Flood risk reduction measures for the Rhine-Meuse Estuary

Finding the most efficient reduction measure considering spatial planning strategies

Master Thesis

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TU Delft

HKV LIJN IN WATER

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by

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To obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Monday December 16th, 2024 at 10:45 AM.

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Project Duration:	April, 2024 - December, 2024
Faculty:	Faculty of Civil Engineering, Delft

This thesis is confidential and cannot be made public until December, 2024.

Cover: Rotterdam Waterstad 2100 (DE URBANISTEN & Deltares, 2023)

TU Delft

Preface

Before you lies the master thesis "Flood risk reduction measures for the Rhine-Meuse Estuary: Finding the most efficient reduction measure considering spatial planning strategies".
This thesis has been written as the final graduation requirement of the master Civil Engineering, track Hydraulic and Offshore Structures at the Delft University of Technology.
I have written this thesis between April and December 2024 mostly from my home in Nieuwe-Tonge and the HKV office in Delft.

Researching the subject of flood risk reduction methods and developing a method to estimate their economic efficiency has been very educational for me.
Writing this thesis has brought me new skills like working with the OKADER program, visualization of complex data and executing complex conditional calculations.
Completely understanding the interplay between all facets of this research like hydraulic loading, flood risk reduction methods, probabilistic approach and spatial planning strategies can not be done in the limited time that is available for writing this thesis.
However, I do believe that I have made major strides in understanding these concepts and the relations between them, at least for the Rhine-Meuse Estuary.
Working on this thesis made me feel that all the things I have previously learned in the bachelor and master came together to form the final project for my educational journey.

I would like to thank each of my committee members for their help in the process of writing this thesis, I'm grateful for your kind and knowledgeable approach towards me and my ideas.
I want to thank Dr. Cong and Dr. Hoes specifically for introducing me to the most interesting subject there is; flood risk.
The, appropriately named, Flood Risk course introduced me to the world of risk management based thinking, and brought me the realization that I want to continue on this subject both in education and in my professional career.
I want to thank Dr. Rijcken, specifically for helping me find the right subject at the very beginning of this project and connecting me with HKV.
Ties' skill of storytelling, and his passion of connecting minds and ideas to help us all advance in the rich world of hydraulic engineering is truly inspiring.
Thank you Cees for being my go to for any question or doubt I had during this research, I appreciate all your help and suggestions for improvement, I genuinely enjoyed all the conversations we had.
Special thank you to all the wonderful people at HKV who made me feel at home since day one, and for always providing me with all the support, help and suggestions I would ask for.
I want to thank my family, friends and colleagues for being there for me during this whole process and always reassuring me I was on the right track.

Finally, I want to commemorate my late grandfather, Albert van Wilgen.
During my studies, his steadfast advice to me was always the same: put your education first.
Only after I followed his advice, things started to fall into the right place, I dedicate this report to him.

J.A.A. van Wilgen
Delft, December 2024

Summary

Because of climate change, seawater levels are expected to rise considerably, combining this with increased peak river discharges, results in significant strain on inhabited low lying parts of the world. The Rhine-Meuse estuary is a perfect example of this; a densely inhabited region in between the North Sea and multiple rivers.
The Dutch Delta Program researches the effects of climate change for the Netherlands and proposes multiple alternatives to reduce its effects. An alternative comprises of the implementation of large scale hydraulic interventions, in combination with keeping all dikes up to the norm.
Four alternatives are considered, being; A1: Closed seafront and keeping current water level, A2: Closed seafront, allowing an increase in water level, B1: Closable seafront and retaining river discharge distribution and finally B2: Closable seafront with an altered discharge distribution.

This research determines, and compares, the economic efficiency of the aforementioned alternatives considering different spatial planning scenarios. The economic efficiency of an alternative is calculated by summing the resulting benefits of the alternatives and dividing this by the cost of implementation. A higher economic efficiency indicates that an alternative provides higher value compared to its cost of implementation, this is necessary to help decide if an alternative is worth considering for implementation.
Estimating the impact that spatial planning strategies have on the economic efficiency of the alternatives helps in determining if such strategies need to be accounted for when performing efficiency determinations for similar large scale hydraulic measures.
The benefit of implementing the alternatives consists of the resulting reduction in dike reinforcement cost and reduction in the region's flood risk as compared to the baseline strategy.
The baseline is the strategy to protect the Netherlands like it has been done i.e. reinforce dikes where the failure probability is close to becoming higher than the norm, combined with mainly utilizing closable flood barriers, also known as the open-closable strategy.
All economic factors are converted to present value with a discount rate of 1.6%, alternatives are modeled to be implemented in 2100 and all the alternatives' effects are considered up until 2200.

This study finds that, amongst the four considered alternatives, B2 appears to be the most economically efficient choice, next to that, alternative A1 has comparable economic efficiency.
The efficiency is for a large part a result of the flood risk reduction for unembanked areas, which alternative A1 and B2 specifically, have as an effect. Alternatives A2 and B1 have an economic efficiency far below 1.0 for all spatial planning strategies; thus not worth exploring further based on the considered factors within this research.
Spatial planning strategies have a significant influence on economic efficiency; alternative A1 and B2 become around 30% more efficient for the move to unembanked spatial strategy as compared to the densification one. And reversely, the strategy of developing rural land results in all alternatives having an economic efficiency of below 1.0; being cost ineffective.

In this research, three reference locations are used to determine the flood risk reduction of the alternative, the other economic factors are scaled (normalized) to be in proportion with the reference locations. If the flood risk reduction effects of the alternatives would be determined for the whole Rhine-Meuse Estuary the uncertainty of the applied method would be reduced.
The flood risk reduction determination relies purely on water levels, their frequencies and corresponding damages, taking into account the alternatives' effect on outside water level perseverance would lead to more precise flood damage estimations.
The unembanked flood risk reduction is the governing factor for the economic efficiency of the alternatives making the (local) protection, of unembanked areas specifically, a possible highly cost effective strategy. This should be explored as a new alternative next to the four in this research, possibly made

up out of components of the considered ones.

Contents

1 Introduction

1.1. Motivation

Over a quarter of the worldwide human population lives in near-coastal zones, and an increasing trend in this concentration can be seen (Reimann et al., 2023). Combining this fact with an expected global mean sea level rise of 0.84 meter in the year 2100 (Representative Concentration Pathway 8.5) gives a grounded reason for concern (IPCC, 2022).
Sea level rise will increase the frequency and effect of floods, and will raise the cost of mitigation measures as well (Jonkman et al., 2013; Vitousek et al., 2017; Vousdoukas et al., 2018).
In the Netherlands, specifically within the Rhine-Meuse estuary, this concern is perhaps even more justified. The Rhine-Meuse estuary is home to large amounts of economic activity and has a high population density. Because of the presence of the Port of Rotterdam, an open connection with the North-Sea has been kept. The main rivers, the Meuse and Rhine, are expected to have an increase in peak discharge in the future (Buitink et al., 2023).
Combining these aspects makes the Rhine-Meuse Estuary a leading example of how flood risk will be a defining factor for the future development of a region.

Founded in the year 2019, Knowledge Program Sea Level Rise (Kennisprogramma Zeespiegelstijging (KP ZSS) in Dutch) studies the effects of climate change on the Dutch water system and proposes different alternatives to combat its effects (Zethof et al., 2023). For the Rhine-Meuse Estuary, four alternative system level hydraulic measure combinations are proposed, and their impact on hydraulic loading is calculated (van der Biezen et al., 2024).
A method to compare the economic efficiency of these alternatives, along with the determination of other relevant non-economic indicators, in a well founded way is necessary to guide the decision making process for their possible implementation.

1.2. Problem description

Because of the impacts of climate change on extreme precipitation, seawater levels and river discharges, the flood risk of the Rhine-Meuse estuary will increase if no countermeasures are taken.
To mitigate these impacts, and consequential increase of flood risk, the Netherlands has a national program to develop and implement interventions called the Dutch Delta Program.
This program started in 2014 and is mainly focused on reinforcing dikes through their High Water Protection Program (Hoogwaterbeschermingsprogramma in Dutch).

The High Water Protection Program is a collection of regional water boards together with Rijkswaterstaat (the Dutch national infrastructure body) that designs and performs dike reinforcements.
Specifically, these reinforcements are performed at locations where the flooding safety norms are exceeded, or expected to do so in the near future. These reinforcements often include large-scale replacement of revetments, heightening and or widening of dikes.
For some locations in the Netherlands, these type of reinforcements are not straightforward, or close to impossible, to apply. This is especially the case in the Rhine-Meuse estuary, where, in multiple locations, houses and other buildings are built right next to, or even on top of, primary dikes.
Other limiting factors include the accessibility of a specific location, existence of nearby nature reserves, or the desire to maintain the profile or revetment type (historical value), the need for housing, in this area specifically, amplifies these limitations.
The discussion about how this housing development can fit within this complicated system is being held for some time now; with the Water and Soil as Guiding Principles Program (Water en Bodem Sturend in Dutch) as one of the most important recent initiatives (IenW, 2022).

By implementing large scale hydraulic measures on water-system level, the need for local reinforcements can be delayed, reduced or even prevented. These system level measures have other added benefits like the possible reduction of flood risk, drive innovation and even improving nature.
The ratio of the benefits, these large scale hydraulic measures have, to their cost of implementation is an important consideration for decision makers in deciding if these measures are worth considering. The higher the economic efficiency, the higher the value of such hydraulic measures is compared to their cost.

Because of population growth, the distribution of new dwellings is an important spatial planning subject. The link with spatial planning and large scale hydraulic interventions can be made based on two aspects. Firstly, where and how land is used will influence flood risk directly through the amount of exposure to flooding. Secondly the flooding probability of an area will influence the willingness of living and working there.
The manner, and extend, of how these large scale water system interventions can delay or prevent dike reinforcements is not well discovered yet, but essential in estimating how impactful and efficient interventions could be. Especially, the topic of the interaction between climate change, the implementation of these large scale water system interventions and the influence of, and on, spatial planning is still undiscovered terrain.

Knowledge Program Sea Level Rise (Kennisprogramma Zeespiegelstijging (KP ZSS) in Dutch) running from 2019 to the year 2026, has been brought into existence for multiple purposes, called tracks. Its primary task is to gather information on, and study the expected consequences of, extreme sea level rise on the Dutch water system (IenW et al., 2020; Zethof et al., 2023).
Within the same program multiple flood risk reduction alternatives are explored and their hydraulic effects calculated. The program consists of five tracks; each focusing on a specific part of the analysis. Within the scope of this research, tracks 2 and 4 are the most relevant ones.

Track 2 is a system analysis of the Rhine-Meuse Estuary and estimates the impact of the expected sea level rise and increase peak river discharges on dike failure probabilities and dike reinforcements cost. Furthermore, the viability of the current flood risk management strategies are assessed in the context of potential extreme sea level rise scenarios (Zethof et al., 2023).

Track 4 proposes solutions for the scenario of increasing seawater level rising rates around the year 2100. This is done with three ”directions” namely ”Accommodate”, ”Advance” and ”Protection”.

- ”Accommodate” is a strategy based on a continuous examination of what is needed to keep flood risk at acceptable levels while not (or only partly) reinforcing the primary dikes and barriers (Zanting & Bouw, 2023).
- ”Advance” proposes a gigantic sea dike of the coast, from the island Walcheren up to the port of Rotterdam (Hekman et al., 2024).
- ”Protection” analyses four strategies with a combination of system level measures such as a closed sea entrance and a altered discharge distribution at Lobith (Kolen et al., 2024).

The ”Protection” direction will provide the alternatives that will be considered in this research.
”Protection” is the only direction in which its mitigating effects on hydraulic loading are thoroughly calculated, making it possible to be implemented in this research.
The other two directions are not on the same level of concreteness and will not be used in this study.

Knowledge Program Sea Level Rise track 4 ”Protection” provides four ”strategies”; four different ways to protect the Netherlands against the expected rise in sea level. These strategies consist of system-level interventions such as building dams at sea entrances and pumping stations to pump out excess river discharge.
In this research the implementation of these strategies (constructing the system measures according to a strategy) combined with the reinforcement of dikes to keep them up to norm until 2200 is called an *alternative*.

Four of these alternatives will be analyzed in this research according to the four strategies from track 4, for three different spatial planning scenarios. The spatial planning scenarios are incorporated as different ratios of dwelling distributions; influencing the alternatives’ reducing effects on the regions flood risk.
The alternatives’ impact will be compared to the ”baseline”. The baseline is equal to the current applied strategy and comprises of executing all necessary dike reinforcements to keep dikes within norm, and utilizing mainly closable flood barriers, known as the open-closable strategy.
The four alternatives comprise of the following components:

- **Alternative A1 (Closed seafront, keeping current water level)**: Closed off Westerschelde and Rhine-Meuse estuary from the sea with locks. Extremely large pumping station at the Nieuwe-Waterweg, and very large one at the Afsluitdijk. Future water levels in Rhine-Meuse estuary and South-West Delta will remain close to current ones.
- **Alternative A2 (Closed seafront, rising water level)**: Rhine-Meuse estuary closed off with water level rising along with sea level. Larger Rhine-Meuse estuary reservoir capacity than alternative A1, combined with a large pumping station.
- **Alternative B1 (Closable seafront, same discharge distribution)**: Keep tides in the South-West Delta, closable barriers at every sea entrance with a very low failure probability.
Rhine-Meuse estuary and South-West Delta gain reservoir capacity combined with a very large pumping station.
- **Alternative B2 (Closable seafront, changed discharge distribution)**: Closed off Rhine-Meuse estuary gains reservoir capacity and a very large pumping station, leading to a theoretical complete erasure of hydraulic loading for the Rotterdam and Dordrecht area. The South-West Delta gains reservoir capacity, tidal influence in the Haringvliet.
If the discharge at Lobith is higher than $12\,000\,\frac{\mathrm{m}^3}{\mathrm{h}}$, the extra discharge will be guided trough the Waal and Haringvliet; alleviating Rotterdam from large discharges trough the Lek.

1.3. Research objectives

The objective of this research is to make a substantiated determination of economic efficiency of the four alternatives, along with the most important non-economic indicators for the decision making process of possible implementation.
The economic efficiency of an alternative is defined as the economic benefits of an alternative divided by its implementation cost, both compared to the baseline. The economic benefit consists of three factors given in the numerator of Equation 1.1.

$$Economic\,efficiency\,of\,alternative = \frac{A+B+C}{D} \tag{1.1}$$

Where:

$$A = reduction\,of\,flooding\,probability\,and\,effect\,of\,unembanked\,areas\,[€]$$
$$B = reduction\,of\,flooding\,effect\,of\,embanked\,areas\,[€]$$
$$C = reduction\,of\,dike\,reinforcement\,costs\,[€]$$
$$D = cost\,of\,alternative\,system\,measures\,[€]$$

A visualization of these economic factors is shown in Figure 1.1.

The factors A, B and C consists of the difference between the mentioned economic values, flood risk or dike reinforcement cost, following the baseline and with an alternative implemented.
For the baseline the hydraulic loading is equal to the Very Extreme climate change scenario used for Knowledge Program Sea Level Rise track 2. The alternatives hydraulic loading follow the same path but after they are implemented they cause a reduction, implementation is in the year 2100.
Determining the four economic factors should be done in such a way that they are directly comparable, this is secured by expressing these factors as the present value in the year 2025, all the economic and non-economic factors are calculated up to the year 2200.

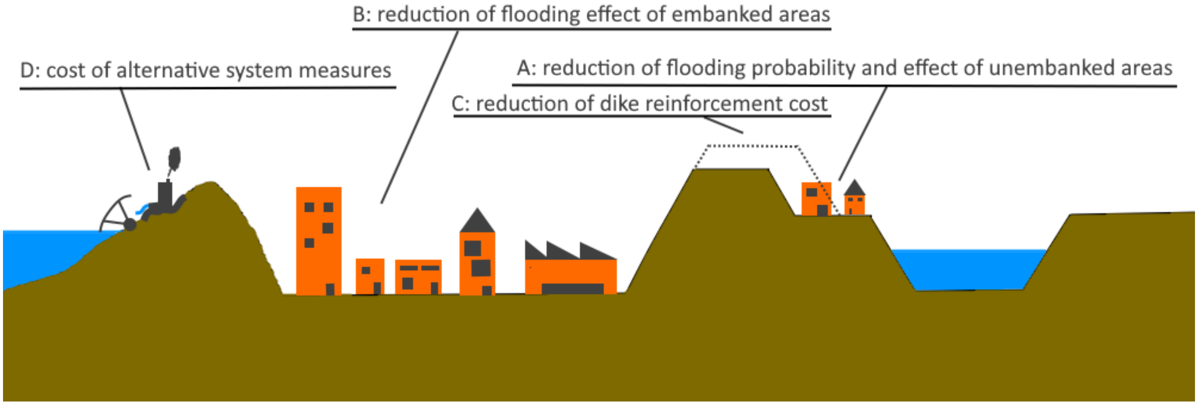


Figure 1.1: Economic efficiency factors visualized, adapted from (Vellinga et al., 2014)

The efficiency determination is based fully on economic factors while a policy maker or stakeholder can be interested in other non-economic benefits of the alternatives as well.
For this reason two relevant non-economic indicators are determined:

- The reduction of the number of dike reinforcements
- The dike reinforcement land use reduction

1.4. Research questions

The main research question that will be answered in this research will be the following:

- **How do the proposed flood risk management alternatives compare in terms of economic efficiency across various spatial planning scenarios for the Rhine-Meuse estuary?**

The sub questions that have to be answered to adress the main research question will be the following:

- What is the future hydraulic loading of the Rhine-Meuse Estuary because of climate change and what is the alternatives influence on it?
- What is the impact of an alternative on the necessary future dike reinforcement costs?
- How many dike reinforcement instances are averted by implementing the alternatives and how much land use is avoided?
- To what extend do the proposed alternatives reduce flood risk of unembanked areas?
- To what extend do the proposed alternatives reduce flood risk of embanked areas?
- What is the normalized economic efficiency of the alternatives?
- How will different spatial planning strategies affect the economic efficiency of the alternatives?

1.5. Approach

This research starts with an exploration of existing research on flood risk, spatial planning and the connection between these two. The definitions, equations and concepts found in this conceptual research will be referenced to later on.

The Rhine-Meuse Estuary is considered as the region for the economic and non-economic factors, the alternatives are based on their desired effects on this area specifically.
For the flood risk determination three regions are used as a reference, based on their location and available data. Specifically an unembanked region, a dense embanked and rural embanked area are chosen to make it possible finding what influence these characteristics have on the efficiency of the alternatives.

The hydraulic loading for now up until 2200 is provided for by Knowledge Program Sea Level Rise track 2 and 4. The expected hydraulic loading is given as water level frequency curves for all dike sections in the Rhine-Meuse Estuary both for the baseline as for each alternative.
The hydraulic loading for the baseline and alternatives, will be the input for the following two steps, dike reinforcement demand and flood risk estimation.

To find the dike reinforcement cost reduction, number of averted reinforcement instances and land use reduction, the hydraulic loading is imported in a program called OKADER.
OKADER creates a timeline of necessary dike reinforcements needed to keep the failure probabilities equal to the current norms. OKADER will also give monetary cost estimations, per year, for these reinforcement operations as well as the land use needed (de Grave, 2024).

The reduction in flood risk, that the alternatives will cause, is calculated for each of the three considered locations. For each of the locations a damage curve is created that will have a damage estimation for all relevant outside water levels, the damage curve is an extrapolation of LIWO scenarios (Snippen, 2021).
With LIWO being the Dutch national database for water and flooding and having damage estimations for multiple outside water levels for the locations considered.
Multiplying the damage curve with the water level frequency curves will result in the measure of flood risk; the Estimated Annual Damage (EAD) both for the baseline and alternatives.

The influence of spatial planning on the economic efficiency of an alternative is incorporated by factoring the flood risk estimations based on the amount of added dwellings according to each spatial planning strategy.
The spatial planning strategies are based on three spatial distributions of future housing needs; densification, moving to unembanked areas and developing embanked rural areas.
These three strategies determine the distribution of future expected housing development, which will influence the flood risk estimations trough the increase in exposure.

Finally a well founded comparison is made for all four alternatives, taking into account the economic and non-economic factors and the influence of the different spacial planning strategies.
These factors should give guidance to policy makers and stakeholders in the decision making process to implement, if any, which alternative and provide insight on the cross influences.

1.6. Reading guide

Chapter 2 will introduce the basic concepts of flood risk, spatial planning and its cross influences.
The outline of the method and a description of how the economic and non-economic factors will be determined is given in chapter 3.
Chapter 4 will introduce the general hydraulic characteristics of an estuary and specifies for the Rhine-Meuse, also describing the measures that the alternatives comprise of extensively. Chapter 4 will also display the future hydraulic loading increase, as well as the impact the alternatives will have on this.
The economic factors that will determine the efficiency of the alternatives are given in chapter 5 and 6. Chapter 5 presents all effects of implementation fo the alternatives that are related to dike reinforcement, chapter 6 does the same but for flood risk reduction.
Finally, the influence of spatial planning strategies on the efficiency of the alternatives is determined in chapter 7, all results are then collected in the final chapter 8.

2
Flood risk and spatial planning

This chapter explores the existing research on the two main components of this research, the most important principles are given. Starting with the most relevant definitions of flood risk and corresponding equations. After, the definition of spatial planning and its context within flood risk is given.
These definitions, principles, outcomes- and methods of existing research will guide the later chapters.

