs means a 90% confidence interval of [€2 million / km, €25 million / km]. This uncertainty also dominates the final estimations. Uncertainty in for example the speed of sea level rise yields a significantly smaller interval. Considering for example the 95% confidence bounds of the IPCC SSP-8.5 scenario, implies that the W+ climate scenario is reached in ca. 2075 (upper bound) or ca. 2150 (lower bound). Assuming that the same reinforcements are still needed, but in a different year, this yields a 95% confidence bound of the NPV of [€563 million, €865 million]. Naturally, when other climate change scenarios are considered this range can become larger, but the SSP-8.5 scenario is principally used in the context of flood protections.

Note that obviated costs are considered until the point where the W+ conditions are reached. In other words, the final considered year and the division of the total obviated costs is changed. For slow and fast climate change, this means that the final year of savings in respectively 2075 and 2150. After that moment, other system-changing interventions are expected. And any additional savings beyond that point fall outside the scope of this thesis.

Table P.11 Yearly contributions towards the total obviated reinforcement costs corrected to NPV

Year	obviated costs (€M)	contribution to NPV (€M)	Year	obviated costs (€M)	contribution to NPV (€M)
total:	*€ 1352 million*	*€779.2 million*	2065	20.86	11.97
2030	13.78	13.78	2066	20.88	11.79
2031	13.80	13.58	2067	20.89	11.61
2032	13.82	13.39	2068	20.91	11.44
2033	13.84	13.19	2069	20.93	11.27
2034	13.86	13.00	2070	20.95	11.10
2035	13.88	12.82	2071	20.97	10.94
2036	13.89	12.63	2072	20.99	10.78
2037	13.91	12.45	2073	21.01	10.62
2038	13.93	12.27	2074	21.03	10.46
2039	13.95	12.09	2075	21.04	10.30
2040	13.97	11.92	2076	21.06	10.15
2041	13.99	11.75	2077	21.08	10.00
2042	14.01	11.58	2078	21.10	9.85
2043	14.03	11.41	2079	21.12	9.70
2044	14.04	11.25	2080	21.14	9.56
2045	14.06	11.08	2081	21.16	9.42
2046	14.08	10.92	2082	21.18	9.28
2047	14.10	10.77	2083	21.19	9.14
2048	14.12	10.61	2084	21.21	9.00
2049	14.14	10.46	2085	21.23	8.87
2050	20.58	14.98	2086	21.25	8.74
2051	20.59	14.76	2087	21.27	8.61
2052	20.61	14.54	2088	21.29	8.48
2053	20.63	14.32	2089	21.31	8.35
2054	20.65	14.11	2090	21.33	8.23
2055	20.67	13.90	2091	21.34	8.11
2056	20.69	13.69	2092	21.36	7.98

Year	obviated costs (€M)	contribution to NPV (€M)	Year	obviated costs (€M)	contribution to NPV (€M)
2057	20.71	13.49	2093	21.38	7.87
2058	20.73	13.29	2094	21.40	7.75
2059	20.74	13.09	2095	21.42	7.63
2060	20.76	12.90	2096	21.44	7.52
2061	20.78	12.71	2097	21.46	7.41
2062	20.80	12.52	2098	21.48	7.30
2063	20.82	12.33	2099	21.49	7.19
2064	20.84	12.15	2100	21.51	7.08

Appendix Q Full hydraulic model and control

The hydraulic model schematization in SOBEK and Real time control module are attached in a separate file.

REFERENCES

Agtersloot, R., & Paarlberg, A. (2016). *WAQUA Productieberekeningen Rijn-Maasmonding.* Delft: Deltares.

Albers, T. (2022a). *Beoordeling Grevelingendam.* Rijkswaterstaat RWS-PRK-P4-R15-Grevelingendam-Veiligheidsrapportage.

Albers, T. (2022b). *Beoordeling Philipsdam.* Rijkswaterstaat RWS-PRK-P4-R11-Philipsdam-Veiligheidsrapportage.

Arcadis. (2022). *Onderzoek aanzanding kust Haringvlietmonding.*

Bakker, A. M., Louchard, D., & Keller, K. (2017). *Sources and implications of deep uncertainties surrounding sea-level projections.*

Balla, A., Blaas, M., Boheemen, Y. v., Brinke, W. t., Broekhuizen, A., Burgers, R., . . . van Zetten, R. (2019). *Het verhaal van de Rijn-Maasmonding.*

Beaufort, G. (2022). *Deltaplan Grote rivieren.*

Berke, L., & Lavooij, H. (2018). *DELTA21 en Waterveiligheid: Kostenbesparend alternatief voor dijkverhogingen.* Delta21 v.o.f.