2.1. Flood risk

The widely accepted definition of risk written by the United Nations: “Risk is the expected loss (of lives, persons injured, property damaged, and economic activity disrupted) due to a particular hazard for a given area and reference period” (UN DHA, 1992).
In the context of this research which focuses on the effects of climate change, and corresponding impact of human behavior on flood risk, the following definition of the Intergovernmental Panel on Climate Change (IPCC) is more relevant:
Reisinger et al. (2020) states: ”The potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change.
Relevant adverse consequences include those on lives, livelihoods, health and well being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.”.

In the case of flood risk this potential impact becomes a flooding; the inundation of normally dry land with relatively large amounts of water. Risk can also be described as a function (Samuels et al., 2009):

$$risk = probability * consequence \tag{2.1}$$

Where probability is how likely a flooding is to occur. The consequence is the sum of expected losses in terms of lives lost, injuries and damages when flooding occurs.
This function is directly applicable for floodplains. Here the expected damages can be directly related to the expected probability of certain water depths occurring on the adjacent water body.
If a dike is in between the water body and the area of flooding, probability of flooding is not just the chance of water level occurrence, but rather the chance this water level reaches the area where damages can occur (a dike breach). In this case probability is a function of both water level probabilities and dike failure probabilities.

Especially considering spatial planning, the amount of assets, people and activities that are under threat of flooding are important considerations for the determination of flood risk. This can be Incorporated explicitly in the definition for flood risk by adding "exposure" as a variable. In function form (Samuels et al., 2009):

$$risk = probability * exposure * vulnerability \tag{2.2}$$

Exposure is defined as the sum of people, assets, and activities threatened by a potential hazard (flooding), often dependent mainly on the land use and -density behind the considered dike.
Vulnerability can be defined as how sensitive the exposed objects are to flooding, for example the amount of damage that is inflicted to housing or industrial structures when a flooding happens.

2.2. Measures of flood risk

In flood risk three measures of risk are used, the maximum accepted value of these three determine the regulatory safety standards for flood protection.

Economic risk is the cost of expected damages, in euros often expressed in expected annual value of damage (EAD). This is the product of annual flooding probabilities and corresponding economic damages. This type of risk is most often used in the cost-benefit analysis to determine the cost efficiency of reinforcements and new flood protection measures. The current flood protection norms in the Netherlands are calculated using a economic optimization, where investments plus risk are at the lowest point; point C in Figure 2.1.

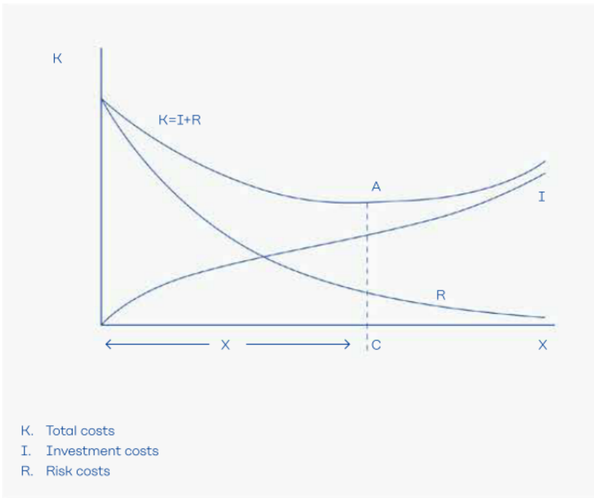


Figure 2.1: Principle of economical optimization (Kok et al., 2017)

Societal risk is given by the likelihood that a large number of casualties are inflicted by a flooding. The probability of a flooding where a large number of casualties happen has a large impact on the feeling of safety. When such an event happens it dominates public discourse and such an event is perceived as something that has to be prevented at (almost) all cost. Societal risk can be expressed as a graph, the FN-curve, which gives the cumulative probability for each number of casualties.

Individual Risk expresses the possibility that an individual, living permanently at a specific location, will die because of a flooding event. This risk is expressed as local individual risk (LIR) and accounts for the possibility of evacuation. In the Netherlands this LIR is set as a maximum of 1/100.000 for all inhabitants living in embanked areas. For unembanked areas there are no set requirements for flood protection (Kok et al., 2017).

2.3. Flood risk mitigation layers

If any of the risk measures is considered too high, flood risk mitigation measures must be taken. These measures can be divided into three flood risk mitigation strategies, also called layers of safety:

- Reduce the flood risk by reducing hydraulic loading of an area, most often done with the construction of dikes, dams and flood barriers. Having lower hydraulic loading reduces the probability of a flood and can lower the consequence when a flooding occurs.
- Lowering the consequence of a flooding by steering the spatial planning of an area.
  Steering on both, where houses and industrial areas are build, and to what extend these buildings are capable of withstanding a flooding.
  It is important to note that spatial planning has a direct influence on the exposure variable, not on the probability.
- Lowering the consequence of a flood by effective flood reduction management.
  This often comprises of having predetermined evacuation plans, and enough crisis personal and material to reduce the exposure. Because of the high predictability of high hydraulic loading this method can be an effective one.
  This type of flood risk reduction is the most impactful on the casualties and fatalities of a flooding.

Putting effort into these three layers of safety can reduce the flood risk to acceptable levels. The aforementioned economic optimization, hydraulic loading profile and area building characteristics, often determines the distribution of effort into each safety layer. (Kok et al., 2017)

2.4. Spatial planning

The European Spatial Planning Observation Network (ESPON) defines spatial planning as a strategy "to create a more 'rational' territorial organization of land uses and the linkages between them" (Dimitriou & Thompson, 2007).
In the context of flood risk, the rationality can be translated as building in such a way that the buildings' addition to flood risk of the region will be minimal. The addition of flood risk because of buildings is dependent on where dwellings, and industrial areas, are based and if flood proofing is considered in the design and construction. In this research spatial planning is defined as the distribution ratio of dwellings over a region.

The Dutch national government has a spatial planning policy based on national interests like, improving the economy, improvement of roads and railways, and protecting the country against floods.
The governments spatial planning policy is based on the Resolution of spatial planning (Besluit ruimtelijke ordening in Dutch). Since the 1st of January 2024 this law, and many comparative ones, have been replaced by one single law called the Environment and Planning Act (Omgevingswet in Dutch).

Spatial planning regarding housing construction and development of industrial areas are the responsibility of the municipalities. The Plan of Destination (Bestemmingsplan in Dutch) is the most important tool that is used to form a policy; these plans describe the intended purpose of all the surface area of the Netherlands.
Finally, the policy for the nationwide landscaping is in the hands of the provinces, for which they have a special council, the Inter provincial deliberation (Interprovinciaal Overleg in Dutch).
It is the provinces' task to have sufficient green areas in and around the cities and urban areas.
The expectations of developments in spatial planning that the governments, provinces and municipalities have are reported in the Structural vision on infrastructure and space (Structuurvisie Infrastructuur en Ruimte in Dutch) (BZK, n.d.).

2.5. Connection between flood risk on spatial planning

The probability of flooding of a certain area will impact the use and intensity of use of this area, due to psychological effects or national/regional destination plans. The other way around, the use and intensity of use of a certain area will impact the expected effects of a flooding.
These effects create a complicated interlinkage, or even iterative process, between flood risk estimations, land use, flood defense measures, and the economic and population growth of an area (Di Baldassarre et al., 2013). A simplified diagram of this iterative process between spatial planning and flood risk, along with the intermediaries, is given in Figure 2.2. The most important concepts and existing research of this process are given in the following paragraphs.

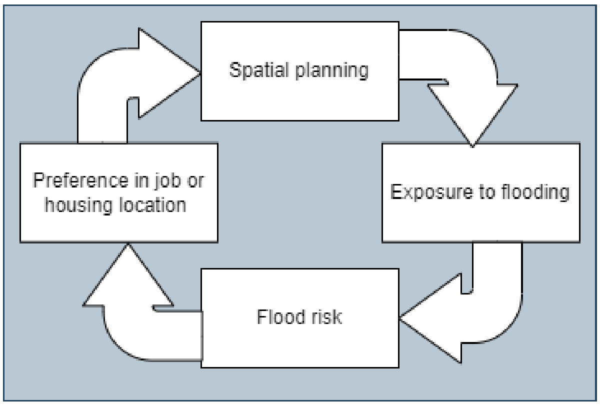


Figure 2.2: Iterative process between spatial planning and flood risk

2.5.1. Flood risks influence on spatial planning

Tol et al. (2003) states that ”The possibilities for dealing with very high river discharges should become one of the guiding principles for national spatial planning.”. Traditionally, spatial planning analyses with regard to flood risk only takes into account the difference between unembanked- and embanked areas. An important improvement would be defining different risk zones within embanked areas based on distance from breach, elevation levels and influences from ”obstacles”.
Based on these risk zones, flood risk reduction measures could be implemented like compartmentalization or improved emergency pumping stations (Pols et al., 2007). Implementing these spatial planning solutions for the most flood prone zones can reduce flood risk without having to improve dikes or flood barriers.

Especially for people living in a flood prone area, choosing where to live or work can be based on the flooding probabilities of said area. This concept of people moving their housing and economic activities to areas with a lower chance of flooding is known as the *levee effect* (White, 1945). The most flood protected areas, often along a river, will have higher rate of urban expansion, as seen in Figure 2.3. Paradoxically this effect can heighten the flood risk to higher values than before the construction of a flood defense because feeling safer leads to complacency (Ferdous et al., 2020).

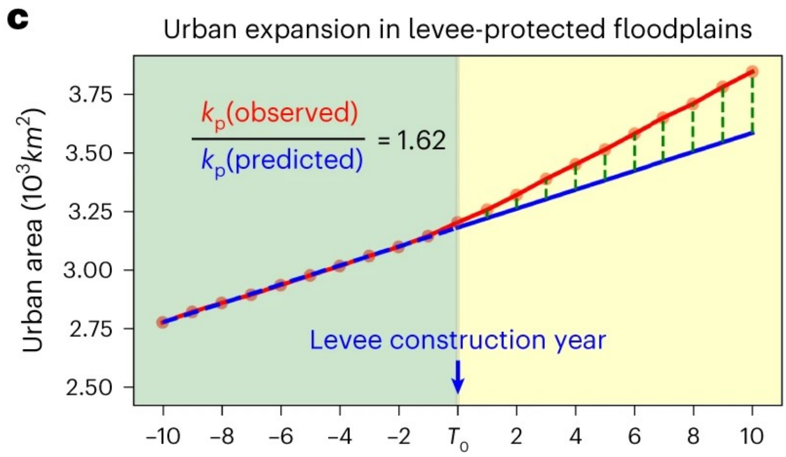


Figure 2.3: Levee effect on urban expansion visualized (Ding et al., 2023)

In the Netherlands, the Delta Program is the leading program that connects governmental bodies, provinces, municipalities and waterboards to protect the country against flooding and have maintain a sufficient supply of fresh water. This program consists of Delta Decisions (Deltabeslissingen in Dutch) and Preferred Strategies (Voorkeursstrategieen in Dutch).
A Delta Decision is a combination of frameworks, norms and structural choices of how to protect the Netherlands against flooding, prevent fresh water shortages and make the country more resistant to the effects of climate change.
The Preferred Strategies are more concrete interpretations and their implications, of the Delta Decisions, for a certain region.

Five Delta Decisions are given, each with a specific region or subject in focus, the most relevant to spatial planning being the Delta Decision on spatial planning adaptation (Deltabeslissing Ruimtelijke adaptatie in Dutch).
The Delta Decision on spatial planning adaptation proposes cooperation between the Dutch government, provinces, municipalities, and waterboards to make the country more resistant to climate change. This goal is set to be achieved in the year 2050 and should be accomplished by taking in to account the possible effects of climate change in policy making and development planning.
Among other things, this could influence the location of residential developments and industrial/commercial areas by being based on the local flood risk profile (IenW & EZK, 2014).
The Deltaprogram is updated yearly, the reports give an list of more concrete sub goals and an overview of already successful progressions (IenW et al., 2020).

The recent policy Water and Soil as Guiding Principles Program (Water en Bodem Sturend in Dutch) steers to have land development being guided by the risk of water nuisance/flooding, drink water quality deterioration, drink water availability and soil subsidence (IenW, 2022).
The Spatial Consideration Framework Climate-Adaptive Built Environment (Ruimtelijk Afwegingskader Klimaatadaptieve Gebouwde Omgeving. in Dutch) is an important component of the aforementioned policy.
The Spatial Consideration Framework Climate-Adaptive Built Environment provides a map for each guiding risk which shows at what locations this risk makes building development advisable or not, this in a range of seven grades of advisability.
This consideration framework is meant to help policy makers to make well-considered choices in the where, how and when spatial development should occur (Kolen et al., 2023).

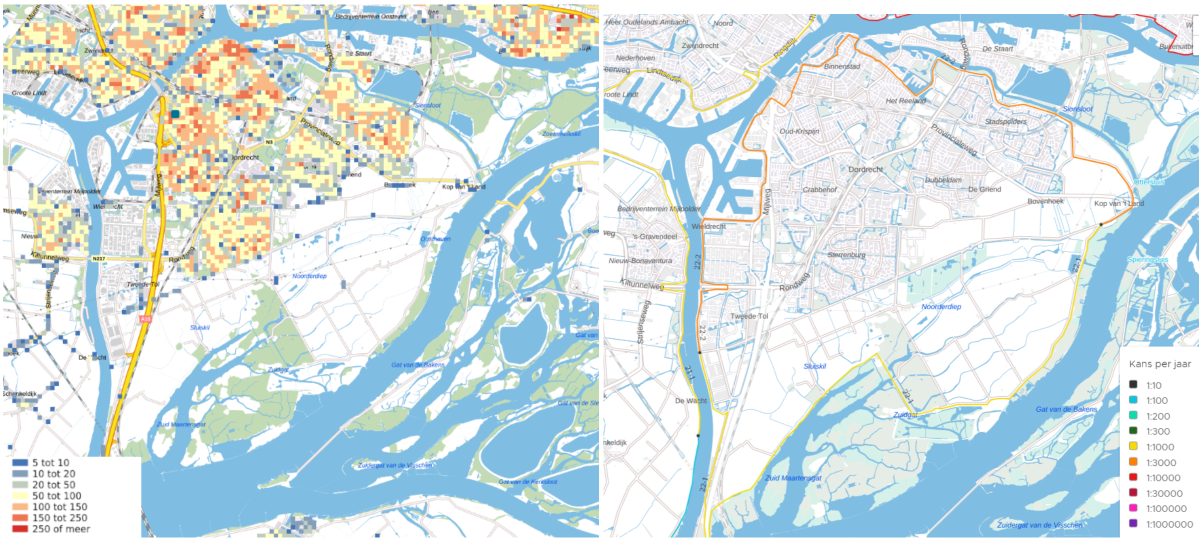
2.5.2. Spatial plannings influence on flood risk

Spatial planning properties of an area, like population density or the presence of compartmentalization dikes, has influence on the consequence of a flooding. In the Netherlands, the expected consequence of a flood determines the accepted failure probability of a dike section. The higher the expected consequence of a flood, the lower the accepted probability of flooding of this area.

The accepted flooding probabilities are determined by extensive flood risk modeling of multiple possible breach locations in a dike section. Ultimately, through a cost-benefit analysis that compares the expected consequences of floods, and the cost of bringing the dikes to a certain failure probability, the norm is determined. If the local individual risk or societal risk is higher than the maximum set value there will be deviation from this economic optimum (Deltaprogramma, 2014).

The consequence of a breach is determined using a Damage and Victims Module (Schade en Slachtoffer Module (SSM) in Dutch); a model that predicts economic damages and loss of life due to a flood event. Both of these consequences are influenced by population density; directly, or trough the number of dwellings per geographical unit. An important factor for determining flooding damages is the category of land use (Kok et al., 2004).

An example, within the Rhine-Meuse Estuary, where the the flood risk (specifically accepted flooding probability) is determined by spatial planning is the Island of Dordrecht. The north side of Dordrecht is densely populated, the south side is not, as seen in Figure 2.4a. Using the above-described method resulted in the primary dike trajectory around the north side having a maximum allowed failure probability of 1/3000 and the south trajectory of 1/1000 as seen in Figure 2.4b.



(a) Population density Dordrecht per 100x100m (van Leeuwen & Venema, 2023)

(b) Maximum allowed failure probabilities of primary dikes around Dordrecht (HWBP, n.d.)

Figure 2.4: Population density and allowed failure probability of dikes around Dordrecht

3 Method

To find an answer to the research questions, multiple parameters of the four alternatives need to be determined. This chapter will describe the method of determining the parameters that are needed to answer the research questions, starting with the general method given in a figure with a short description of each element.
After, this chapter will be in the same order as the research is structured, starting with the hydraulic loading and the alternatives' effect on it. The hydraulic loading will then be input for the dike reinforcement cost calculation and unembanked and embanked flood risk determination. These three economic factors, together with the cost of the implementation of the alternatives itself, determine the economic efficiency of the alternatives.

3.1. Method flow chart

To be able to make a fair and well-founded comparison, the economic efficiency determination (Equation 1.1) needs to be done identically for each of the four alternatives.
Figure 3.1 gives an overview of the method that will be used in this research.

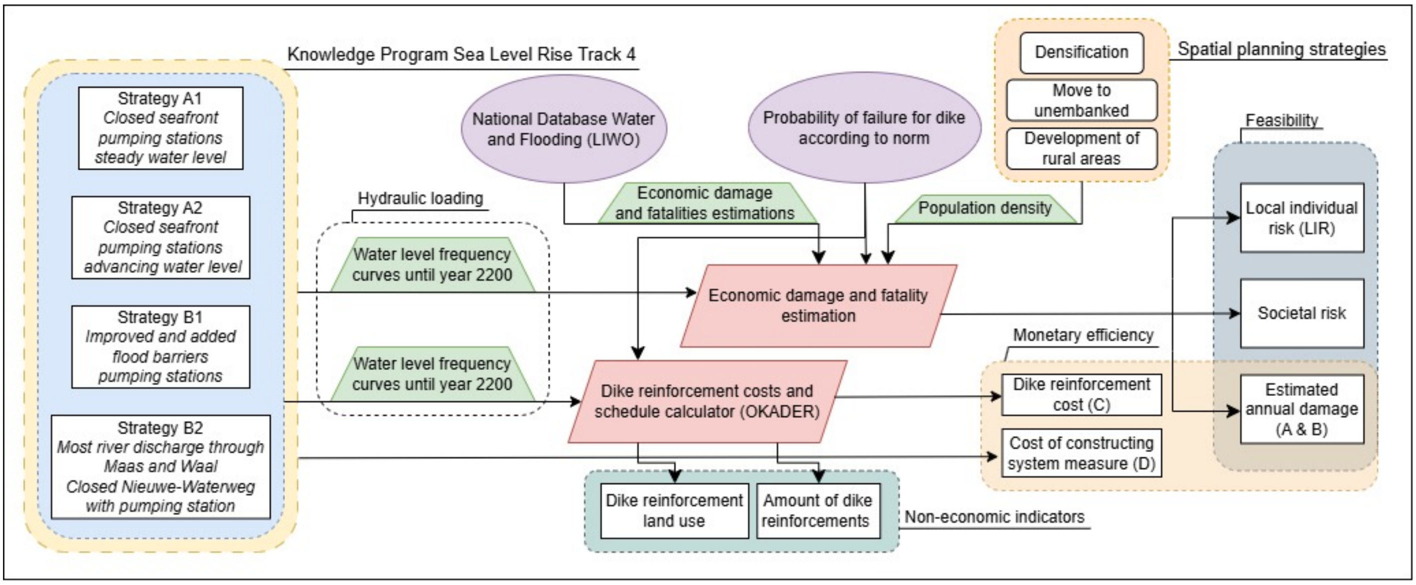


Figure 3.1: Research method flowchart

Starting on the left, in the yellow rectangle, are the four strategies from Knowledge Program Sea Level Rise track 4.
This research defines alternatives as the choice to implement a strategy from the Knowledge Program Sea Level Rise including subsequent necessary dike reinforcements up until 2200.
The hydraulic loading has been calculated for all dike sections throughout the Rhine-Meuse Estuary for each alternative and made available for this research.
The hydraulic loading will be instrumental in determining the necessary dike reinforcements and flood damage estimations. The determinations of these two parameters are visualized in the red parallelograms.

Dike reinforcement schedules and cost, on dike section level, are calculated using the program OKADER.
The economic damage caused by floods and corresponding fatality estimations will be done using a publicly available database of multiple flooding locations with corresponding damage and fatality estimations. This database is called National Information system water and flooding (LIWO in Dutch); the most complete and well structured database of its kind in the Netherlands.
The damage and fatality estimations are given for multiple outside water levels and corresponding return periods.
The available damage and fatality estimations are used to create a damage curve; a curve that has a damage estimation for all relevant water levels. Multiplying this damage curve times the discretized water level frequency curve, and normalizing per year, results in the estimated annual damage (EAD); given on the right of Figure 3.1.
For the determination of the local individual risk (LIR) the exact same method will used as for the EAD only now with a fatality curve, resulting in the LIR and societal risk.
The spatial planning strategies will be incorporated in these calculations by scaling the damage and fatality curve by the ratio of amount of dwellings added according to the strategy.

3.2. Hydraulic loading of baseline and alternatives

The implementation of the alternatives will lower the hydraulic loading in the Rhine-Meuse Estuary. The hydraulic loading is the main input parameter for the determination of the dike reinforcement cost and the areas embanked and unembanked flood risk; the three economic benefits that are in the numerator of the alternatives' efficiency equation.

3.2.1. Hydraulic loading for baseline

Knowledge Program Sea Level Rise track 2 provides the hydraulic loading for the baseline; a water level frequency curve for every dike section of the Rhine-Meuse Estuary, without the implementation of any of the alternatives considered.

The current and future hydraulic loading is found using the Norm Giving High-water Processor Version 5 (Maatgevend Hoogwater processor versie 5 (MHWp5) in Dutch). Its input is based on the Rhine-Meuse Estuary hydraulic profile and the climate change effects.
MHWp5 is an overlaying program that connects multiple software modules and generates a database of physical hydraulic conditions with its 1D SOBEK3 module (Thonus, 2023).

The output of SOBEK3 consists of water depths for many different boundary conditions like sea water level, wind speed, and direction and river discharges.
The MHWp5 is used to calculate hydraulic loading of the Rhine-Meuse Estuary for up to 3 meters of sea level rise on the North Sea. Knowledge Program Sea Level Rise demands the effects of up to 5.4 meter sea level rise, the hydraulic loading from 3.0 to 5.4 meter sea level rise is qualitatively extrapolated.

The hydraulic boundary conditions are sourced from the Boundary Condition Generator Water Models V2.3.0 (RandvoorwaardenGenerator WaterModellen (BRGWM) in Dutch).
The module Golfgenerator V1.0.1 calculates corresponding wave heights for all water depths corresponding to the BRGM boundary conditions.
Finally these hydraulic conditions are collected in the HRD Generator (Databasegenerator) V1.2.0 and used by the HydraNL-module (Oerlemans et al., 2022).

HydraNL is a probabilistic model that calculates hydraulic loading statistics, a special version of this program (V2.8.3) is used for Knowledge Program Sea Level Rise.
Hydra-NL calculates water level frequency curves using statistic and probabilistic methods, where it considers many different combinations of probable boundary conditions like flood barrier closure failures and river discharge amounts (Duits, 2020).

Hydraulic loading has been modeled for the current year and the years 2050, 2100, 2150, and 2200. For the years 2050 up to 2200 four timelines were modeled, these timelines are representative of four climate change scenarios; Low, Moderate, Extreme and Very Extreme.
These timelines are not equal to the KNMI scenarios (KNMI is the Royal Dutch Meteorological Institute) but have been determined in very close deliberation between Rijkswaterstaat and KNMI.
Table 3.1 gives the boundary conditions of the Hydra-NL model for all timelines.
The river discharge scenarios are based on the "GL" and "WH" climate change scenarios. Where the first letter stands for the climate change temperature scenario and the second letter points to the expected influence of air flow pattern. GL represents moderate climate change with low influence form air flow patterns and WH higher climate change and high influence of air flow patterns (Zethof et al., 2023).

Table 3.1: Sea level rise and river discharges used for baseline (Zethof et al., 2023)

Timeline	Sea level rise with respect to 1995 [m]					River discharge scenario				
	2023	2050	2100	2150	2200	2023	2050	2100	2150	2200
N/A	0.05	-	-	-	-		-	-	-	-
Low	-	0.25	0.5	0.75	1.0	-	GL2050	GL2050	GL2050	GL2050
Moderate	-	0.25	0.75	1.3	2.0	-	GL2050	GL2100	GL2150	GL2200
Extreme	-	0.25	1.0	1.8	3.0	-	WH2050	WH2100	WH2150	WH2200
Very Extreme	-	0.25	2.0	3.5	5.0	-	WH2050	WH2100	WH2150	WH2200

3.2.2. Hydraulic loading of alternatives

Knowledge Program Sea Level Rise track 4 provides the hydraulic loading for each of the four alternatives, in the form of water level frequency curves for each dike section of the Rhine-Meuse Estuary, only the ”Very Extreme” timeline is considered.
The impact of the alternatives has been modeled by manually altering the water level frequency curves from the baseline to include the desired effects of the alternatives.
For example; if a system measure is implemented that should keep a regions future hydraulic loading the same as the current one, this is manually altered in the water level frequency curves for the dike section in that specific region. For more complicated effects, a reservoir model has been utilized (Kolen et al., 2024).
A complete description of the measures, that the alternatives exist of, is given in section 4.4.

3.3. Effects on dike reinforcement

To determine the dike reinforcement cost reduction caused by the implementation of the alternatives (factor C in Equation 1.1) a program called OKADER is used.
OKADER is a Matlab based program designed to calculate the reduction of dike reinforcement cost as a result of river widening interventions. The program has been developed by HKV and Deltares and has been used by the High Water Protection Program (Hoogwaterbeschermingsprogramma (HWBP) in Dutch).
OKADER takes as input a extensive list of datasets which describe, for every dike section, the hydraulic loading, strength against this loading and dimensional and cost determining properties.
The full list of all input databases is given in Table 3.2, this table gives an overview of all factors that OKADER accounts for and uses in its calculations.

Table 3.2: Input databases for OKADER

Database	Content (per dike section)
Dike sections	Dike section numbers to be analyzed
Dike section length	Length dike sections
Norm	Accepted failure probability
Subsidence	Subsidence in mm/year
Fragility curve height	Fragility curve parameters height
Fragility curve macrostability	Fragility curve parameters macrostability
Fragility curve piping	Fragility curve parameters piping
Hydraulic loading	Water level frequency curves for multiple years
Dike reinforcement planning	Year of planned reinforcement from HWBP
KOSWAT database	Cost per unit for multiple reinforcement components
CBS price-level index	Cost factor to index from base-year
Max dike construction depth	Maximum dike depth possible without buyouts
Cost innovative piping measure	Cost of implementing innovative piping measure
KOSWAT database green dikes	Cost per unit for multiple reinforcement components
BAG existing buildings	Distance from dike to buildings & building function and area
Location dike toe	Distance of dike toe
Unit price buyout	List of buyout cost for different types of buildings

The hydraulic loading, in the form of water level frequency curves, is given for certain years; OKADER interpolates the hydraulic loading between these years.
The resolution of the calculations is dependent on the time-step, OKADER will calculate the probability of failure starting from the first year and then every time-step after that up until a given end year.

OKADER determines the failure probability of a dike section based on the hydraulic loading and the corresponding fragility curves, the higher the water level the more likely the dike section is to fail.
OKADER accounts for three different failure modes being, overtopping, macro stability and piping, because of the structure of available hydraulic loading data, only the latter two are considered in this research.

If the failure probability is higher than the law-given norm, OKADER calculates the reinforcement cost to keep the dike section up to norm for the next 50 years.
If the hydraulic loading is lowered during those 50 years OKADER will wait with the subsequent reinforcement until the hydraulic loading brings the dikes failure probability to the norm again (de Grave, 2024).

In this research the implementation of the alternatives is in the year 2100, meaning that the hydraulic loading follows the baseline up until that year and after 2100 follows the alternatives altered hydraulic loading. OKADER can deal with this in two different ways, the reduction in hydraulic loading can be used to increase the time between reinforcements or the dimension of the reinforcements.
For this research the time option is chosen, see Figure 3.2, the ”River widening” would be the implementation of the alternatives.

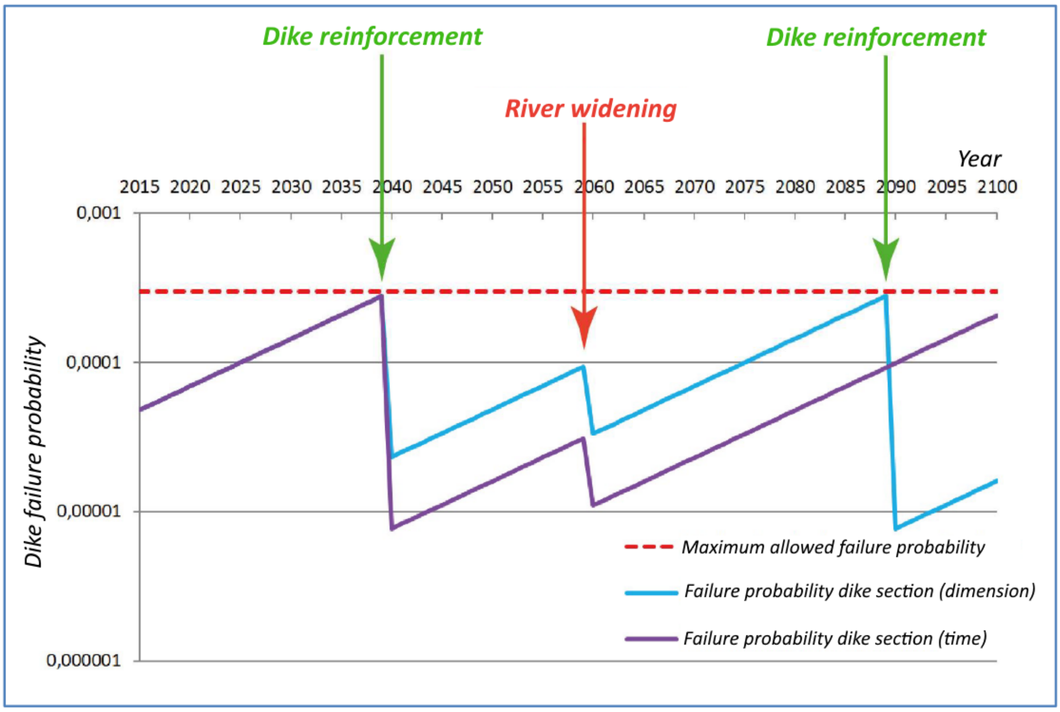


Figure 3.2: OKADER's method of determining when dikes will be reinforced and how hydraulic loading reductions will influence the reinforcements in time delay or dimension reduction, adapted from de Grave (2024).

OKADER's output is extensive; multiple dataframes for every single dike section.
For every dike section OKADER provides the failure probability for every considered failure mechanism for each time-step. As well as the monetary cost to bring the dike section back up to norm for the next 50 years, complete with a time-frame of when these reinforcements occur. Dimensional needs for the reinforcement are also calculated. The monetary cost is given for different reinforcement methods: traditional, using soil additions together with utilizing buyouts, and a combination of both.
In this research only the traditional method (variant 3A of OKADER) will be considered, meaning that the dikes will be widened using soil where possible, if a building makes this impossible a structural solution is applied (de Grave, 2024).
All economic factors in this research are made to present value with a discount rate of 1.6% using Equation 3.1, where r is the discount rate and n is the number of years to be discounted for (Nelen & Schuurmans & Deltares, 2024).

$$Present\ value = future\ value * \frac{1-(1-r)^n}{r} \tag{3.1}$$

OKADER does not only calculate the dike reinforcement cost reduction but also provides for the two non-economic indicators that will be considered in this research, as an effect of the alternatives.
The amount of dike reinforcements averted over the whole Rhine-Meuse Estuary will be calculated for each alternative as compared to the baseline, up until the year 2200.
The land use of the dike reinforcements, done with soil additions, depends on the hydraulic loading as well, this will be extracted from OKADER an summed for the whole Rhine-Meuse Estuary.

3.4. Flood risk reduction

The implementation of the alternatives will lower hydraulic loading, this leads to a lower frequency and severity of flooding for unembanked areas and a lower severity for the embanked; they stay to norm.
Flood risk reduction is given as factor A for the unembanked area and B for the embanked areas in Equation 1.1, the flood risk reduction will be calculated based on LIWO data.
LIWO stands for the National Database Water and Flooding (Landelijk Informatiesysteem Water en Overstromingen (LIWO) in Dutch), being a database of flooding scenarios.
These flooding scenarios are given for critical areas throughout the Netherlands for a multitude of outside water levels per breach location.
An example of an inundation map corresponding to a flooding scenario from LIWO is given in Figure 3.3.

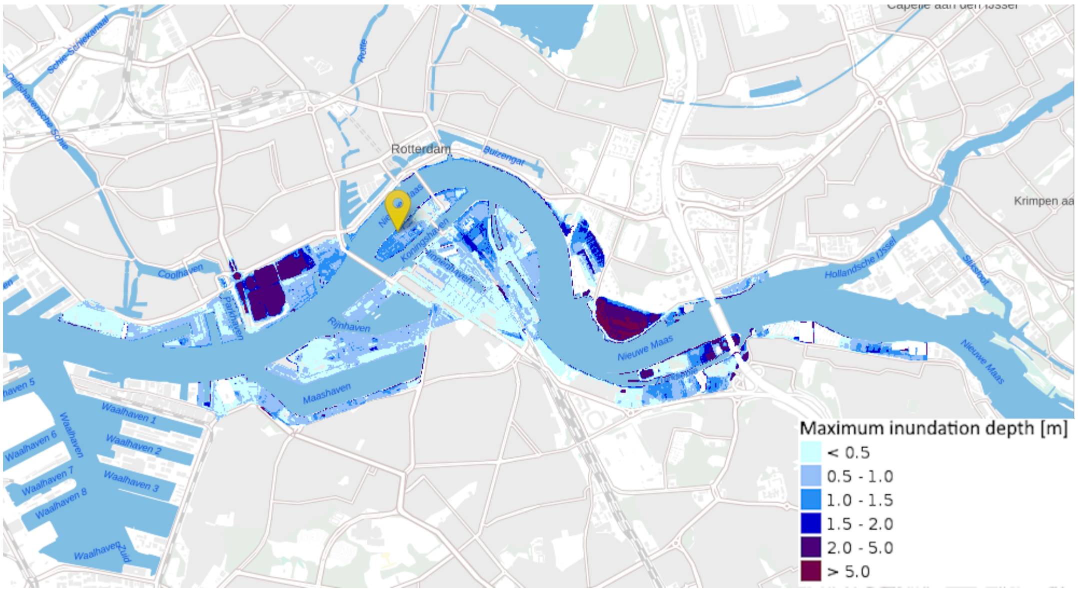


Figure 3.3: LIWO scenario Noordereiland; ID 198_Stedelijk Rotterdam (IenW, 2024b).

The most important principles of how LIWO scenarios were modeled are listed below (De Bruijn et al., 2018).

- Economic damage is determined by inputting a relatively course inundation map into a *Damages and Victims model* (Schade en Slachtoffer module (SSM) in Dutch).
- To determine fatalities, the rising rate of inundation is the most important factor, measured over the first 1.5 meters. Resolution of modeling has to be small enough to take into account railway tracks and similar objects.
- The most common hydraulic modeling software used is a 1D2D Sobek model. This type of model combines a relatively fast 1D model for the main waterway and utilizes a 2D grid to acquire inundation depth and rising rates.
- Flooding patterns are determined by ”outside” water conditions, the moment a breach occurs, how a breach grows, the areas elevation profile, presence of obstacles and the areas' roughness factor.
- For roughness the *Nikuradse* winter roughness is used, this parameter is based on the land use characteristics.
- For the breach the standard is one breach per dike trajectory or more when the location of the breach is significant in determining the consequence.
- A breach is modeled by lowering the crest of the dike to ground level in 10 minutes, initial breach width is set to 10 meters followed by widening according to the *Verheij-van der Knaap* formula.

The scenarios in LIWO give economic damage- and fatality estimations for multiple water levels.
To calculate the reduction in flood risk, that the implementation of the alternatives would result in, a damage and fatality curve is created. This curve consists of a damage and fatality estimations for all relevant water levels for a certain flooding location.
The damage and fatality curves are created by extrapolating the available data from LIWO.
The damage and fatality curves will be multiplied by the relevant, corresponding frequency, resulting in the estimated annual damage (EAD) and estimated annual fatalities. Doing this for the baseline and with the alternatives implemented makes it possible to determine the flood risk reduction as a results of the alternatives. For the formula used to calculate the EAD see Equation 3.2 (Nelen & Schuurmans & Deltares, 2024), T is return period and S is the corresponding damage.
All economic factors in this research are made to present value with a discount rate of 1.6% see Equation 3.1.

$$EAD = \frac{1}{T_1} * S_1 + (\frac{1}{T_2} - \frac{1}{T_1}) * \frac{S_1 + S_2}{2} + (\frac{1}{T_3} - \frac{1}{T_2}) * \frac{S_2 + S_3}{2} + ..etc. \tag{3.2}$$

Because of limited LIWO data quality and quantity three locations in the Rhine-Meuse Estuary will be used as a reference to determine the flood risk reduction effects of the alternatives.
The expectations of where the alternatives will be impactful, amount of available flooding scenarios per location, and considered spatial planning scenarios, leads to three locations that will be considered.
One unembanked location being the Noordereiland in Rotterdam, and two embanked regions; the city of Vlaardingen and the rural municipality of the Hoeksche Waard.

Flood risk reduction is also where spatial planning starts to play a role.
Three spatial planning strategies are considered; densification, moving to unembanked and developing rural areas. These spatial planning strategies will affect the amount of dwellings considered for each location. The ratio of current number of dwellings to future number of dwellings will be used to scale the damage curves and thus the flood risk estimations.
The initial flood risk reduction will be calculated with the most likely spatial planning strategy being densification. After that, the other two are considered and their effects on the alternatives flood risk reduction calculated.

3.5. Economic efficiency

With the alternatives' reduction of dike reinforcement cost (C) and the reduction in flood risk of the unembanked and embanked areas (A and B, respectively), the economic efficiency can be calculated.
The economic efficiency is determined by four factors as can be seen in Equation 3.3, in the numerator are the alternatives' benefits as compared to the baseline and in the denominator is the cost of the alternative implementation.

$$Economic\, efficiency\, of\, alternative = \frac{A + B + C}{D} \tag{3.3}$$

Where:

$$A = reduction\, of\, flooding\, probability\, and\, effect\, of\, unembanked\, areas\, [€]$$
$$B = reduction\, of\, flooding\, effect\, of\, embanked\, areas\, [€]$$
$$C = reduction\, of\, dike\, improvement\, costs\, [€]$$
$$D = cost\, of\, alternative\, system\, measures\, [€]$$

The reduction in flood risk of the unembanked and embanked areas (A and B) are determined for three locations within the Rhine-Meuse Estuary, while the reduction of dike reinforcement cost (C) and the cost of the alternative system measures (D) is calculated for the whole Rhine-Meuse Estuary.
This is why the latter two factors need to be normalized, this is done by factoring them to the amount of dwellings in the flood risk determined areas to the amount of total dwellings affected.
In this research the total number of dwellings affected is taken as all dwellings within the relevant waterboards of the Rhine-Meuse Estuary.

4

Hydraulic characteristics and loading

The hydraulic loading will be the main input parameter for the dike reinforcement cost reduction estimation and the flood risk estimations. The implementation of the alternatives will lower the hydraulic loading leading to less need of dike reinforcement, lower flooding damages and a lower flooding frequency for unembanked areas.
This chapter start with a description of the hydraulic characteristics of an estuary and the factors that influence the hydraulic loading. Specifying the hydraulic characteristics, with their origins, of the Rhine-Meuse estuary and describing the human interventions made on the hydraulic system.
The hydraulic measures, that the alternatives consist out of, are given and described extensively.
And finally, the alternatives' impact on the hydraulic loading, on the three reference locations for the flood risk determination, is given.

4.1. Estuaries

Pritchard (1967) defines an estuary as the following: *"An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage"*.
The hydraulic loading of an estuary is governed by discharge waves from rivers, tides, waves, and wind. Hydraulic characteristics of an estuary are governed by the bathymetry, and geometrics like the width of the entrance and the length of the estuary itself.
Estuaries are often a source of fertile land, combined with sources of fresh water, makes them favored places to live; 21 of the worlds 30 largest cities in the world are located near estuaries.
Sea level rise has a significant impact on hydraulic loading of an estuary, not only by the sea level rise itself; tidal ranges can increase 10 to 20% per meter of sea level rise. Simultaneously, peak monthly river discharges are also expected to increase in the future due to climate change (Falloon & Betts, 2006; Khojasteh et al., 2020).

4.2. The Rhine-Meuse estuary

The Rhine-Meuse Estuary, as the name implies, is the region surrounding the branches from the Rhine; the Lek and the Waal, and the Meuse. The general shape of this region was formed in the Pleistocene era, hundreds of thousands years ago, when the rivers Rhine and Meuse found their way into the North sea all the way from their origins in the center of Switzerland and the Northeast of France. The current stream patterns can be largely traced back to the advancing and retreating of ice sheets, which shaped deep valleys and ridges (Nienhuis, 2008).
The Rhine-Meuse Estuary acquired a character more closed off of the sea after *sandy barriers* (strandwallen in Dutch) were formed between land and sea around 3000 BC. A flooding, occurring around 1500 BC, formed the current Meuse breach (Maasmonding in Dutch), where the Nieuwe Waterweg and Hartelkanaal are presently.

The infamous St. Elizabeth Flood in 1421 AD put large parts of the Rhine-Meuse Estuary under water and breached a new outlet to the sea; the Haringvliet. In the years after this great flood large parts of were embanked. The construction of these dikes would set, for a large part, the current profile of the Rhine-Meuse Estuary.
In the most recent three centuries the rivers were channelized and deepened, while large swathes of land were (re)claimed and embanked (Maas, 2000).

The most recent highly defining event for the Rhine-Meuse Estuary was the Great Flood of 1953 (De Watersnoodramp in Dutch). A terrible flood covering 150.000 hectares of land with over 1800 fatalities as a result. The hydraulic conditions of this storm have a combined return period of a relatively low 200 years but still led to grave consequences.
To prevent this from happening ever again the Deltaplan was initiated. By shortening the coastline, using a combination of dams and flood barriers, the to be protected length of dikes would be greatly reduced. These dams, flood barriers and dike reinforcements were all based on the "Delta level"; the water level that corresponded to a 4000 year return period (Goemans & Visser, 1987).
A map showing all dams and flood barriers build through the Deltaplan, with corresponding year of construction, is given in Appendix A.