Besluit gebruik stormvloedkering Nieuwe Waterweg. (2009, december 22).

Bijl, W. (2006). *Achterlandstudie Maeslantkering.* RWS-ZH/AP/2006/04 ISBN 90-369-4823-1: Ministerie van Verkeer en Waterstaat.

Bossenbroek, J. (2017). *Beoordeling veiligheid primaire waterkeringen 2017-2023 Normtraject 20-3 - Geervliet-Hekelingen.* Ridderkerk: Waterschap Hollandse Delta.

Bossenbroek, J. (2020). *Beoordeling veiligheid primaire waterkeringen 2017-2023 Normtraject 25-3 – Goeree Volkerak-Zoommeer.* Ridderkerk: Waterschap Hollandse Delta.

Botterhuis, T., Rijcken, T., Kok, M., & Toorn, A. v. (2012). *Onderzoek faalkans in kader van Kennis voor Klimaat.*

Buijs, M. (2021). *Optimizing the use of Delta21 for flood prone areas not.* [Master's thesis, Delft University of Technology]: https://repository.tudelft.nl/islandora/object/uuid%3Aec174eb1-ff4e-4227-b034-c0e971d1da4f?collection=education.

Chbab. (2010). *Analyse faseverschil tussen opzet en getij bij Hoek van Holland.* Deltares.

Chbab. (2012). *Achtergrondrapport WTI-2011 voor het Benedenrivierengebied - concept hydraulische randvoorwaarden HR2011 voor de Benedenrivieren.* Deltares. doi:Deltares rapport 1204143-003-ZWS-0030

Chbab. (2016). *Basisstochasten WTI-2017 Statistiek en statistische onzekerheid.* Deltares.

Chbab, H. (2016). *Basisstochasten WTI-2017 Statistiek en statistische onzekerheid.* Deltares.

Chbab, H., & Groeneweg, J. (2017). *Modelonzekerheid belastingen, Wettelijk Beoordelingsinstrumentarium WBI-2017.* Deltares 1209433-008.

Commissie voor Verkeer en Waterstaat. (2006). *Vaststelling van de begrotingsstaat van het Infrastructuurfonds voor het jaar 2006.* Sdu Uitgevers. KST95779 0506tkkst30300A-59 ISSN 0921 - 7371.

Dekker, T. (2014). *Synthesedocument Rijnmond-Drechtsteden.* Programmateam Rijnmond-Drechtsteden.

Delta21 v.o.f. (2021a). *Delta21 goed voor de maeslantkering*. Retrieved from Delta21.nl: https://www.delta21.nl/delta21-goed-voor-de-maeslantkering/

Delta21 v.o.f. (2021b, april 19). *De deltacommissaris praat verder met Delta21.* Retrieved from Delta21.nl: https://www.delta21.nl/de-deltacommissaris-praat-verder-met-delta21/

Deltaprogramma | Rijnmond-Drechtsteden. (2011). *Deltaprogramma 2012 Probleemanalyse Rijnmond-Drechtsteden.*

Deltares. (2018). *Mogelijke gevolgen van versnelde zeespiegelstijging voor het Deltaprogramma.*

Deltares. (2019). *D-Flow 1D Technical Reference Manual.* Delft: Deltares.

Donkers, D. H. (2021). *Conceptual Design of the Spillway into the Energy Storage Lake of Delta21.* [Master's thesis, Delft University of Technology]: https://repository.tudelft.nl/islandora/object/uuid%3A922e4904-153a-42b5-ac5e-c5a866a1c7d4?collection=education.

Duits, M., & Kuijper, B. (2020). *Systeemdocumentatie Hydra-NL versie 2.8.* HKV lijn in water. PR4315.10.

Eeden, E. v. (2021). *A new dynamic landscape for the Haringvliet.* [Master's thesis, Delft University of Technology]: https://repository.tudelft.nl/islandora/object/uuid%3A7b1a14c3-5e77-407e-97be-9cfd866418a8?collection=education.