4.2.1. Rhine-Meuse estuary hydraulic profile

The hydraulic profile of the Rhine-Meuse estuary is governed by the discharge from the Rhine, Meuse and water level on the North Sea. In Figure 4.1 the main rivers, waterways and flood barriers of the Rhine-Meuse Estuary are shown.
There are five main rivers coming into the estuary; the Hollandse Ijssel, Lek, Beneden Merwede, Nieuwe Merwede, and the Bergsche Maas.
The Lek is an offshoot from the Rhine, the Nieuwe Merwede and Beneden Merwede from the Waal (another offshoot from the Rhine) and the Bergsche Maas from the Meuse.
The Hollandsche Ijssel is dammed off from the Rhine and is only supplied with minimal discharge from multiple pumping stations that discharge (in)directly on this water body.

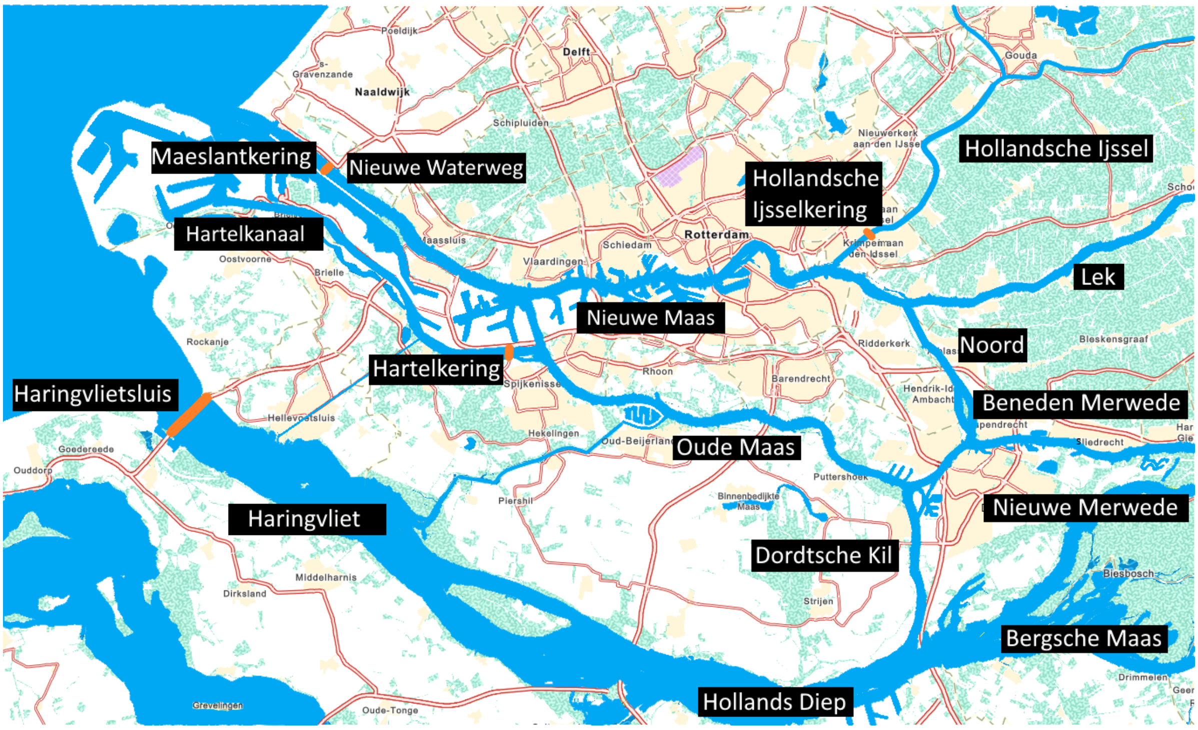


Figure 4.1: Main rivers, waterways and flood barriers of the Rhine-Meuse estuary.

Year-averaged discharge volumes for the main rivers of the RMe are shown in Figure 4.2, based on data acquired in 2006.
The discharge going through Rhine branch, the Waal, is a multitude higher than that of the Rhine branch Lek and the river Meuse. Water finds its way to sea mostly via the Nieuwe-Waterweg.

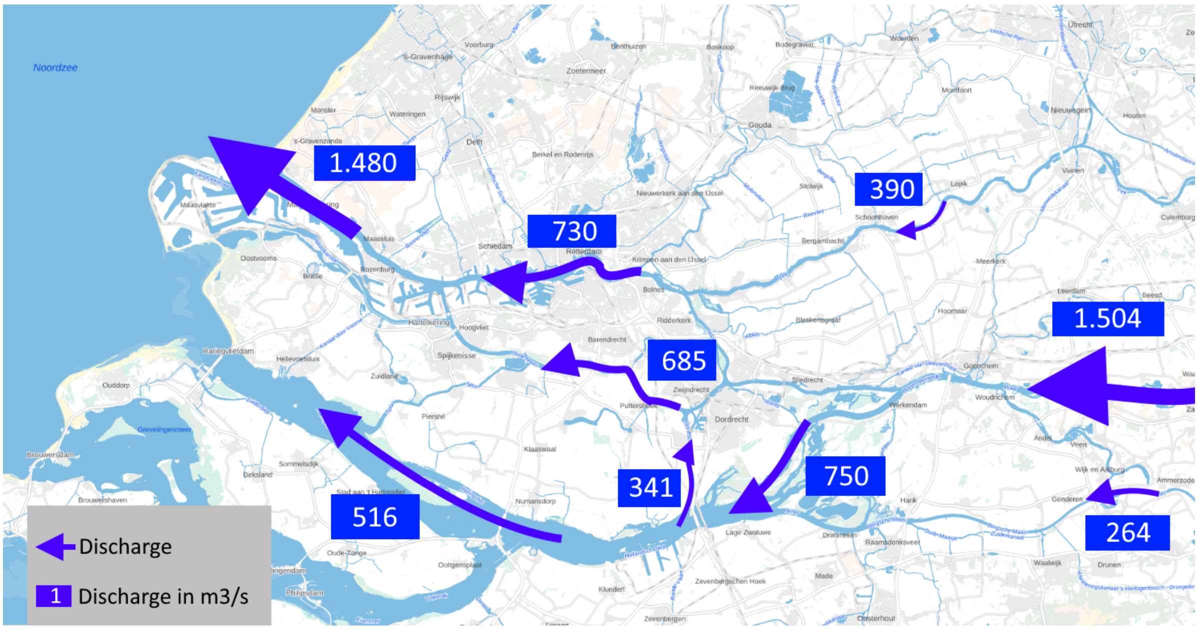


Figure 4.2: Year-averaged discharges through the main rivers Rhine-Meuse estuary, adapted from Vellinga et al. (2014).

Protection from high sea water levels is provided by four very large flood barriers, these flood barriers were all build following the Deltaplan. The maximum accepted failure probabilities of these flood barriers are set in the Environment and Planning Act (Omgevingswet in Dutch), section Decision on quality of living environment (Besluit kwaliteit leefomgeving in Dutch) as shown in Table 4.1.

Table 4.1: Acceptable failure probability of flood barriers, in order of construction year (BZK, 2024)

Flood barrier	Accepted failure probability	Type of failure
Hollandsche Ijsselkering	1/200	Failure to close
Haringvlietsluis	1/1000	Protection level
Maeslantkering	1/100	Failure to close
Hartelkering	1/10	Failure to close

These flood barriers lower the hydraulic loading by closing the entrance ways into the Rhine-Meuse Estuary. Each flood barrier has a predetermined water level that will start the closure procedure.
The Maeslantkering, Hollandsche Ijsselkering and Hartelkering are closable flood barriers, instead of permanent dams, because of shipping demands. For the Haringvlietsluis the ecological aspect of keeping tidal flow was the deciding factor to be a closable flood barrier.

4.2.2. Regions of dominant hydraulic conditions

Combining the influence on hydraulic loading of the rivers' discharges, the North Sea and the protection from flood barriers, described in subsection 4.2.1, the Rhine-Meuse Estuary can be divided in areas by what conditions dominate hydraulic loading.
These so-called "regions of dominant hydraulic conditions" give insight into what process or condition is the most dominant factor for the hydraulic loading of a specific area, in Figure 4.3 the six defined regions are given.

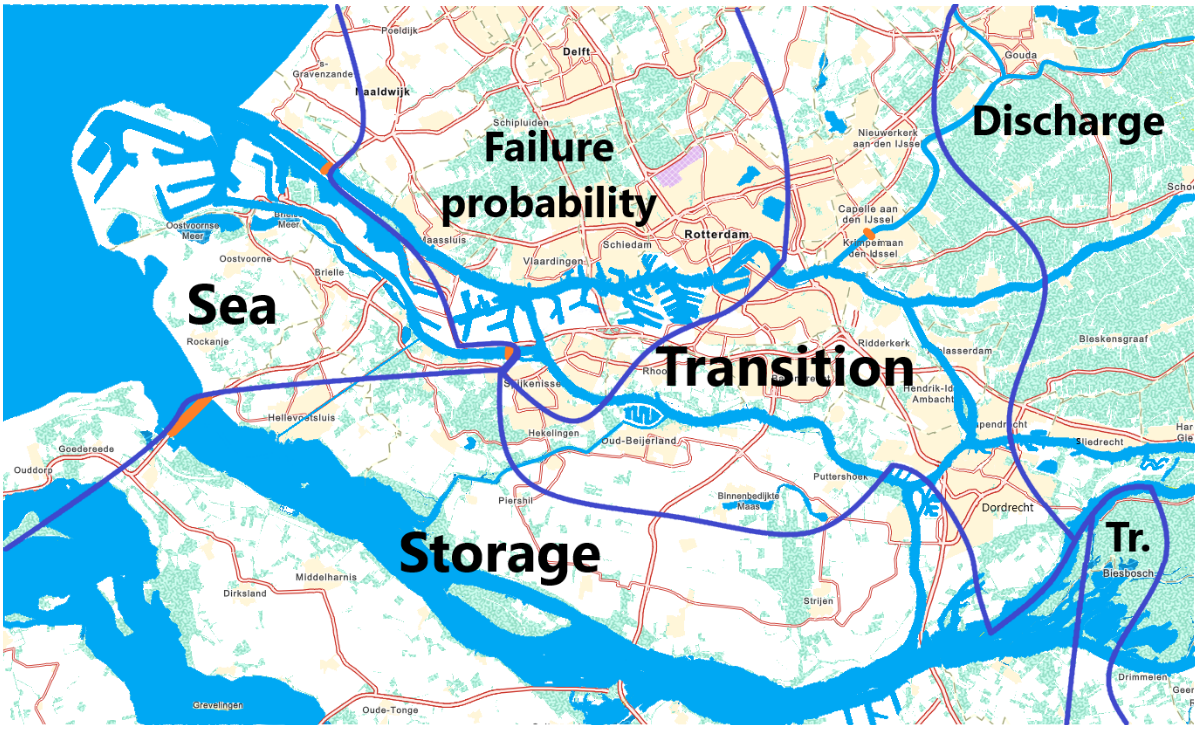


Figure 4.3: Regions of dominant hydraulic conditions, adapted from Kramer et al. (2017).

Beginning on the west side, the North Sea is the dominant hydraulic loading up until the three main flood barriers; The Maeslantkering, Haringvlietsluis and the Hartelkering.
The hydraulic loading just behind the Maeslantkering and Hartelkering is governed by the failure probability of said barriers. Behind the Haringvlietsluis, on the Haringvliet and Hollands Diep, the storage capacity/usage of these water bodies is dominant for the hydraulic loading.
On the East side of the RMe the peak discharges of the rivers Rhine, Meuse and Waal are the determinative factors on the hydraulic loading on embanked and unembanked areas.
Finally, in between the river discharge dominated and storage/failure probability dominated areas are the transition zones. The transition zones are dominated by both river discharges, and failure probability/storage capacities, depending on conditions and the location within these zones.

An important note here is that these dominant hydraulic regions are determined by the current parameters of the rivers, waterways, the North Sea and implemented hydraulic structures.
The implementation of large scale hydraulic interventions like those that are part of the alternatives, described in section 4.4, will most likely alter these regions quite dramatically.

4.3. Hydraulic loading baseline

This section will give an example of the increase of hydraulic loading that is expected for the baseline, all hydraulic loading is given as water level frequency curves that consists of expected water levels for all relevant return periods.
To determine the benefit of the alternatives (factors A,B and C) the dike reinforcement cost and flood risk are determined with the hydraulic loading following the baseline, then compared to the same factors but with the hydraulic loading following the alternatives.

All mentioned aspects in section 4.2, that influence the hydraulic profile of the Rhine-Meuse Estuary, were used to calculate the hydraulic loading, how these water level frequency curves were determined is described in subsection 3.2.1.
Knowledge Program Sea Level Rise track 2 provides water level frequency curves for all dike sections in the Rhine-Meuse Estuary for the years 2023, 2050, 2100, 2150 and 2200.

Figure 4.4 shows the water level frequency curve for the years 2023, 2100 and 2200 near Noordereiland, a dense and unembanked urban area in the middle of the lower Rhine-Meuse Estuary. This type of increase can be seen in a very similar way for almost all of the Rhine-Meuse Estuary especially on the water bodies that are primarily hydraulically loaded by the North Sea.
The hydraulic loading for the Noordereiland is taken as the hydraulic loading of dike section 14002008, this dike section is right next to the Noordereiland along the river Nieuwe Maas.

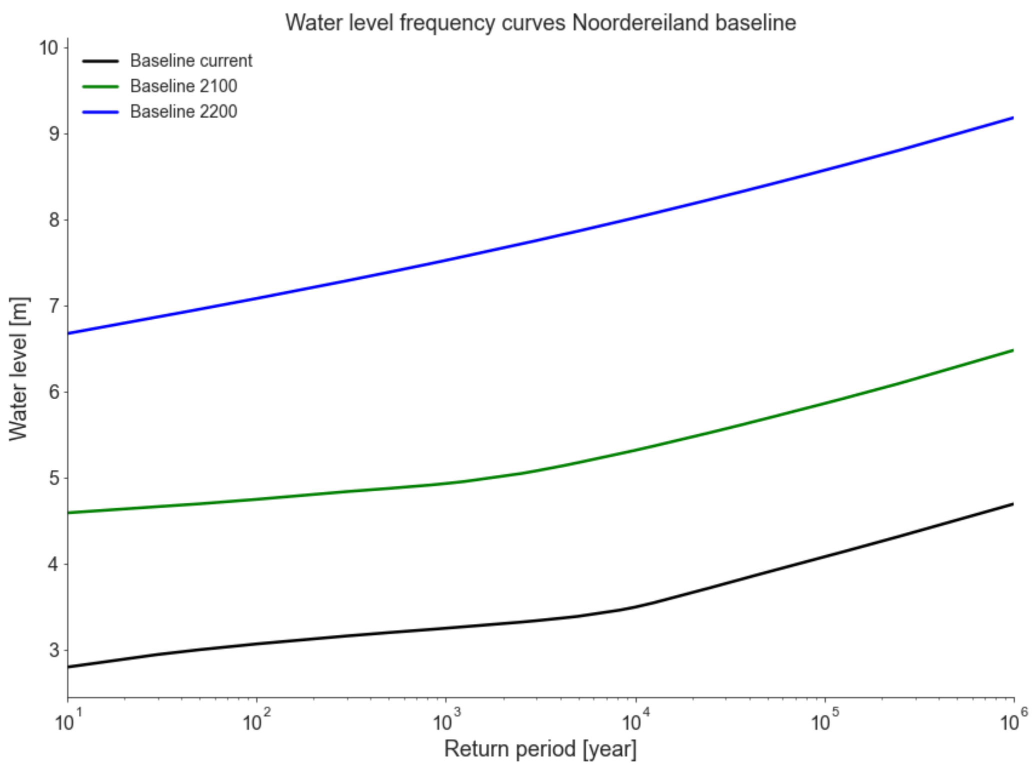


Figure 4.4: Hydraulic loading, as water level frequency curves, for Noordereiland following baseline.

It is clear that for all return periods the expected water level will rise significantly from 2023 to 2100 and even more from 2100 to 2200.
If no large scale interventions are implemented (like the alternatives described in section 4.4), this increase in hydraulic loading will result in significant dike reinforcement needs and added flood risk of all areas within the Rhine-Meuse Estuary.

4.4. Considered alternatives

This chapter will describe the measures that the alternatives consist out of and give examples of their reduction of hydraulic loading when implemented, as opposed the baseline.
Knowledge Program Sea Level Rise track 4 has proposed four different strategies, which will be described in this section.
The implementation of these strategies (constructing the system measures according to a strategy) combined with the reinforcement of dikes to keep them up to norm current is called an alternative.
These alternatives are different ways to protect the Netherlands against the expected hydraulic loading increase based on the "Very Extreme" timeline of Knowledge Program Sea Level Rise track 2 (baseline).

If the current method of protecting the Netherlands against flooding an securing fresh water supply, which is given in the Deltaprogram 2015, does not suffice anymore the proposed strategies could offer necessary additional protection from climate change effects (IenW & EZK, 2014).
The strategies consist of system-level interventions such as building dams at sea entrances and pumping stations to pump out excess river discharge.

The alternatives are build up out of *system choices* and *building blocks*.
A system choice is a location exceeding choice, like the choice if there will be a closable flood barrier, or permanent dam, between the sea and estuary, or if the river discharge distribution will be altered.
These system choices will determine for a large part how the hydraulic loading will be altered on the Rhine-Meuse Estuary wide level.

Building blocks are physical measures taken to reduce hydraulic loading or salt intrusion, the list of building blocks used for track 4:

- Sluices, locks, flood barriers
- Pumping stations
- Dikes and dams
- Sandy coast
- Unembanked areas

Combinations between the building blocks and system choices were made to form the alternatives.

A collective of representatives from the most relevant hydraulic construction companies, Rijkswaterstaat and the Deltaprogram were asked for their insights. Five *hackatons* were organized for this, were the principles and boundary conditions were shared (van der Biezen et al., 2024).
In every subsequent hackaton the solutions became increasingly concrete and these eventually led to the four alternatives that are described in the next four subsections.
In the next four subsections an extensive list of measures and principles of each alternative is given, all sourced from the main report of Knowledge Program Sea Level Rise direction "Protection" (van der Biezen et al., 2024).

4.4.1. Alternative A1 (Closed seafront, keeping current water level)

Alternative A1 is characterized by a closed seafront, where the water level on the inside of this seafront is kept close to Normal Level at Amsterdam (Normaal Amsterdams Peil (NAP) in Dutch).
The inside water level is kept to the desired level by discharging excess water at low tides through outlets and later, when higher sea levels are expected, by using large pumping stations.
In addition to pumping stations, to protect unembanked areas, the river discharge will be stored in added reservoir capacity within the Delta area.
Most of the logistics between sea shipping and inland shipping has to go over land or via sluices.

To keep salt intrusion to an acceptable level, innovative sluices would have to be implemented.
This alternative leads to the water level corresponding to a return period of 10.000 years, within the Rhine-Meuse estuary, being similar to current ones.
To preserve the fresh water supply, extra reservoir capacity is added on the Ijsselmeer, Markermeer and in the South West Delta. These buffers hold extra fresh water for when a drought is expected.
The reservoir water levels are kept in such a way that unembanked areas are not exposed to more flood risk and will be lowered when there is a forecast for high water on the North Sea and high river discharge. A simple visualization of alternative A1 is given in Figure 4.5.

A list of system choices that have been made for alternative A1 is given:

- Seafronts will be closed with dams or locks with virtually no salt intrusion.
- Intended daily water levels:
  - NAP on the Westerschelde, South West Delta, and Rhine-Meuse Estuary.
  - NAP -0.4 m for the Amsterdam-Rijnkanaal.
  - NAP -0.4 m for the Ijsselmeer in the winter and NAP -0.2 m in the summer.
- A reservoir capacity of $1000\,\mathrm{km}^2$ in the Rhine-Meuse estuary and South West Delta.
- Necessary pumping capacities:
  - Rhine-Meuse Estuary and South West Delta $5000\,\frac{\mathrm{m}^3}{\mathrm{s}}$ corresponding to 2 meters sea level rise and $15\,500\,\frac{\mathrm{m}^3}{\mathrm{s}}$ for 5.4 meter sea level rise.
    These amounts are based on keeping the increase of flood risk of unembanked areas to a minimum.
  - $600\,\frac{\mathrm{m}^3}{\mathrm{s}}$ for the Westerschelde and an addition to the existing pumping capacity of $100\,\frac{\mathrm{m}^3}{\mathrm{s}}$ to serve the Amsterdam-Rijnkanaal and Noordzeekanaal.
  - An estimation for the Ijsselmeer is $1200\,\frac{\mathrm{m}^3}{\mathrm{s}}$, this capacity does not remove the need for dike reinforcements.
- Two fresh water reservoirs are created; for this function the water level on the Ijsselmeer and Markermeer can increase by 1 meter. For the Rhine-Meuse Estuary and the South West Delta an increase up to NAP +2.0 m is possible, this would not cause significant negative effects on the unembanked areas.
- Planning the usage of the fresh water reservoir capacities is necessary to keep inner water levels from impacting dike reinforcement needs as well as the flood risk of unembanked areas.