Elshof, A. (2014). *Basisdocument DPNH Buitendijkse gebieden.*

Expertise Netwerk Waterveiligheid. (2019). *Houdbaarheid Nederlandse waterveiligheidsstrategieën bij versnelde zeespiegelstijging.*

Geerse, C. (2013). *Belastingmodellen WTI-2017. Gevoeligheidsanalyses en adviezen voor eventuele aanpassingen aan Hydra-Ring.* HKV lijn in Water. PR2647.40.

Geerse, C. (2013). *Correlatie tussen stormvloeden en afvoeren voor de benedenrivieren.* HKV Lijn in water PR2442.

Görgen, K., Beersma, J., Brahmer, G., Buiteveld, H., Carambia, M., Keizer, O. d., . . . Volken, D. (2010). *Assessment of Climate Change Impacts on Discharge in the Rhine River Basin: Results of the RheinBlick 2050 Project.*

Haasnoot, M., Diermanse, F., Kwadijk, J., ., Winter, R. d., & Winter, G. (2019). *Strategieën voor adaptatie aan hoge en versnelde zeespiegelstijging.* Deltares.

Haga, H., Slagter, D., Gözüberk, I., Broeze, L., Kremers, T., Bartels, R., & Kool, E. (2021). *Referentiekader projectaanpak HWBP*. Utrecht: Hoogwaterbeschermingsprogramma (HWBP).

Hegnauer, M., Kwadijk, J., & Klijn, F. (2015). *The plausibility of extremely high discharges in the river Rhine.* Deltares.

Horick, Q. v. (2023). *Design of the navigation and discharge channel in the tidal lake of the Delta21 project.* [Master's thesis, Delft University of Technology]: https://repository.tudelft.nl/islandora/object/uuid%3Ac3a7d367-3627-4e7d-93a3-1d9f4b565643?collection=education.

HWBP. (2020). *Jaarbericht 2020.* alliantie Hoogwaterbeschermingsprogramma .

HWBP. (2023). *Definitief programmavoorstel HWBP 2024-2035*. alliantie Hoogwaterbeschermingsprogramma . Retrieved from https://www.hwbp.nl/documenten/jaarplannen/2021/12/09/definitief-programmavoorstel-2023-2034

HWBP. (2023, juni 12). *HWBP in cijfers (stand per 31 december 2022)*. Retrieved from website Hoogwater beschermingsprogramma: https://www.hwbp.nl/projecten/kengetallen-hwbp

Informatiehuis Water. (n.d.). *Waterveiligheidsportaal*. Retrieved from https://waterveiligheidsportaal.nl/#!/nss/nss/assessment

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability - Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on climate change.* Cambridge University Press.

Jacquemin, L. (2021). *Delta21: Improved Design of the Pump-Turbine Station.*

Jonkman, B., & Meyer, H. (2022, november 16). Klemmend beroep op Deltacommissaris: Kom met een plan. *De Ingenieur*.

Jonkman, S., Vrijling, J., & Kok, M. (2008). Flood risk assessment in the Netherlands: a case study for dike ring South Holland. *Risk Analysis: an international journal*(05(28)), 1357-1373.

Jorritsma-Lebbink, A. (1997). Besluit gebruik stormvloedkering Nieuwe Waterweg. *Staatscourant nr. 86*, p. 9.

Keizer, I., Bars, D. L., Valk, C. d., Jüling, A., Wal, R. v., & Drijfhout, S. (2022). *The acceleration of sea-level rise along the coast of the Netherlands started in the 1960s.* EGUsphere. doi:10.5194

Klerk, W. J., Winsemius, H. C., Verseveld, W. J., Bakker, A. M., & Diermanse, F. L. (2015). *The co-incidence of storm surges and extreme discharges within the Rhine-Meuse delta.* Environmental research letters 10 035005.

Koninklijk Nederlands Meteorologisch Instituut. (2021). *Klimaatsignaal 2021.*

Kramer, N., Smale, A., Bieman, J. d., & Chbab, H. (2017). *Hydraulische Belastingen Benedenrivieren.* Deltares 1230087-004-HYE-0001.

Lavooij, H., & Berke, L. (2019). *Delta21 een actualisering van het plan.*

Leemans, J. (2007). *Afvoerverdeling Rijntakken - Case 2.* TU Delft.

Lemans, M. (2007). *Case Afvoerverdeling Rijntakken.* Arnhem: TU Delft & RWS RIZA.

Ministerie van Financiën. (2020). *Rapport Werkgroep discontovoet 2020.* Rijksoverheid.

Ministerie van Infrastructuur en Milieu. (2012). *Basic documentation Maeslant Barrier Module 1.* Rijkswaterstaat M00-ALG-01-EN.

Ministerie van Infrastructuur en Milieu. (2019). *Regeling veiligheid primaire waterkeringen 2017 - Bijlage III Sterkte en veiligheid.*

Ministerie van Infrastructuur en Waterstaat. (2019). *Feitenanalyse veranderende kostenramingen Hoogwaterbeschermingsprogramma.*

Ministerie van Infrastructuur en Waterstaat. (2021). Retrieved from rijkswaterstaat.nl: https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/deltawerken/maeslantkering#zie-ook

Ministerie van Infrastructuur en Waterstaat. (2021a). *Schematiseringshandleiding macrostabiliteit WBI 2017.*

Ministerie van Infrastructuur en Waterstaat. (2021b). *Schematiseringshandleiding piping WBI 2017.*

Ministerie van Infrastructuur en Waterstaat. (2022). *Schematiseringshandleiding Grasbekleding WBI 2017.*

Montfoort, M. v., Haaren, D. v., Leeuwen, P. v., Duits, M., Wegman, C., & Tigchelaar, J. (2022a). *Eerste Beoordeling Primaire Keringen Overstromingskans Dijktraject 34-4.* Breda: Waterschap Brabantse Delta.

Montfoort, M. v., Haaren, D. v., Leeuwen, P. v., Duits, M., Wegman, C., & Tigchelaar, J. (2022b). *Eerste Beoordeling Primaire Keringen Overstromingskans Dijktraject 34-5.* Breda: Waterschap Brabantse Delta.

Nieuwenhuijzen, L. v., & Bos, M. (2004a). *Waterkeringsveiligheid langs Volkerak-zoommeer.* Royal Haskoning DHV. 9P4722.A0/R002/LVN/IL/Nijm.

Nieuwenhuijzen, L. v., & Bos, M. (2004b). *Waterkeringsveiligheid langs Volkerak-zoommeer verbindende waterkeringen.* Royal Haskoning DHV. 9P4722.B0/R001/LVN/LDW/Nijm.

Oerlemans, C. (2020). *The missing link in adaptive delta management.* [Master's thesis, Delft University of Technology]: https://repository.tudelft.nl/islandora/object/uuid%3Aebc4c396-97f7-42ad-ba0f-72af97eebb35?collection=education.

Oppenheimer, M., Glavovic, B., Hinkel, J., Wal, R. v., Magnan, A., Abd-Elgawad, A., . . . Sebesvari, Z. (2019). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*.

Pleijter, G. (2022). *Beoordeling Oesterdam.* Rijkswaterstaat RWS-PRK-P4-R09-Oesterdam-Veiligheidsrapportage.

Rijcken, l. D., Mooyaart, i. L., Oerlemans, I. C., & Ziel, i. F. (2023, mei 5). Hollandkering als aanvulling op de Maeslantkering. *Land en Water, 63*, pp. 10-12.

Rijcken, T., & Meijman, K. (2022, oktober 11). Moet Nederland het Westen prijsgeven aan het water? *NRC*. Retrieved from https://www.nrc.nl/nieuws/2022/10/11/watermanagers-roeren-zich-in-discussie-we-moeten-ons-juist-niet-terugtrekken-voor-de-stijgende-zeespiegel-a4144835

Rijksoverheid. (2021). *Nationaal Deltaprogramma 2022.*

Rijksoverheid ministeries van IenW & EZK. (2015). *Nationaal Waterplan 2016-2021.* Rijksoverheid.

Rijkswaterstaat. (2007a). *Systeemanalyse Rijn-Maasmonding.* RWS WD rapport 2007.005 ISBN 9789036914413.

Rijkswaterstaat. (2007b). *Planologische Kernbeslissing (PKB) Ruimte voor de Rivier deel 4.* Rijkswaterstaat.

Rijkswaterstaat. (2011). *Waterbergingsplan Volkerak-Zoommeer.* Rijkswaterstaat. VZM 1412027 v14.

Rijkswaterstaat. (2012). *Basic Documentation Maeslant Barrier.*

Rijkswaterstaat. (2019). *Inzetprotocol Waterberging Volkerak-Zoommeer Versie 4.1.* bedrijfsinformatie Inzetprotocol Waterberging. Rijkswaterstaat.