4.4.2. Alternative A2 (Closed seafront, rising water level)

Alternative A2 is very similar to A1 in keeping a closed seafront, the difference lies in the fact that the inside water level will rise along the North Sea level to keep discharging water at low tide possible. When the tide is low on the North Sea the river discharge can be let out, the discharge gates close again when the tides turn.
Because of the rising water levels on the inside of the water system the unembanked areas will experience higher hydraulic loading.

Opposed to the Rhine-Meuse Estuary and the South West Delta; the Amsterdam-Rijnkanaal, Noordzeekanaal and the Ijsselmeer will have the same intended water level as the current ones.
The fresh water reservoir on the South West Delta will be larger than the one of alternative A1 because there is a larger tidal discharge capacity. A simple visualization of alternative A2 is given in Figure 4.5.

A list of system choices that have been made for alternative A2 is given:

- Seafronts will be closed with dams or locks with virtually no salt intrusion.
- Intended water levels:

- Rising along with North Sea level on the Westerschelde, South West Delta, and Rhine-Meuse Estuary.
- NAP -0.4 m for the Amsterdam-Rijnkanaal.
- NAP -0.4 m for the Ijsselmeer in the winter and NAP -0.2 m in the summer.

- A reservoir capacity of $1000\,\mathrm{km}^2$ in the Rhine-Meuse estuary and South West Delta.
- Necessary pumping capacities:
  - Rhine-Meuse Estuary and South West Delta $3000\,\frac{\mathrm{m}^3}{\mathrm{s}}$
  - An addition to the existing pumping capacity of $100\,\frac{\mathrm{m}^3}{\mathrm{s}}$ to serve the Amsterdam-Rijnkanaal and Noordzeekanaal.
  - An estimation for the Ijsselmeer is $1200\,\frac{\mathrm{m}^3}{\mathrm{s}}$, this capacity does not remove the need for dike reinforcements.
- Two fresh water reservoirs are created; the water level on the Ijsselmeer and Markermeer can increase by 1 meter.
- Because of the tidal discharge possibilities the water levels on the Rhine-Meuse Estuary and South West Delta can be emptied relatively quickly as compared to alternative A1.

4.4.3. Alternative B1 (Closable seafront, same discharge distribution)

For this alternative the North Sea front is not closed permanently but closable flood barrier are utilized, this for the Rhine-Meuse Estuary, South West Delta and the Westerschelde.
The probability of failure when closing the flood barriers is greatly decreased; to 1 in 10.000 closing demands. Similar to Alternatives A1 and A2 there are pumping stations to discharge the river discharges and there will be reservoir capacity for the peak discharge situations.

The water level for which the flood barriers will close will rise partially along sea level rise, this will keep the closing frequency within acceptable limits. Expected is for 2 and 3 meters sea level rise would result in 6 closures per year, for 5.4 meters it would mean almost daily necessary closures.
Still, there are variants of this alternative that have a higher closing level which will reduce the amount of closures. The North Sea front of the Ijsselmeer, Amsterdam-Rijnkanaal and Noordzeekanaal are the same as in strategies A1 and A2.
Fresh water reservoir capacity will be added on the Ijsselmeer and Markermeer in the same manner as for strategies A1 and A2.
A simple visualization of alternative B1 is given in Figure 4.5.

A list of system choices that have been made for alternative B1 is given:

- Seafronts of the Rhine-Meuse Estuary and South West Delta (including the Westerschelde) will be closed with flood barriers. The failure probability of closure will be 1 in 10.000 closure demands. The inside water level will be kept so that the closure frequency is around 6 times a year.
- Intended water levels:
  - NAP -0.4 m for the Amsterdam-Rijnkanaal and Noordzeekanaal.
- A reservoir capacity of $690\,\mathrm{km}^2$ in the Rhine-Meuse estuary and South West Delta made out of the Haringvliet, Grevelingen and Volkerak-Zoommeer.
  The Oosterschelde and Westerschelde will be not utilized for this reservoir capacity.
  Just like alternative A2, there will be lower reservoir capacity than A1 because of the higher starting water level on the inside of the barriers.
- A reservoir capacity of $2000\,\mathrm{km}^2$ on the Ijsselmeer and Markermeer where the water level can increase by 1 meter.
- Necessary pumping capacities:
  - Rhine-Meuse Estuary and South West Delta $3000\,\frac{\mathrm{m}^3}{\mathrm{s}}$.

- An addition to the existing pumping capacity of $100\,\frac{m^3}{s}$ to serve the Amsterdam-Rijnkanaal and Noordzeekanaal.
- An estimation for the Ijsselmeer is $1200\,\frac{m^3}{s}$, this capacity does not remove the need for dike reinforcements.

4.4.4. Alternative B2 (Closable seafront, changed discharge distribution)

Alternative B2 has the same North Sea front as B1; movable flood barriers with a very low closure-failure probability. The difference lies inland; a different discharge distribution for the main rivers of the Rhine-Meuse Estuary. When the river discharge coming into the Netherlands is higher than $12\,000\,\frac{m^3}{s}$ the rivers Boven-Rijn, Waal, Boven-Merwede, Nieuwe-Merwede, Hollands Diep and the Haringvliet will guide this water to the North Sea, this main water corridor is inspired by the Beaufort plan (Beaufort, 2021).
The Meuse will also be connected to this corridor at the Dutch town of Lith.
The Haringvliet will have a movable flood barrier that will only close at extreme North Sea conditions or when salt intrusion happens at a high rate.
The South West Delta will be connected to the Haringvliet, creating reservoir capacity.
There is a possibility to let the sediment settle in the corridor creating opportunities for nature development, however this would lead to an increase in hydraulic loading on adjacent dikes.

By relieving Rotterdam and Dordrecht from high river discharges the water level in this *Deltapolder* will be constant around NAP. The Deltapolder is closed of the North Sea and has sluices on the Spui, Dordtse Kil and the Beneden Merwede.
The river Lek discharges on this Deltapolder and a pumping station ensures the inside water level stays at NAP. The Lek and Ijssel are very much relieved in this alternative but can be utilized in the case of low river discharges to keep the fresh water distribution sufficient. A simple visualization of alternative B2 is given in Figure 4.5.

A list of system choices that have been made for alternative B2 is given:

- The creation of a high water level corridor on the Waal, discharging into the North Sea through the Haringvliet.
- The Haringvliet will be separated from the North Sea with a movable flood barrier and will be a part of a reservoir together with the South West Delta.
- When the incoming discharge into the Netherlands is larger than $12\,000\,\frac{m^3}{s}$ the excess is discharged through the Waal.
- In the rivers Beneden Merwede, Dordtse Kil and the Spui new locks will be realized that act as a dam. The Nieuwe Waterweg will be closed of from the North Sea, creating the Deltapolder having a water level equal to NAP.
- The Westerschelde will stay an open estuary, the water level within the Noordzeekanaal and Amsterdam-Rijnkanaal will be NAP -0.4 m.
- A fresh water reservoir capacity of $2000\,\mathrm{km}^2$ on the Ijsselmeer and Markermeer similar to Alternative A1 and A2. A Fresh water reservoir in the Rhine-Meuse Estuary of $120\,\mathrm{km}^2$ with a water level fluctuation of 2 meters.
- Necessary pumping capacities:
    - For the Deltapolder to discharge the water coming in from the Lek; $3000\,\frac{m^3}{s}$.
    - An addition to the existing pumping capacity of $100\,\frac{m^3}{s}$ to serve the Amsterdam-Rijnkanaal and Noordzeekanaal.
    - An estimation for the Ijsselmeer is $1200\,\frac{m^3}{s}$, this capacity does not remove the need for dike reinforcements.
- Unembanked areas outside of the Deltapolder will need extra measures to keep flood risk of these areas acceptable. Expected is that, especially adjacent to the high water level corridor, the

hydraulic loading increase will lead to added necessary dike reinforcements.

A visualization with the most important aspects of the four alternatives is given in Figure 4.5.

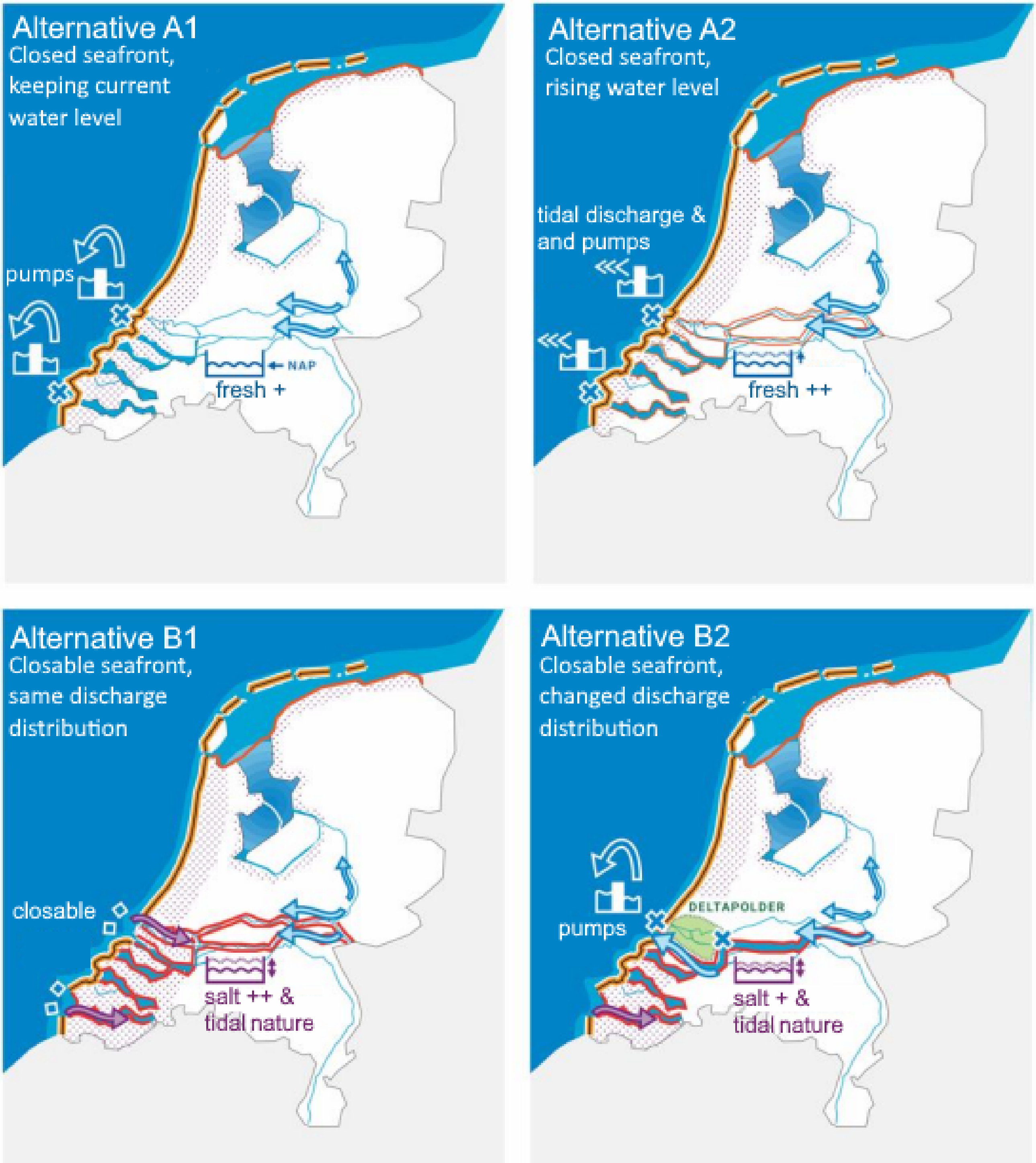


Figure 4.5: Symbolization of the four alternatives, adapted from van der Biezen et al. (2024).

4.5. Alternatives' impact on hydraulic loading

The influence of the alternatives on hydraulic loading is determined for each alternative by altering the water level frequency curves from the baseline.
How the water level frequency are altered is explained in subsection 3.2.2, the desired effects of the alternatives is translated into the water level frequency curves of the relevant dike sections.

To give an example the water level frequency curves for the baseline, and for each of the alternatives, is given for dike section 14002008 next to Noordereiland in the year 2100 in Figure 4.6 and the year 2200 in Figure 4.7.

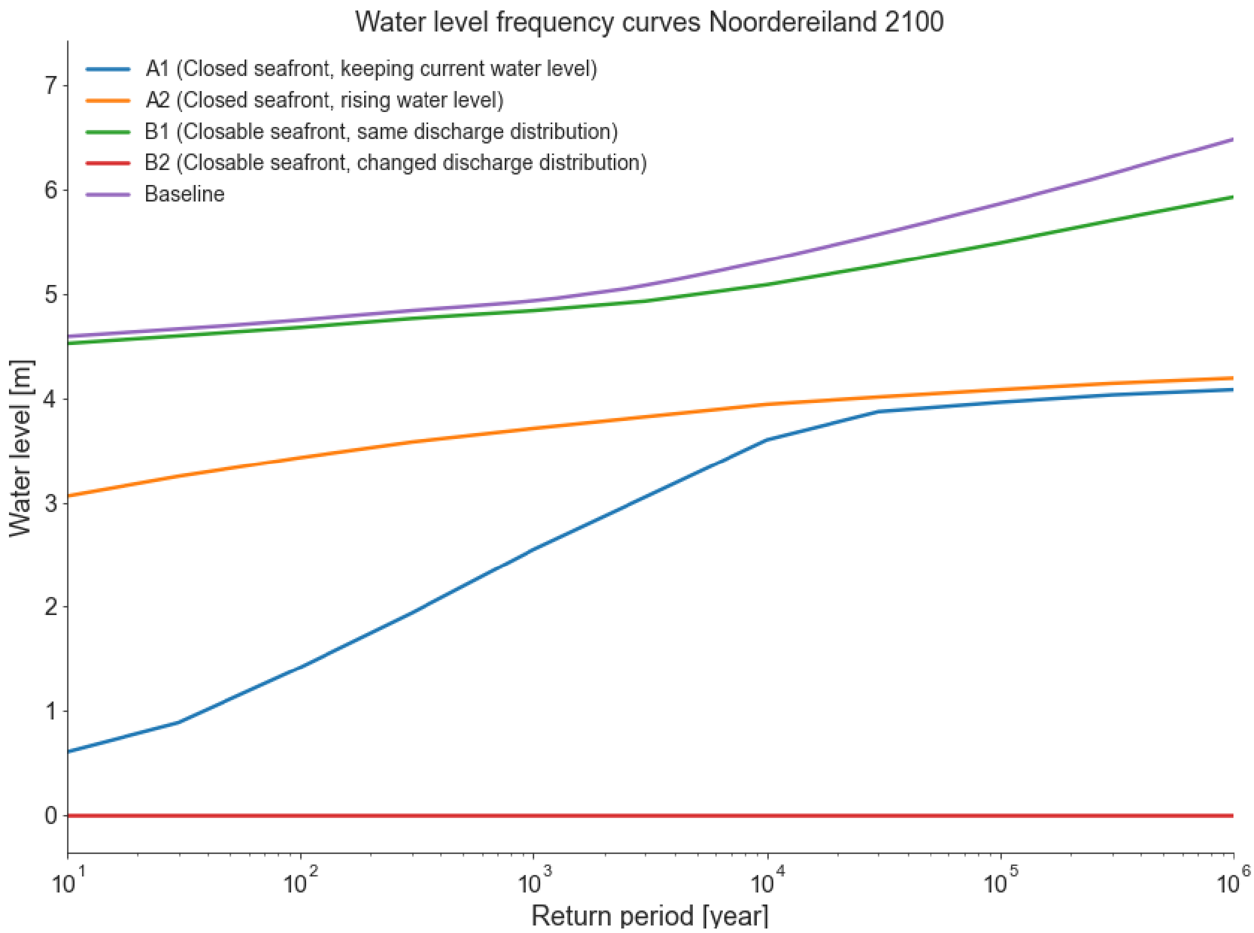


Figure 4.6: Hydraulic loading for Noordereiland in 2100 for baseline and alternatives

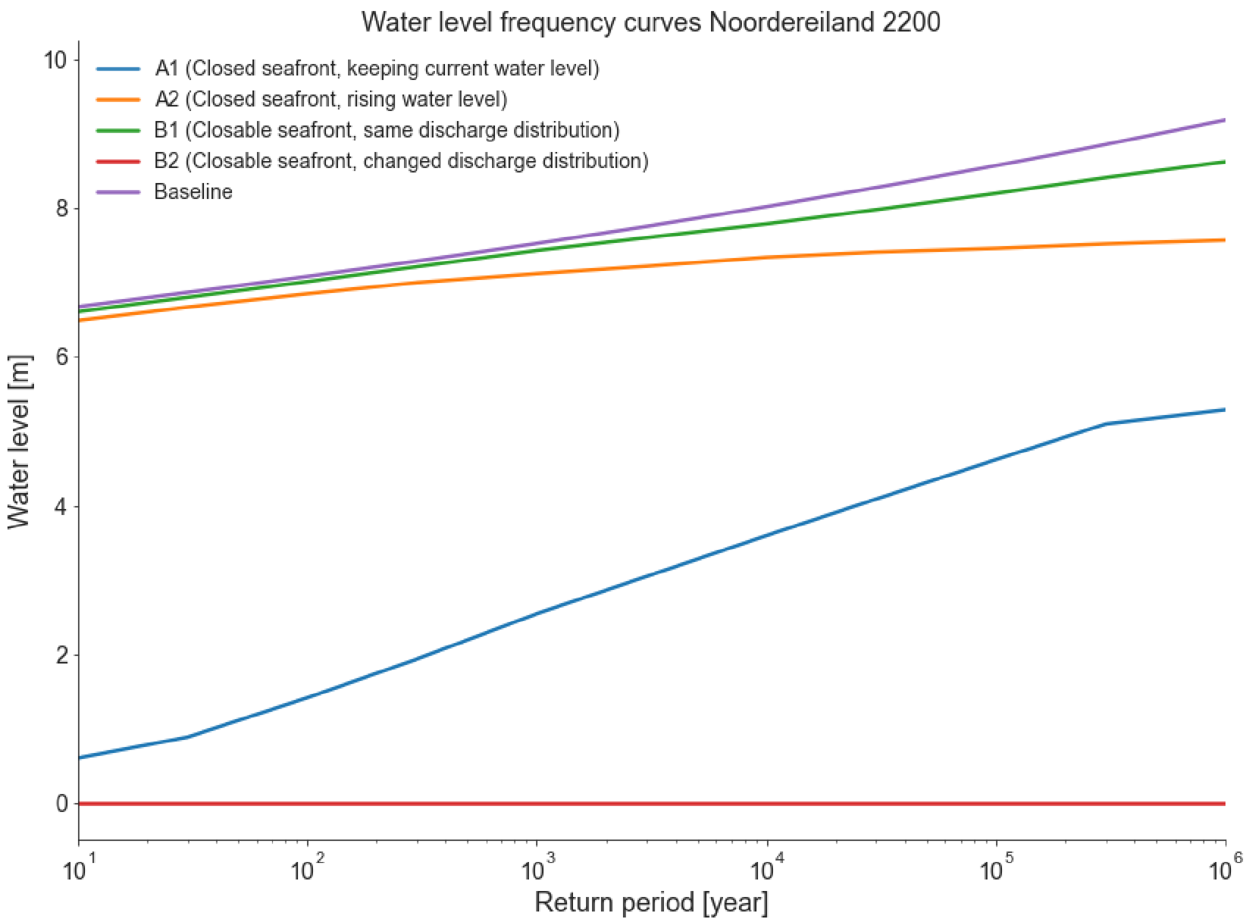


Figure 4.7: Hydraulic loading for Noordereiland in 2200 for baseline and alternatives

In these figures we can clearly see that the hydraulic loading of the baseline is the highest for all return periods, in line with expectations.

- The hydraulic loading corresponding to when alternative A1 is applied is vastly reduced compared to the baseline especially for the lower return periods.
- Alternative A2 causes a significant reduction of hydraulic loading in 2100 but this diminishes to almost nothing in 2200, a result of the internal rising water level that is accepted for this alternative.
- Alternative B1 has almost no reduction in hydraulic loading, neither in 2100 or 2200, only a very small reduction can be seen in the extremely high return periods.
- Alternative B2 is so impactful, for the area that this dike section resides in, that the hydraulic loading is modeled as being equal to zero, all hydraulic loading is mitigated by the measures corresponding to this alternative.

Water level frequency curves are given for the locations that are used as reference in the flood risk reduction determination in Appendix B and Appendix C for a dike section near Vlaardingen and Hoeksche Waard respectively.
The expected alternatives' impact on water levels, corresponding to a 10.000 year return period, in the year 2200 is given in Appendix D.
Now the hydraulic loading is determined for both the baseline, and with the alternatives implemented, the corresponding dike reinforcement reduction can be determined in chapter 5 and flood risk reduction in chapter 6.

5
Dike reinforcements

Now the hydraulic loading has been determined for the baseline, and with the alternatives implemented, the corresponding dike reinforcement needs can be determined.
The dike reinforcement cost reduction, as a result of the alternatives, being factor C in Equation 1.1, and the two non-economic indicators being dike reinforcement related as well, this is a significant part of this research.
The dike reinforcement need will be calculated using the OKADER program, relevant output consists of the dike reinforcement cost, with and without the alternatives implemented, number of dike reinforcements and the land use of the reinforcements, all up to the year 2200.