Rijkswaterstaat. (2023, mei 10). *Alg. informatie Haringvlietsluizen*. Retrieved from website Rijkswaterstaat: https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/deltawerken/haringvlietsluizen

Ruiz, R. A., Vilder, L. d., Prasasti, E., Aouad, M., Luca, A. D., Geisseler, B., . . . Goseberg, N. (2022). Low-head pumped hydro storage: A review on civil structure designs, legal and environmental aspects to make its realization feasible in seawater. *Renewable and Sustainable Energy Reviews*(160). doi:https://doi.org/10.1016/j.rser.2022.112281.

Schropp, M. (1999). *Regelbereik afvoerverdeling Rijntakken.* Arnhem: Directoraat-Generaal Rijkswaterstaat.

Sewberath-Misser, V. (2022). *Improving the reliability of the Maeslant barrier in the Delta21 configuration.*

Sloff, K., Sligte, R. v., Huismans, Y., & Fuhrhop, H. (2012). *Morphological model of the Rhine-Meuse Delta.* Deltares. 1205961-001.

Slootjes, N., & Thijssen, A. (2013). *Memo Nadere analyse waterberging Grevelingen.* Deltares.1208318-001-VEB-0001.

Smale, A. (2018). *Werkwijzer bepaling Hydraulische Ontwerprandvoorwaarden.* Deltares. 11202226-009-GEO-0002 .

Smorenburg, F., Kampman, W., & Broek, M. v. (2022). *Hoofdrondrapport veiligheidsoordeel WBI2017 Normtraject 27-4.* Waterschap Scheldestromen NL22-648800269-24702.

Spaargaren, F. (2014, september 10). Sluit de Nieuwe Waterweg af. *De Ingenieur*.

Steffelbauer, D. B., Riva, R. E., Timmermans, J. S., Kwakkel, J., Bakker, M., & . (2022). Evidence of regional sea-level rise acceleration for the North Sea. *Environmental research letters*.

Sterl, A., Brink, H. v., Vries, H. d., Haarsma, R., Meijgaard, E. v., & . (2009). An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate. *Ocean Science*.

Tijssen, A. (2010). *Memo Stormopzetduur bij Hoek van Holland - effecten op de toetspeilen.* Deltares, 1202341-003-ZWS-0014.

Tweede Kamer der Staten-Generaal. (2006). *Vaststelling van de begrotingsstaat van het Infrastructuurfonds voor het jaar 2006.* 30 300 A nr59.

Valk, C. d., & Steelzel, H. (1997). *Modelling statistics of storm duration to assess the reliability of dunes as flood protection: Preliminary investigation.* TU Delft.

Verschoor, B. (2023). *The Delta Barrier - A climate robust preliminary design of the Delta21 storm surge barrier.* [Master's thesis, Delft University of Technology]: https://repository.tudelft.nl/islandora/object/uuid%3Afaaa63b2-a07c-4214-81a3-05dff6f9163c.

Vreede, J. d. (2006, maart 2). HOEK VAN HOLLAND. De waterkering in de Nieuwe Waterweg blijkt in 1997 te zijn opgeleverd met tientallen fouten, die er toe leiden dat de kering niet altijd sluit als het moet. . *Algemeen Dagblad (AD)* .

Vriend, H. d., Kok, M., Pol, J., & Hegnauer, M. (2016). *Heeft de Rijnafvoer bij.* Expertise Netwerk Waterveiligheid.

Vuren, S. v., Levelt, O., Pol, J., Meij, R. v., Grave, P. d., Nugroho, D., . . . Kruif, A. d. (2017). *Beleidsstudie Kostenreductie Dijkversterking door Rivierverruiming.* Rijkswaterstaat.

Waterwet. (2009, januari 29). Retrieved november 09, 2021, from https://wetten.overheid.nl/BWBR0025458/2021-07-01

werkgroep Financiële uitwisseling tussen dijkversterking en rivierverruiming. (2019). *Eindadvies verkenning 'Financiële uitwisseling tussen dijkversterking'.* Nationaal Deltaprogramma; Rijksoverheid.

Werkgroep Financiële uitwisseling tussen dijkversterking en rivierverruiming. (2019). *Eindadvies verkenning 'Financiële uitwisseling tussen dijkversterking'.* Nationaal Deltaprogramma; Rijksoverheid.