The method for determining the dike reinforcement needs is given in section 3.3, more specific methodological choices are given in this chapter, as well as the presentation of the results. The results are used for a preliminary economic efficiency determination, only taking into account the dike reinforcement cost reduction and Rhine-Meuse Estuary specific cost factors of the alternatives.
If the reduction in dike reinforcement cost already exceeds the cost of implementing the alternative, it would mean that the alternative is already cost effective on this single factor.

5.1. Dike reinforcements costs

OKADER calculates dike reinforcement cost estimations for every dike section and for multiple methods of reinforcement, lower hydraulic loading results in a lower dike reinforcement demand. In this research only the most common current reinforcement technique is considered; soil additions to the dike width where possible, and structural solutions when existing nearby buildings make the widening impossible, in OKADER output this reinforcement technique is given as Variant 3A (de Grave, 2024).

The hydraulic loading,in the form of water level frequency curves, are inputted into OKADER for the baseline and with the alternatives implemented. Up until the year 2100 the water level frequency curves are all equal to the baseline, after 2100 the input for the alternatives becomes their altered water level frequency curves.
In Figure 5.1 the cumulative dike reinforcement cost is given, for the baseline and alternatives up until the year 2200, all converted to present value with a discount rate of 1.6%.

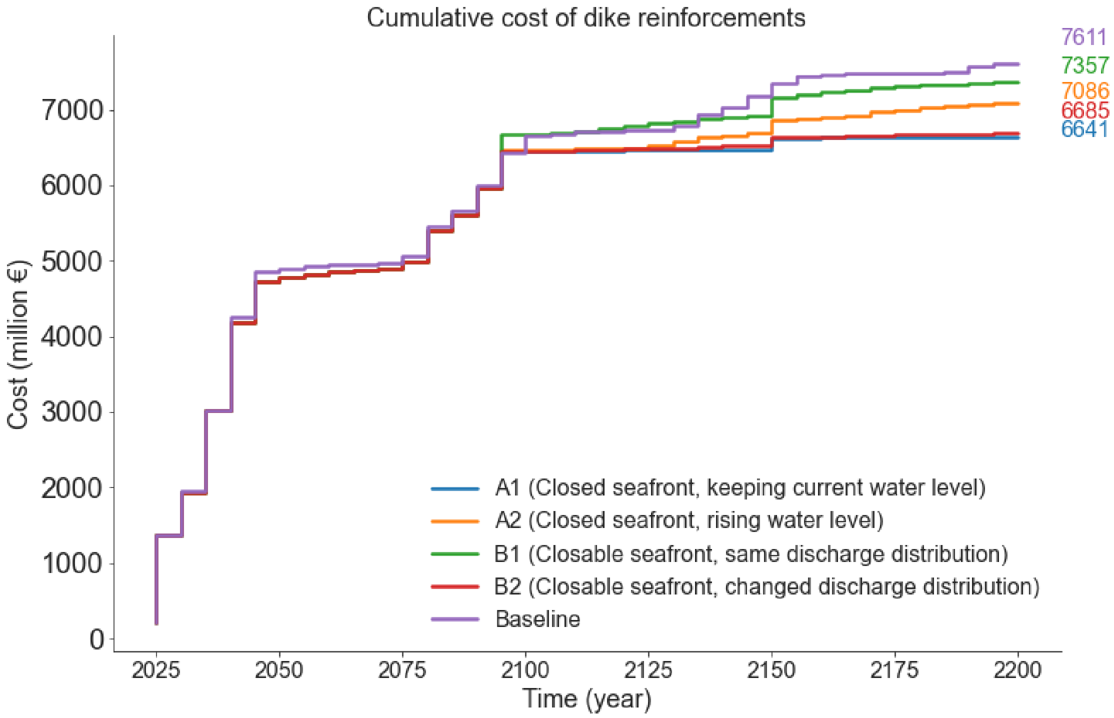


Figure 5.1: Cumulative dike reinforcement cost in present value up until 2200 for baseline and alternatives, the number at right the end of each line being the final present value of the cumulative cost.

As expected the cumulative dike reinforcement cost is equal up to the year 2100 for the baseline and alternatives. After 2100 the deviation starts, where especially the alternatives A1 and B2 have significant dike reinforcement cost reduction. This is a result from their large impact on the lower Rhine-Meuse Estuary hydraulic loading as can be seen in Figure 4.6.
The reduction in dike reinforcement cost compared to the baseline is for alternatives A1 and B2 around a billion euros and for alternatives A2 and B1 around half that.

The hydraulic loading is given to OKADER as water level frequency curves, because of computational related reasons OKADER cant deal with water levels that are zero or do not increase for increasing return periods.
The water levels, in the region of Rotterdam and Dordrecht, are given as zero for all return periods for when alternative B2 is implemented. In the case of alternative B2, the water level frequency curves are manually altered to have a water level slightly above zero for all return periods and having a small increase in water level for each increase in return period; this step is necessary to have OKADER work with this data.

Because the dike reinforcements are executed with a 50 year period in mind, cutting the cost of at the year 2200 leaves residual strength (or value) in the dike sections.
This residual value after the year 2200 is not taken into account in this research although this could influence the cost of reinforcements for the period after 2200.
The residual value does not influence the cost reduction significantly enough to make a alternative or baseline change order in total dike reinforcement cost reduction, in part because of the very high discount period.

5.2. Cost of each alternative

With the dike reinforcement cost reduction determined a preliminary efficiency determination can be made for the implementation fo the alternatives. The cost of implementation of each of the four alternatives is estimated for Knowledge Program Sea Level Rise track 4 up until the year 2100 and 2200.
The most important part of the cost of implementing the alternatives is determined by the choice of building blocks like building dams and pumping stations.
The operating cost is determined by estimating the energy use of the pumping stations and multiplying these by an average electricity cost (van der Biezen et al., 2024).

The cost that will be considered for this research will be a selection of cost factors that are determined within track 4.
Only the direct relevant cost that will be made to lower the hydraulic loading on the considered dike sections of the Rhine-Meuse Estuary will be used. This includes the cost of constructing hydraulic structures, pumping stations and pumping energy cost.
Excluded are the cost of dike reinforcements; these have their own account in this research, the cost to lower flood risk of unembanked areas, and the cost of reinforcement of dikes and dunes of other areas than the Rhine-Meuse; these are independent of an alternative and thus not useful in a comparison.
The considered costs are given for the baseline and each alternative in Table 5.1.

Table 5.1: Considered cost factors of each alternative and baseline until the year 2200 in billion Euro (van der Biezen et al., 2024)

	Hydraulic structures [B€]	Pumping stations [B€]	Pumping energy cost [B€]
Baseline	14	0	0
A1 (Closed seafront, keeping current water level)	9	23	11
A2 (Closed seafront, rising water level)	22	8	11
B1 (Closable seafront, same discharge distribution)	16	8	11
B2 (Closable seafront, changed discharge distribution)	27	7	2.3

To keep the cost of implementing the hydraulic measures of an alternative comparable to the dike reinforcement cost, the costs in Table 5.1 will be converted to a present value using a 1.6% discount rate.

For this research the hydraulic structures and the pumping stations are modeled as all being constructed in the year 2100. The energy cost for the pumping stations is distributed over the years 2100 until 2200, for present value the period to 2150 is used.
The present values of the alternative cost factors are given in Table 5.2.
The difference to the baseline is also given, later to be used in the efficiency determination of the alternatives. The hydraulic structures cost for the baseline consists of the cost for keeping existing hydraulic structures up to the norm in the future.

Table 5.2: Present value of cost factors of each alternative and baseline until the year 2200 in billion Euro

	Hydraulic structures [B€]	Pumping stations [B€]	Pumping energy cost [B€]	Total [B€]	Exceeding baseline [B€]
Baseline	4.3	0	0	4.3	-
A1 (Closed seafront, keeping current water level)	2.7	7.0	1.5	11.2	6.9
A2 (Closed seafront, rising water level)	6.7	2.4	1.5	10.6	6.3
B1 (Closable seafront, same discharge distribution)	4.9	2.4	1.5	8.8	4.5
B2 (Closable seafront, changed discharge distribution)	8.2	2.1	0.3	10.6	6.3

5.3. Preliminary economic efficiency determination

With the direct cost of implementing the alternatives determined, and the reduction in dike reinforcement calculated, a preliminary comparison can be made.
Table 5.3 shows the preliminary efficiency of each alternative when only the dike reinforcement cost reduction and alternative implementation cost are considered.

Table 5.3: Preliminary efficiency determination, accounting for dike reinforcement cost reduction and cost of implementation only.

	Reinforcement cost reduction [B€]	Cost of alternative [B€]	Direct efficiency [-]
A1 (Closed seafront, keeping current water level)	0.97	6.9	0.14
A2 (Closed seafront, rising water level)	0.53	6.3	0.08
B1 (Closable seafront, same discharge distribution)	0.25	4.5	0.06
B2 (Closable seafront, changed discharge distribution)	0.93	6.3	0.15

The preliminary economic efficiency is below 1.0 for all alternatives meaning that just the reduction in dike reinforcement cost does not make the implementation of the alternatives cost effective.
Other benefits of the alternatives like flood risk reduction need to be taken into account to achieve possible cost effectiveness, the alternatives' flood risk reduction is determined in chapter 6.
Non-economic indicators are extracted from OKADER as well, these added advantages are the reduction in amount of reinforcements and the reduction in land area used.

5.4. Reduction number of dike reinforcements

For this research the benefit of hydraulic loading reduction is the increase in time between reinforcement, and not dimensional reduction (see Figure 3.2), this results in the amount of reinforcements until 2200 being reduced compared to the baseline.
The amount of averted reinforcements, caused by the implementation of an alternative, is extracted per dike section from OKADER.
The amount of reduced reinforcements compared to the baseline is given on a map of the Rhine-Meuse Estuary for each alternative in Figure 5.2 until Figure 5.5.

A limited amount of sections, varying per alternative, have an increase in amount of reinforcements; these are colored yellow or orange in the figures. This could have multiple reasons; particularities in the calculations, higher hydraulic loading because of altered backwater curves, errors in the hydraulic loading input, or errors in any of the input parameters in OKADER for these specific sections.

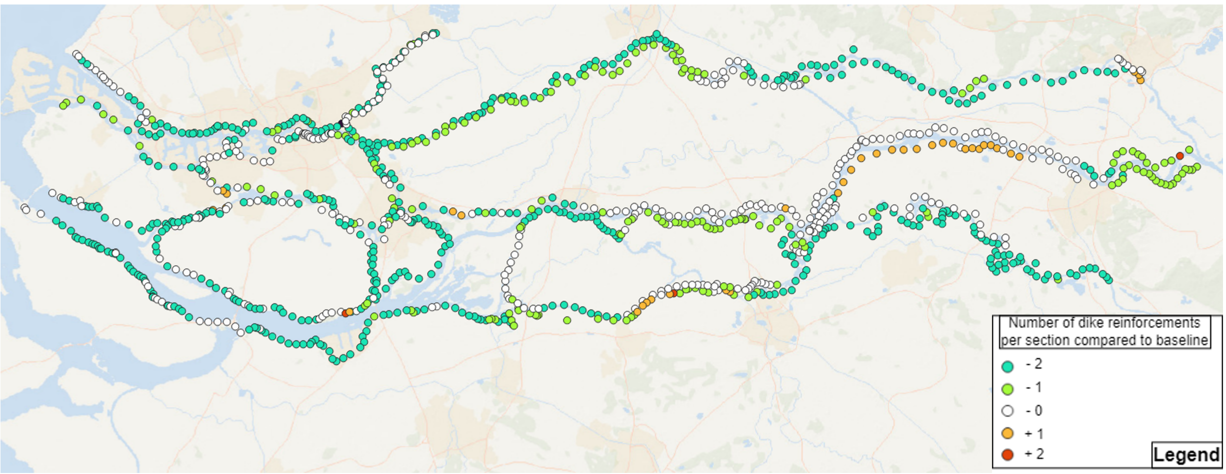


Figure 5.2: Difference in amount of dike reinforcements per section until 2200 when A1 (Closed seafront, keeping current water level) is implemented as compared to baseline.

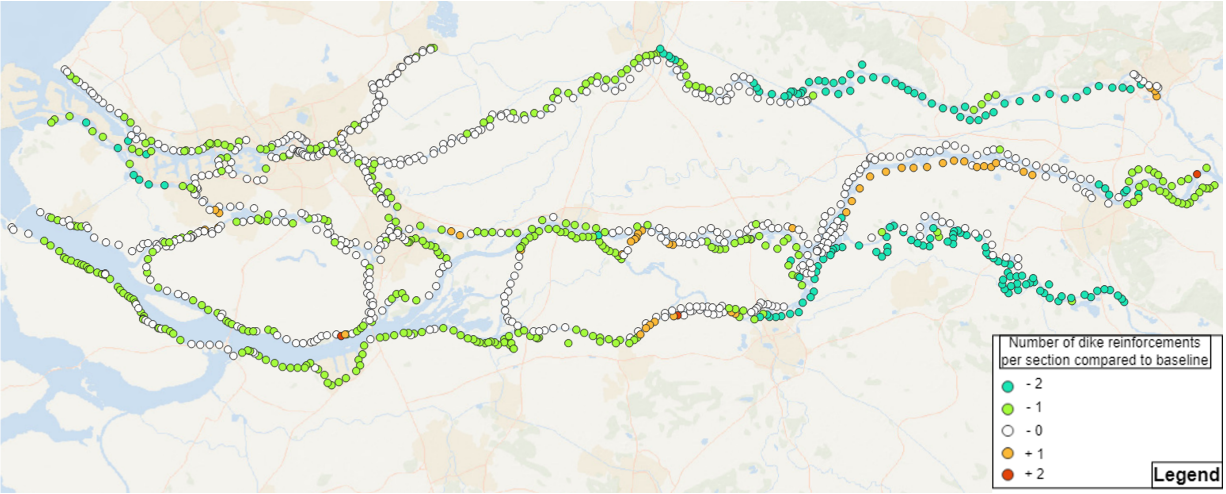


Figure 5.3: Difference in amount of dike reinforcements per section until 2200 when A2 (Closed seafront, rising water level) is implemented as compared to baseline.

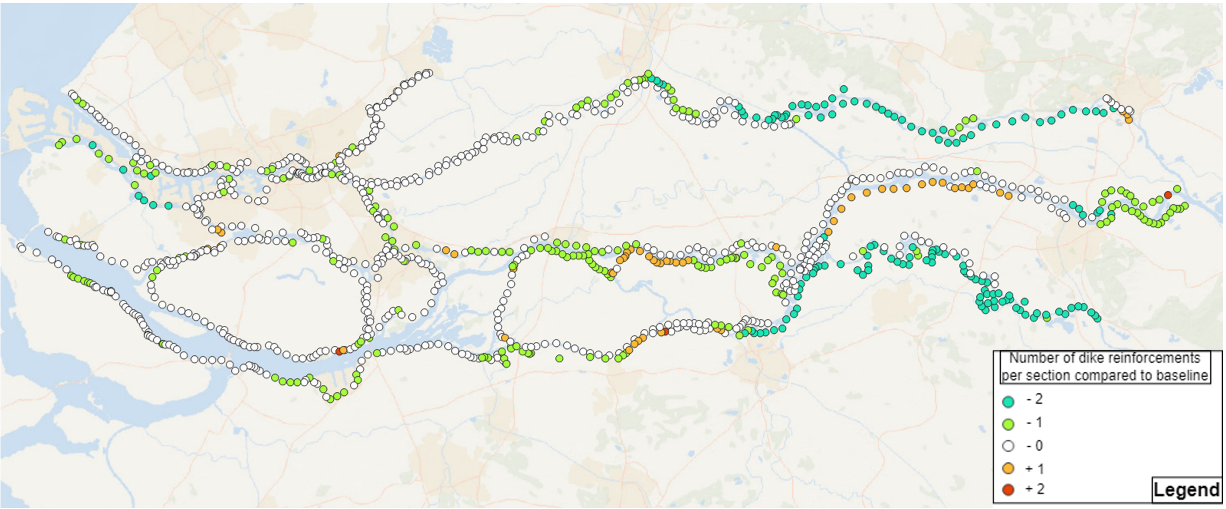


Figure 5.4: Difference in amount of dike reinforcements per section until 2200 when B1 (Closable seafront, same discharge distribution) is implemented as compared to baseline.

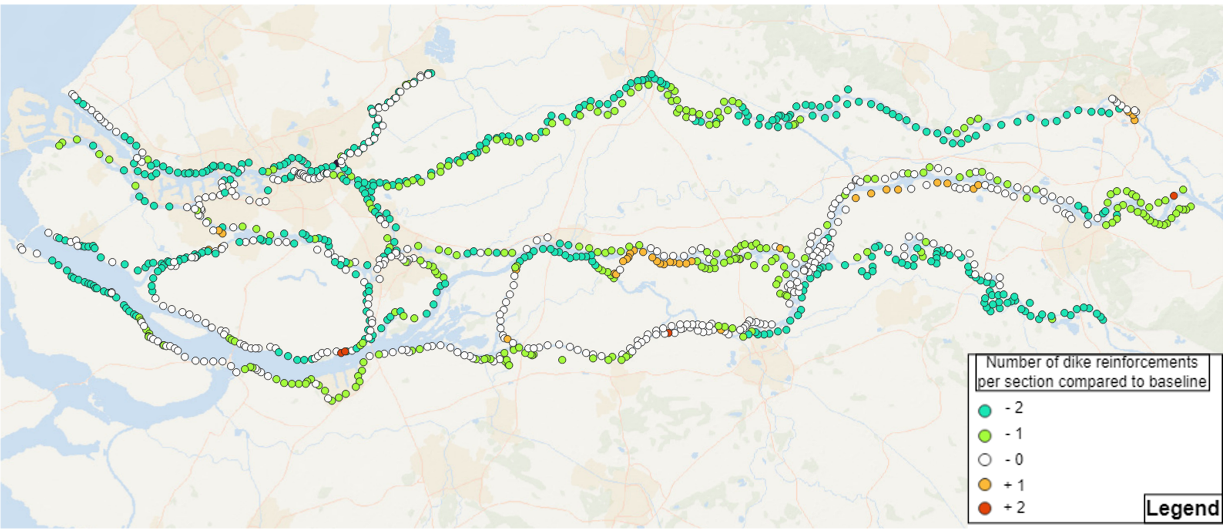


Figure 5.5: Difference in amount of dike reinforcements per section until 2200 when B2 (Closable seafront, changed discharge distribution) is implemented as compared to baseline.

The location and amount of averted dike reinforcements in Figure 5.2 until Figure 5.5 is not wholly in line with expectations if Figure D.1, from Appendix D, is considered.
This could have multiple reasons; the hydraulic loading effects caused by the implementation of the alternatives is manually altered in the baselines water level frequency curves, leading to the possibility of not taking into all (2nd order) effects into account or containing human made mistakes.
The hydraulic loading reduction, as a result of the implementation of the alternatives, is given as hydraulic loading data for all considered return periods, in Figure D.1 only the 10.000 year return period is given. The OKADER dike reinforcement determination considers the hydraulic loading for all years between 2025 and 2200 with a 5 year resolution, Figure D.1 solely shows the alternatives' reduction of hydraulic loading in the year 2200.
Finally, in this research, OKADER considers macrostability and piping as the failure mechanisms of dikes, overtopping is not considered in its calculations, this could explain some discontinuity between the expectations from Figure D.1 and the averted dike reinforcement maps Figure 5.2 until Figure 5.5.
Total amount of dike reinforcements the implementation of the alternatives reduce compared to the baseline until 2200 is given in Table 5.4.

Table 5.4: Number of dike reinforcements and reduction, compared to the baseline, for each alternative and baseline until 2200.

	Number of reinforcements	Reduction to baseline
Baseline	2940	-
A1 (Closed seafront, keeping current water level)	1757	1183
A2 (Closed seafront, rising water level)	2328	612
B1 (Closable seafront, same discharge distribution)	2493	447
B2 (Closable seafront, changed discharge distribution)	1898	1042

Table 5.4 provides one of the two considered non-economic indicators, averted dike reinforcements.
The results are mostly as expected, most reductions can be seen for alternative A1 and B2; these two alternatives cause a large hydraulic loading reduction, especially for the lower Rhine-Meuse Estuary.
The expectation is that that the cost reduction of dike reinforcement is in close relation to the amount of averted dike reinforcements seen in these figures, especially because the amount of dike reinforcements for A2 and B1 are around half those of A1 and B2, just like the cost reduction is.

5.4.1. Significance of averted dike reinforcement

Executing dike reinforcements often involves moving enormous amounts of soil and or driving in steel sheet piles deep into the ground. These activities create nuisance to the surrounding in the form of, among others, traffic, road closures, inaccessibility to housing or businesses, operation of heavy machinery, vibrations, soil settlements and noise.

The soil settlements and vibrations resulting from these reinforcements can cause nearby buildings to form cracks and get damaged. The act of driving the sheet piles into the ground creates the risk of disturbing aquifers, resulting in extreme soil disturbance (van Baars, 2020).
Existing cities, villages, specific buildings and even the dike itself could be protected, or highly valued, as historic landmarks. Removing these historic landmarks is often not possible or permitted, while at the same time damaging these older buildings is a grave concern (van der Poel, 2023).

Another limiting factor in dike reinforcements can be environmental laws. Protected areas of nature can be so close to the dike body that widening in a certain direction is not permitted (Eikelboom, n.d.).
The disturbance of soil and running machinery used for dike reinforcements both emit nitrogen which, in too large concentrations, is harmful for the environment (Van Breemen & Van Dijk, 1988).
Nitrogen emitting activities have to be permitted by the relevant municipality or province when the emissions are nearby a Natura 2000 area, this can lead to delays or even cancellations of dike reinforcement projects (BIJ12, n.d.; Waterschap Rivierenland, 2024).

Considering all of the above stated downsides, challenges, and restraining factors of dike reinforcement, the amount of averted dike reinforcements resulting from the implementation of the alternatives, could be considered as an significant advantage next to of the economic impact.
The downsides, challenges, and restraining factors of dike reinforcements also hold for the measures that have to be implemented for the alternatives. These measures include, among others, the construction of locks, pumping stations, dams and large flood barriers. To create a fair comparison between the baseline and the alternatives on this topic, these effects should be estimated as well.

5.5. Land use

The reduction of hydraulic loading by the alternatives does not only result in a reduction in the amount of dike reinforcements but also the land surface area that the reinforcements need, being the second considered non-economic indicator.
If a dike would fail on the failure mode stability or piping, the traditional reinforcement method is to widen the dike body by adding a soil berm, thus taking up otherwise utilizable land surface.

The alternatives lower the hydraulic loading and thus the failure probability for both piping and macro stability, this lowers the widening need and thus the land use for reinforcements.
The total land use of all dike reinforcements until the year 2200 for the baseline and with the alternatives implemented is given in Table 5.5.
These are extracted from the OKADER output variant 3A and is calculated by multiplying the maximum width needed for either stability or piping reinforcement and multiplying this with the soil measure length defined in the OKADER output.

Table 5.5: Land use for dike reinforcement considering stability and piping until the year 2200.

	Total land use [km^2]	Reduction to baseline [km^2]
Baseline	5.1	-
A1 (Closed seafront, keeping current water level)	3.6	1.5
A2 (Closed seafront, rising water level)	4.5	0.6
B1 (Closable seafront, same discharge distribution)	4.3	0.8
B2 (Closable seafront, changed discharge distribution)	3.9	1.2

Table 5.5 shows that each alternative causes a reduction in dike reinforcement land use ,compared to the baseline, these numbers are in line with both the cost reduction (Table 5.3) and the reduction in amount of reinforcements (Table 5.4).
The largest land use reduction can be seen for alternative A1 and B2 just like for dike reinforcement cost reduction and reduction in amount of reinforcements.
Alternative A1 and B2 save more than 4 times the area of Noordereiland in Rotterdam ($0.25\,\mathrm{km}^2$), this land area would otherwise be lost to dike widening. This amount of land surface saved, over the whole Rhine-Meuse Estuary until 2200, is only considered significant if this reduction would occur in very dense and desirable areas.

The average price per square meter for the possible development of residential housing in the province of South-Holland is around 450 euros, agricultural land is worth around 10 euros per squared meter (iTX BouwConsult, 2019; Wat is mijn huis waard, 2024).
This 45 factor difference results in the location, of where the land use reduction materializes, to be very important how significant this effect could be taken as a economic factor as well.
The value of the land surface area that is saved from being used by dike reinforcement is not taken into account for the economic efficiency calculation of the alternatives, see Equation 1.1, the implementation of the alternatives will also lead to land being used for the corresponding measures.

6

Flood risk determination

Because the alternatives have a reducing effect on the hydraulic loading, it can be assumed that this will lead to, in addition to lower dike reinforcement needs, a reduction in flood risk.
The reduction in flood risk will be the biggest economic advantage of the alternatives next to the reduction in dike reinforcement cost.
A large part of the alternatives' economic efficiency determination is related to flood risk with economic factors A and B being the flood risk reduction for unembanked and embanked areas respectively, see Equation 1.1.

The reference locations that are considered in the flood risk reduction calculations are primarily chosen on the quality of the available LIWO scenarios. For the flood risk determination multiple water levels, with corresponding damage estimations are needed for a single location.
The unembanked area considered as a reference location is Noordereiland, this location is chosen because it is the only location for which LIWO provides a large amount of flooding scenarios for a residentially utilized unembanked area. The Noordereiland scenario in LIWO encompasses more than the Noordereiland itself, it includes nearby unembanked neighborhoods.
The two embanked reference areas are the dense city of Vlaardingen and the rural municipality Hoeksche Waard. The usage of these as reference locations is based on their population density, their location within different regions of hydraulic conditions (see subsection 4.2.2) and the amount of water levels and damage estimations available in LIWO.

The flood risk reduction of the alternatives, as compared to the baseline, will be expressed as the difference in present value of the Estimated Annual Damage (EAD) determined following the method as described in section 3.4.
While the general method is described in section 3.4 this chapter mentions the specific parameters and presents the outcomes of the flood risk reduction determination. All damage estimations in this chapter are based on the densification spatial planning strategy, provided in section 6.1.

The Estimated Annual Damage (EAD) will be determined for the years 2100 and 2200 with the corresponding hydraulic loading of the baseline and each of the four alternatives.
A damage curve will be extrapolated based on the available LIWO scenarios, this damage curve will be used to determine damage estimations for all water levels up until the most extreme one being for the baseline in the year 2200.
Multiplying the frequencies of these water levels with the corresponding damage, extracted from the damage curve, results in the total EAD, see Equation 3.2.

In this research, the dike reinforcement cost reduction and cost of implementing the alternatives is considered for the whole Rhine-Meuse Estuary while for flood risk reduction determination, three reference locations are used. This is why the dike reinforcement cost reduction and cost of implementing the alternative will be scaled back (normalized) to be in the same proportion as the flood risk reduction locations considered.

6.1. Future dwelling densification

Because the EAD is estimated for the years 2100 and 2200 the expected population density increase of the Rhine-Meuse Estuary will have to be accounted for; this has a direct impact on the exposure component of the flood risk estimations.

To account for this the *densification* spatial planning strategy is applied, meaning that the plan capacity (total number of houses planned for development) of 367.100 between 2023 and 2042 will be distributed over the three aforementioned refernce locations in direct ratio to the current number of dwellings (Groenemeijer, 2023; Rijken et al., 2016).
The calculations assume this plan capacity is developed within the three locations before 2100, and the number of dwellings stay stabile until the year 2200.
Current, to be distributed, and future number of dwellings of the three locations is given in Table 6.1

Table 6.1: Current, to be distributed, and future number of dwellings of the three locations (CBS, 2023).

	Current dwellings	Distributed from plan capacity	Total for 2100 and 2200
Noordereiland	21314	187910	209224
Vlaardingen	19535	172226	191761
Hoeksche Waard	790	6965	7755
Total	41639	367100	408739

The distributed dwelling ratio is based on the ratio between current dwellings and the, to be distributed plan capacity. This results in 51% of the plan capacity moving to Noordereiland, 47% to Vlaardingen and 2% to Hoeksche Waard.
The current amount of dwellings is based on the affected regions according to the most severe LIWO scenario inundation map. For the Noordereiland this means that multiple surrounding, unembanked, neighborhoods also fall under the Noordereiland location name, eight in total. Vlaardingen has three neighborhoods affected and Hoeksche Waard only the "Strijen Buitengebied" region.

The amount of dwellings in the years 2100 and 2200 will be used to factor the damage curves, that are based on the current amount of dwellings, to include the expected increase in exposure because of the future increase in dwellings.
The increase factor in dwellings, for the Noordereiland area specifically, could be difficult to realize but if a conscious effort is made to increase dwellings in this region it would not be unthinkable.

6.1.1. Issuance level

Because of the higher flooding probability of unembanked areas, there has been a search for methods to lower the risk that comes with further development of these areas.
The municipality of Rotterdam introduced the *uitgiftepeil*; an issuance level as compared to a certain base level (NAP) where new streets and buildings have to be constructed above.
In Rotterdam this uitgiftepeil is set at NAP + 3.6 meters for regular construction and at NAP + 3.9 for sensitive buildings like special industries (Trouwborst et al., 2018).

This will result in all new construction, considered in the future dwelling densification, to be build above this level in in the unembanked area.
This is incorporated into the calculation of the unembanked EAD by having all hydraulic loading under this level to have no addition to the EAD component that accounts for the future addition of dwellings.

6.2. Unembanked flood risk reduction

For the unembanked area the Noordereiland region in Rotterdam will be used as reference.
The Noordereiland is an island located in the Nieuwe Maas, having an area of around $0.25\,\mathrm{km}^2$.
The area that is considered is larger than the actual island itself; it encompasses most unembanked neighborhoods around the Noordereiland as well: Noordereiland, Feijenoord, Kop van Zuid Entrepot, Kop van Zuid, Katendrecht, Nieuwe-Werk, De Esch and Oud Ijsselmonde.
These are considered within the Noordereiland flood risk determination because the corresponding most severe LIWO scenario causes inundation in all these areas.

6.2.1. Noordereiland

The hydraulic loading of the Noordereiland will be taken as the water level frequency curves for dike section 14002008, these can be seen in Figure 4.6 and Figure 4.7.
The damage curve will be based on the *Stedelijk Rotterdam* LIWO scenario.
This LIWO scenario has 17 damage estimations for 17 water levels of the Nieuwe Maas ranging from 2.9 until 3.9 meter, the inundation map corresponding to the highest level can be seen in Figure 6.1. Some of the 17 water levels are duplicates but have different damage estimations; the result of multiple research programs providing the scenarios in LIWO, the damage estimations for these water levels are averaged to have a single damage estimation for each water level.

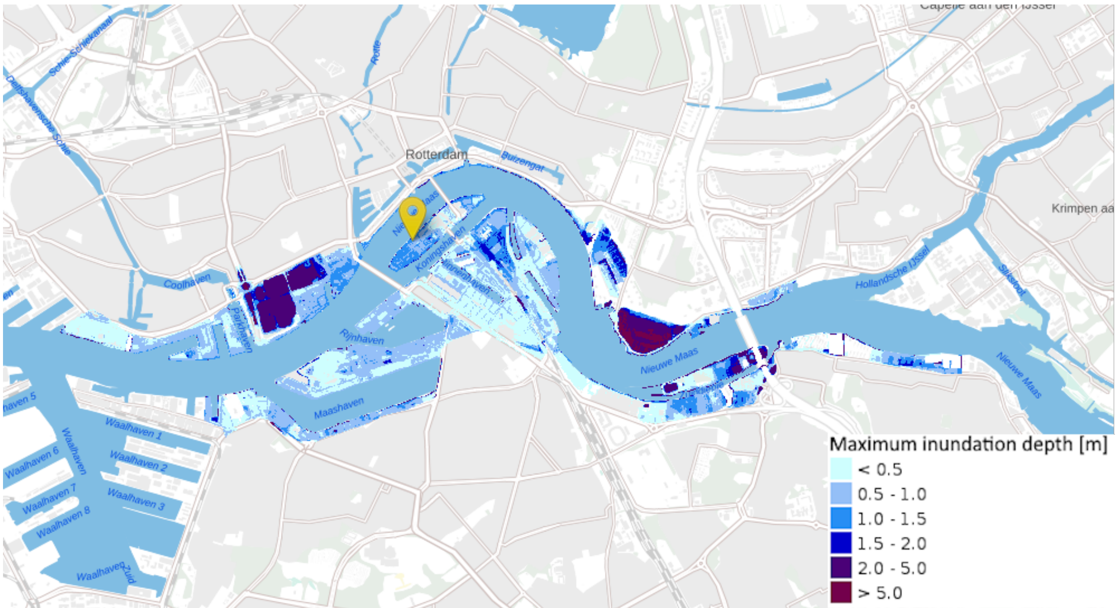


Figure 6.1: Inundation map corresponding to most extreme LIWO scenario Noordereiland; ID 198_Stedelijk Rotterdam (IenW, 2024b).

LIWO is filled with flooding scenarios from multiple different sources, the Noordereiland LIWO scenario is created as assignment from the Municipality of Rotterdam (Royal HaskoningDHV, 2018). A complete list of parameters and damage model inputs is given in Appendix E

Damage curve Noordereiland

A damage curve is needed to obtain a damage estimation for each possible water level that can occur in the baseline or any of the alternatives.
To create the damage curve, the damage estimations have to be extrapolated to a water level that fits the maximum water level that can occur according to the baseline.

When the water level of the Nieuwe Maas is equal to 3.9 meters, the whole unembanked area is taken as inundated.
Damage estimations above this water level are modeled in the Damages and Victims model (Schade en Slachtoffer module (SSM) in Dutch) (Deltares, 2024).
Damage estimations are created by adding 1 meter of inundation depth to the inundation map at full unembanked area coverage, parameters used for this simulation are given in Appendix E. Now there is a damage estimation for multiple discrete points from 2.9 up to 9.9 meters of water level on the Nieuwe Maas voor the Noordereiland, see the orange line in Figure 6.2. Note that these damage estimations are based on current number of dwellings.

This water level - damage relation is fit with three 3rd order polynomials, using the least squares method, to gain damage estimations for all water levels from 2.9 to 9.9 meters.
The 3rd order fit, in three separate parts, is given in Figure 6.2.

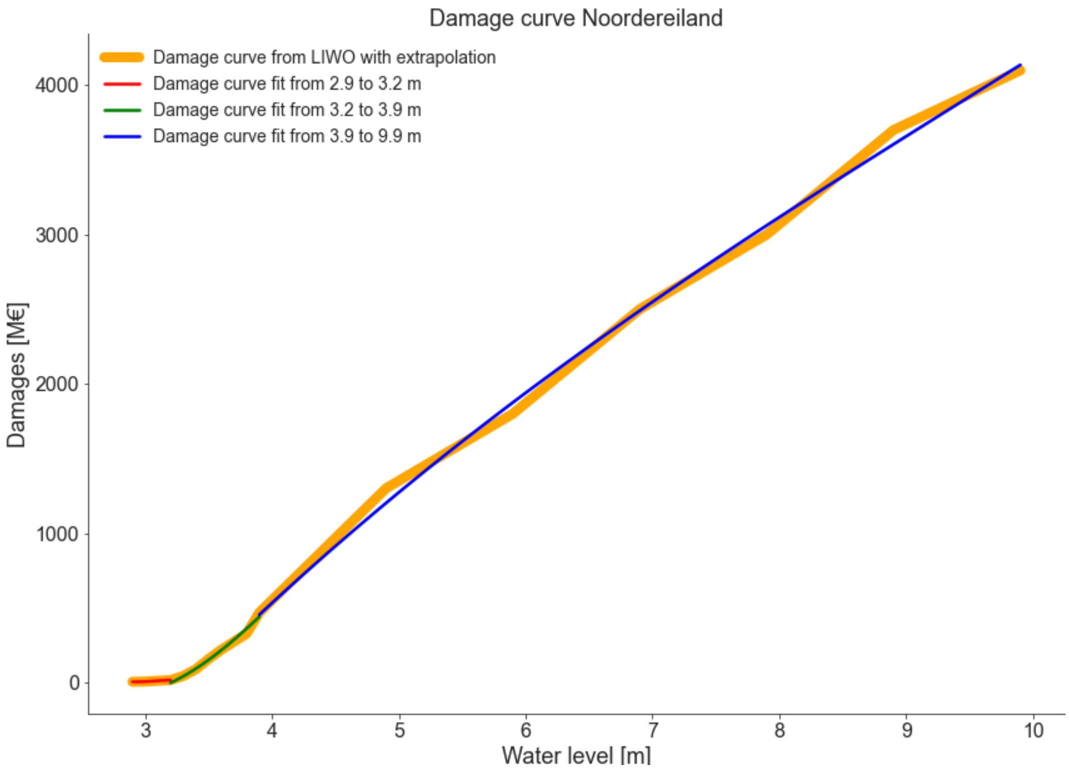


Figure 6.2: Damage curve, based on total direct economic damages for Noordereiland (including surrounding unembanked areas) from LIWO scenarios, with third order fit in three parts.

The Nieuwe Maas water level of 2.9 meters is taken as the start of damages (water reaches ground level); all water levels below this level are taken as having no effect on the damage estimations.

Finally, the obtained damage curve is used to get a damage estimation for each possible occurring water level at Noordereiland. To obtain the Estimated Annual Damage (EAD), all damages are multiplied by the frequency of occurrence of corresponding water levels and summed, this for the baseline and alternatives, see Equation 3.2.

The resulting EAD is then multiplied with the ratio of expected densification of the Noordereiland (see Table 6.1), taking into account the issuance level.
The EAD for 2100 and 2200 is converted to its present value using a discount rate of 1.6%, the same as for the dike reinforcement cost reduction, see Equation 3.1.

The resulting present value of the EADs for the baseline and each alternative for the year 2100 and 2200 are given in Table 6.2 and Table 6.3.

Table 6.2: Present value of the Estimated Annual Damage (EAD) Noordereiland for baseline and alternatives in 2100 following densification strategy.

	EAD 2100 [M€]	Reduction to baseline [M€]	Reduction to baseline [%]
Baseline	633	-	-
A1 (Closed seafront, keeping current water level)	0.1	633	-99%
A2 (Closed seafront, rising water level)	4.8	628	-99%
B1 (Closable seafront, same discharge distribution)	603	29	-5%
B2 (Closable seafront, changed discharge distribution)	0.0	633	-100%

Table 6.3: Present value of the Estimated Annual Damage (EAD) Noordereiland for baseline and alternatives in 2200 following densification strategy.

	EAD 2200 [M€]	Reduction to baseline [M€]	Reduction to baseline [%]
Baseline	1510	-	-
A1 (Closed seafront, keeping current water level)	0.2	1510	-99%
A2 (Closed seafront, rising water level)	1444	74	-5%
B1 (Closable seafront, same discharge distribution)	1490	23	-2%
B2 (Closable seafront, changed discharge distribution)	0.0	1510	-100%

The same pattern can be seen as for the dike reinforcement demand, alternative A1 and B2 have the most impact and A2 and B1 significantly less. This is in line with expectations based on the water level frequency curves for the Noordereiland.
The EAD for the Noordereiland following the baseline is massive, especially in the year 2200, the hydraulic loading for this location is extremely high and multitudes of the current hydraulic loading.

6.3. Embanked flood risk reduction

The dense city of Vlaardingen and the rural municipality of Hoeksche Waard are taken as a reference to determine the embanked flood risk reduction as effect of the alternatives.
Vlaardingen lies west of Rotterdam along the Nieuwe Maas, also called the Scheur at this location, and has an surface area of around 27 km^2.
The Hoeksche Waard is a very rural municipality, technically an island surrounded by the Spui, Oude Maas and the Hollandsch Diep with a total surface area of around 324 km^2.

The area that is considered is smaller than the whole city of Vlaardingen; it encompasses the neighborhoods that are affected by the flooding according to the available LIWO scenario: Vlaardingen centrum, Vlaardinger Ambacht and Westwijk.
The LIWO scenario that will be used for the Hoeksche Waard area will be a flooding that is a result of a dike breach in the south of the island, resulting in the neighborhood Strijen Buitengebied being the one area considered.

Because the dikes in the Rhine-Meuse Estuary are kept up to norm, in the baseline and for the alternatives, there will be assumed that no damages occur when the hydraulic loading is below the hydraulic loading that the dike is supposed to retain.
This is specified as the dike norm and defers to a return period, not a water level. All water levels that occur with a lower return period than the dikes norm will have zero contribution to the EAD of the embanked areas.
This norm is 1/10.000 per year for dike trajectory 14-3 along Vlaardingen and 1/300 per year for trajectory 21-2 along the southern side of Hoeksche Waard (HWBP, n.d.).

6.3.1. Vlaardingen

The hydraulic loading for Vlaardingen will be taken as the water level frequency curves for dike section 14003015, these can be seen in Appendix B.
The damage curve will be based on a LIWO scenario based on the failure of the Vlaardingen schutsluis, part of the dike trajectory 14-3; having the same acceptable failure probability.
The schutsluis is taken instead of the dike breach for this location because the resulting flooding map was better scalable for the schutsluis than for the dike breach.

This LIWO scenario has three damage estimations for three water levels of the Nieuwe Maas ranging from 3.45 until 4.71 meter, the inundation map corresponding to the highest level can be seen in Figure 6.3.
A list of available parameters and damage model inputs is given in Appendix E.

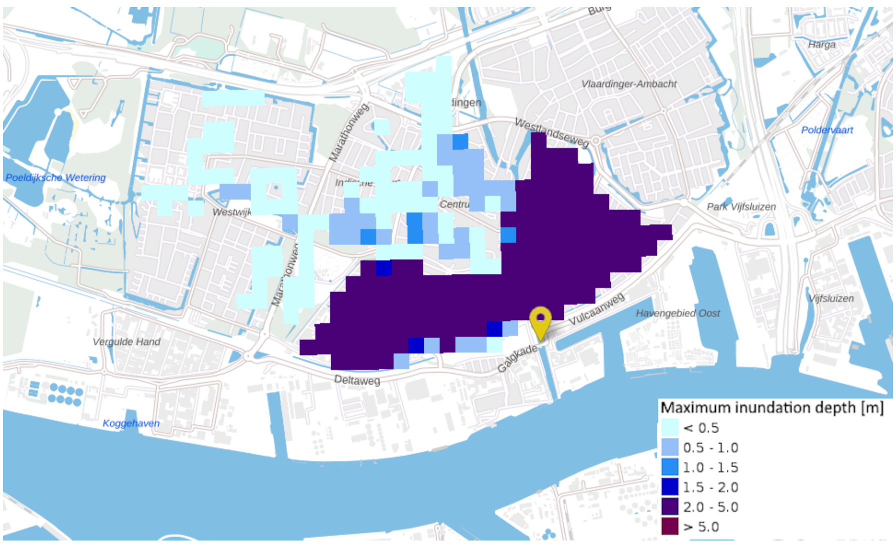


Figure 6.3: Inundation map corresponding to most extreme LIWO scenario Vlaardingen; C1_TP0D_MM375_mbb_RM2_REF3 (IenW, 2024b).

Damage curve Vlaardingen

To create the damage curve, the damage estimations have to be extrapolated to a water level that fits the maximum water level that can occur according to the baseline and the alternatives. To take into account both the inundation increase, and the added flooded land coverage, the damage estimations from the LIWO scenario are extrapolated directly.

A zero damage for zero water level outside of the dike is added manually to get a more sensible result in the lower regions of the hydraulic loading.
The damages are extrapolated using a single 3rd order polynomial (found by least square method), based on the double zero point and the three LIWO damage estimations with corresponding water levels.

Now there is a damage estimation from 0.0 up to 9.7 meters of outside dike water level on the Nieuwe Maas for Vlaardingen, see the blue line in Figure 6.4.
Note that these damage estimations are based on current number of dwellings.

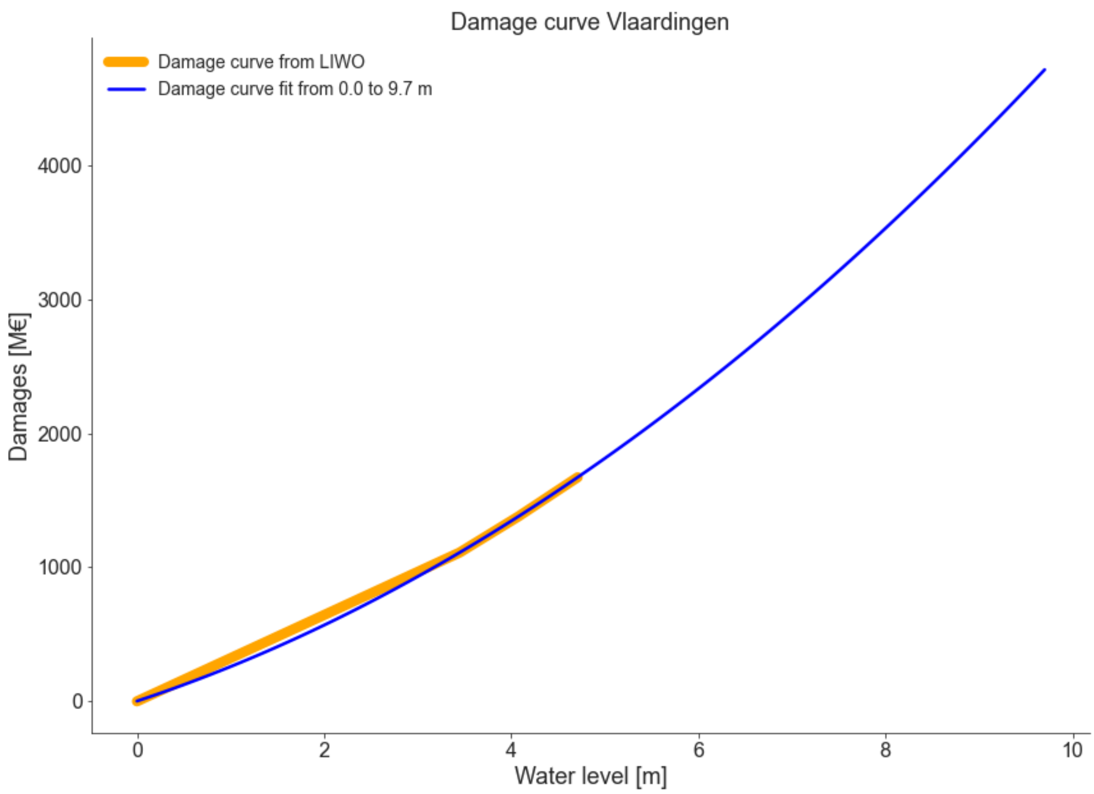


Figure 6.4: Damage curve, based on total direct economic damages for Vlaardingen from LIWO scenarios, with third order fit.

To obtain the Estimated Annual Damage (EAD) all damages, corresponding to a water level that has a higher return period than the dike norm, are multiplied with its corresponding expected frequency, using Equation 3.2.
The resulting present value, taking into account densification, of the EADs for the baseline and each alternative for the year 2100 and 2200 are given in Table 6.4 and Table 6.5.

Table 6.4: Present value of the Estimated Annual Damage (EAD) Vlaardingen for baseline and alternatives in 2100 following densification strategy.

	EAD 2100 [M€]	Reduction to baseline [M€]	Reduction to baseline [%]
Baseline	1.1	-	-
A1 (Closed seafront, keeping current water level)	0.3	0.8	-75%
A2 (Closed seafront, rising water level)	0.3	0.8	-74%
B1 (Closable seafront, same discharge distribution)	0.4	0.7	-62%
B2 (Closable seafront, changed discharge distribution)	0.0	1.1	-100%

Table 6.5: Present value of the Estimated Annual Damage (EAD) Vlaardingen for baseline and alternatives in 2200 following densification strategy.

	EAD 2200 [M€]	Reduction to baseline [M€]	Reduction to baseline [%]
Baseline	1.9	-	-
A1 (Closed seafront, keeping current water level)	0.3	1.6	-83%
A2 (Closed seafront, rising water level)	0.7	1.3	-66%
B1 (Closable seafront, same discharge distribution)	0.8	1.2	-61%
B2 (Closable seafront, changed discharge distribution)	0.0	1.9	-100%

6.3.2. Hoeksche Waard

The hydraulic loading of the Hoeksche Waard will be taken as the water level frequency curves for dike section 21002029, these can be seen in Appendix C.
The damage curve will be based on a LIWO scenario breaching of dike trajectory 21-2, located along the southern part of the Hoeksche Waard.
This LIWO scenario has three damage estimations for three water levels of the Hollandsch Diep ranging from 2.64 until 3.47 meter, the inundation map corresponding to the highest level can be seen in Figure 6.5.

The Hoeksche Waard LIWO scenario is created as part of the research into compartmentalization dikes for dike trajectories in South-Holland ordered by the Province of South Holland (Vermeulen et al., 2015).
A list of available parameters and damage model inputs is given in Appendix E. The method used for the compartmentalization dikes research flood risk estimations is very similar to that of the Safety of the Netherlands Map 2 (Veiligheid Nederland in Kaart 2 (VNK2) in Dutch) (Jongejan, 2010).

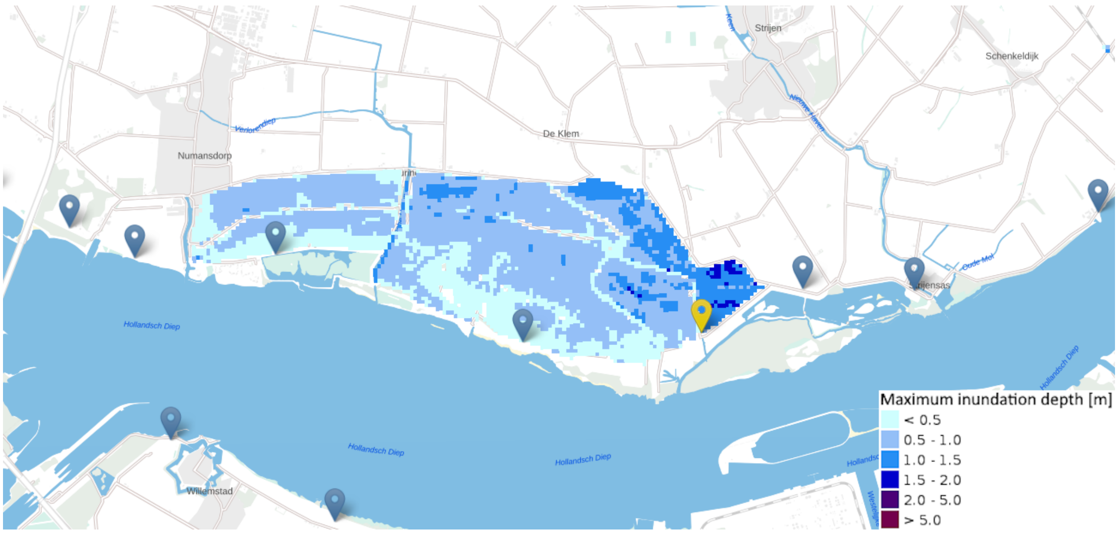


Figure 6.5: Inundation map corresponding to most extreme LIWO scenario Hoeksche Waard; EB_97_tpp2d_QBR_10000_MM_4.25_G_nw_28_Uc=0.5 (IenW, 2024b).

Damage curve Hoeksche Waard

The damage curve for the Hoeksche Waard is created in the exact same manner as the one for Vlaardingen.
The damage curve is based on the LIWO data and, extrapolated with a two part 3rd order fit, up to 9.5 meters of outside dike water level on the Hollandsch Diep, see Figure 6.4.
Note that these damage estimations are based on current number of dwellings.

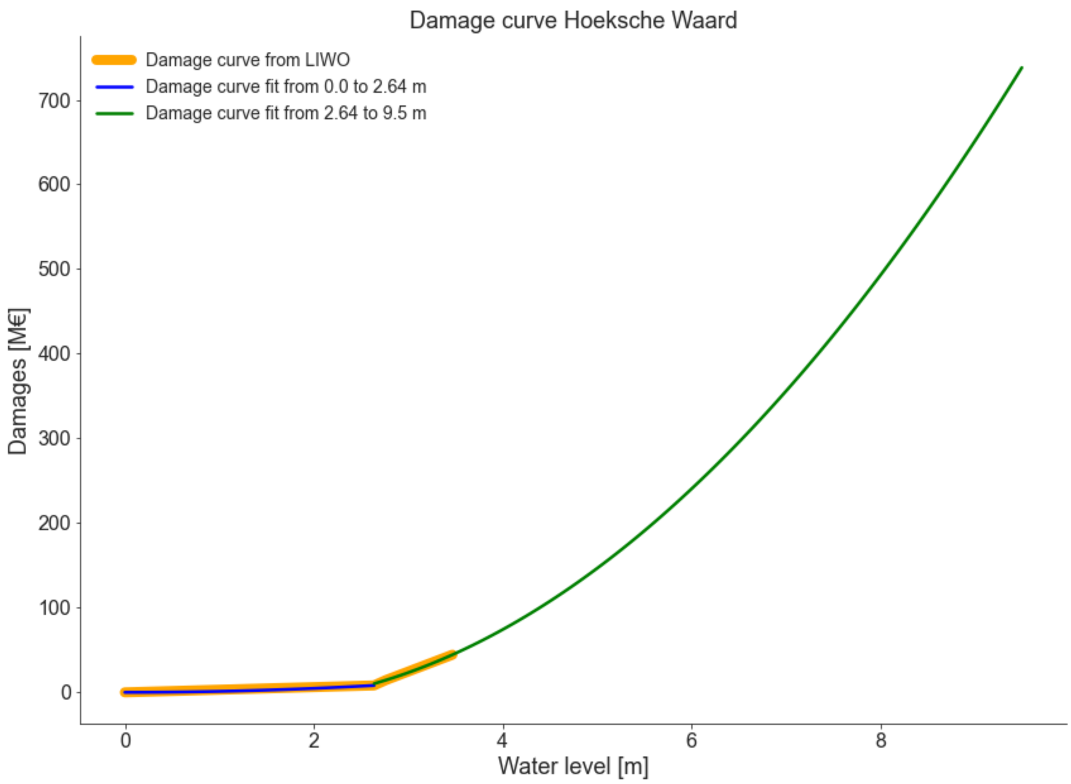


Figure 6.6: Damage curve, based on total direct economic damages for Hoeksche Waard from LIWO scenarios, with third order fit in three parts.

To obtain the Estimated Annual Damage (EAD) all damages, corresponding to a water level that has a higher return period than the dike norm, are multiplied with its corresponding expected frequency.
The resulting present value, taking into account densification, of the EADs for the baseline and each alternative for the year 2100 and 2200 are given in Table 6.6 and Table 6.7.

Table 6.6: Present value of the Estimated Annual Damage (EAD) Hoeksche Waard for baseline and alternatives in 2100 following densification strategy.

	EAD 2100 [M€]	Reduction to baseline [M€]	Reduction to baseline [%]
Baseline	2.4	-	-
A1 (Closed seafront, keeping current water level)	0.1	2.3	-97%
A2 (Closed seafront, rising water level)	0.3	2.1	-90%
B1 (Closable seafront, same discharge distribution)	1.6	0.8	-33%
B2 (Closable seafront, changed discharge distribution)	0.4	1.9	-83%

Table 6.7: Present value of the Estimated Annual Damage (EAD) Hoeksche Waard for baseline and alternatives in 2200 following densification strategy.

	EAD 2200 [M€]	Reduction to baseline [M€]	Reduction to baseline [%]
Baseline	7.4	-	-
A1 (Closed seafront, keeping current water level)	0.1	7.3	-99%
A2 (Closed seafront, rising water level)	5.1	2.3	-31%
B1 (Closable seafront, same discharge distribution)	5.9	1.4	-19%
B2 (Closable seafront, changed discharge distribution)	5.8	1.6	-22%

6.4. Total flood risk reduction and normalization

With the Estimated Annual Damage calculated for both unembanked and embanked areas the total EAD, and EAD reduction because of the alternative compared to the baseline, can be determined.
The preliminary efficiency calculation in Table 5.3 takes into account the dike reinforcement cost and alternative implementation cost for the whole Rhine Meuse Estuary while the flood risk reduction effect of the alternatives is calculation for three reference locations only.
This difference needs to be normalized, to get a fair comparison of efficiency of each alternative compared to the baseline; the dike reinforcement cost reduction and cost of implementing the alternative will be scaled back to be in the same proportion as the three flood risk reference locations.

6.4.1. Total flood risk reduction for densification

With the Estimated Annual Damage (EAD) is calculated for both unembanked and embanked areas the total EAD, and EAD reduction because of the alternative compared to the baseline, can be determined. Total EAD and EAD reduction because of the implementation of the alternatives for the unembanked area and embanked areas can be seen in Table 6.8.

Table 6.8: Present value of the Estimated Annual Damage (EAD) reduction to baseline for alternatives in 2200 following densification strategy.

	Reduction to baseline unembanked [M€]	Reduction to baseline embanked [M€]
A1 (Closed seafront, keeping current water level)	1512	9
A2 (Closed seafront, rising water level)	74	4
B1 (Closable seafront, same discharge distribution)	23	3
B2 (Closable seafront, changed discharge distribution)	1512	4

The difference of the effect on unembanked flood risk is massive, while the embanked flood risk reduction stays close to zero. This is for a large because the damage curve extrapolation is based purely on water level and not on the duration or intensity of flooding.
Also, because of the dikes staying up to norm, a large part of the damage curve is ”cut off” in the EAD calculation, only very extreme events are considered with a very low frequency.

Now these flood risk reductions are known they can be added to the efficiency determination given in Table 5.3, note that the dike reinforcement cost reduction and cost of alternatives are not yet normalized, this is be done in subsection 6.4.2.

Table 6.9: Efficiency determination densification with flood risk reduction before normalization.

	Reinforcement cost reduction [M€]	Reduction in flood risk [M€]	Cost of alternative [M€]	Efficiency [-]
A1 (Closed seafront, keeping current water level)	970	1521	6900	0.36
A2 (Closed seafront, rising water level)	530	78	6300	0.15
B1 (Closable seafront, same discharge distribution)	250	26	4500	0.14
B2 (Closable seafront, changed discharge distribution)	930	1516	6300	0.36

An efficiency below 1 means that the implementation of the alternative has a higher cost than the reduction effects for dike reinforcement cost and flood risk, making it an economically unattractive option. However, while dike reinforcement cost reduction and the alternative implementation is for the whole Rhine-Meuse Estuary, the flood risk reduction is only for the three locations considered in this research. Because of this there needs to be a normalization of all numbers to get a fair efficiency determination.

6.4.2. Efficiency determination with normalization

Because dike reinforcement cost reduction and the alternative implementation cost is considered for the whole Rhine-Meuse Estuary and the flood risk reduction is only for the three locations a normalization is needed.
The normalization will be executed trough the number of dwellings considered for the flood risk reduction in ratio to the the total amount of dwellings that will be affected by the alternatives.
Total amount of dwellings considered for the flood risk reduction is given in Table 6.1 as 408.739.
The total amount of dwellings that is considered to be impacted by the alternatives is determined by considering the relevant waterboards (waterschappen in Dutch) within the Rhine-Meuse Estuary.
The list of waterboards in the Rhine-Meuse Estuary and their relevant number of dwellings:

- Hoogheemraadschap Delfland: 529.400 (HHDelfland, 2022).
- Waterschap Hollandse Delta: 136.500 (RegioZHD, 2024).
- Waterschap Schieland en de Krimpenerwaard: 285.000 (HHSK, 2024).
- Waterschap Rivierenland: 431.000 (Waterschap Rivierenland, 2024).
- Waterschap Brabantse delta: 103.845 (CBS, 2023), municipalities neighboring water bodies.
- Hoogheemraadschap De Stichtse Rijnlanden: 503.946 (CBS, 2023).

A total of 1.704.691 dwellings that will be impacted by the alternatives within the Rhine-Meuse Estuary. The dike reinforcement cost reduction and the alternative implementation cost will be scaled down in proportion to the amount of dwellings already considered in the three reference locations for the flood risk determinations and the total dwellings within all relevant waterboards.

This will result in the dike reinforcement cost reduction and the alternative implementation cost to be divided by 4.17 (Total number of dwellings impacted by alternatives / number of dwellings in reference locations = 1.704.691/408.739) to normalize them.
The resulting efficiency determination is given in Table 6.10.

Table 6.10: Normalized economic efficiency determination following densification.

	Reinforcement cost reduction [M€]	Reduction in flood risk [M€]	Cost of alternative [M€]	Efficiency [-]
A1 (Closed seafront, keeping current water level)	233	1521	1655	1.06
A2 (Closed seafront, rising water level)	127	78	1511	0.14
B1 (Closable seafront, same discharge distribution)	60	26	1079	0.08
B2 (Closable seafront, changed discharge distribution)	223	1516	1511	1.15

After the normalization of the alternatives implementation cost and the reduction in cost of dike reinforcements, the alternatives A1 and B2 now have an efficiency above 1.0 and thus can be considered economically effective to implement for the densification strategy.

The normalization ratio is directly applied to the C and D factors in Equation 1.1, and thus highly consequential to the alternatives' efficiency calculation.
The choice to take into account the number of dwellings within all relevant waterboards is a relatively coarse method to determine the total affected dwellings. If resulting flood risk reduction of the alternatives would be determined for the whole Rhine-Meuse Estuary, instead of the three reference locations, this normalization wouldn't be necessary.

Of the three locations taken into consideration for the flood risk reduction, two are in a heavily beneficial area of the alternatives in regards to the reduction in hydraulic loading.
This reduction is not seen for all parts of the Rhine-Meuse Estuary and thus skews the results when the normalization is applied.

6.5. Local individual risk

Flood risk does not only consist of economic damage but also of possible casualties or even fatalities, the effect of the alternatives have on fatalities is provided by this section.
The Local Individual Risk (LIR) is the probability that a person drowns in the event of a flooding event in any year; in the Netherlands this is set at a maximum of 10E-5 (Van Alphen, 2016).
To determine the Local Individual Risk (LIR) the LIWO fatality data is fit to create a fatality curve, this is done in the exact same manner as the Estimated Annual Damage (EAD).
This fatality curve is used to find a number of fatalities for each water level, applying Equation 3.2 but replacing damages with fatalities results in expected annual fatalities.
The Local Individual Risk or LIR is determined by dividing the annual expected fatalities by the amount of inhabitants.
The amount of inhabitants is determined by multiplying the amount of dwellings (see Table 6.1) by the average amount of inhabitants per dwelling being 2.11 (CBS, n.d.).
For the expected annual amount of fatalities following densification for the years 2100 and 2200 see Table 6.11, Table 6.12 and Table 6.13 for Noordereiland, Vlaardingen and Hoeksche Waard respectively.

Table 6.11: Local Individual Risk (LIR) Noordereiland following densification in 2100 and 2200.

	Expected annual victims in 2100	Expected annual casualties in 2200	LIR in 2100	LIR in 2200
Baseline	66	276	1.5E-4	6.3E-4
A1 (Closed seafront, keeping current water level)	<1	<1	1.9E-8	4.9E-8
A2 (Closed seafront, rising water level)	<1	255	3.9E-7	5.8E-4
B1 (Closable seafront, same discharge distribution)	61	269	1.4E-4	6.1E-4
B2 (Closable seafront, changed discharge distribution	0	0	0.0	0.0

The expected annual victims of the Noordereiland area are not acceptable for the baseline, nor for the alternatives A2 and B1. This will result in a necessity of local, or system level, measures before 2100. These measures could be water barriers around the unembanked areas, or significantly improving other factors that determine the amount of casualties in the case of flooding.
The relevant factors are evacuation time, infrastructure available for evacuation, buildings' vulnerability to flooding and flood warning systems, and predictions of extreme conditions (Green et al., n.d.).

Table 6.12: Local Individual Risk (LIR) Vlaardingen following densification in 2100 and 2200.

	Expected annual victims in 2100	Expected annual casualties in 2200	LIR in 2100	LIR in 2200
Baseline	3	10	7.5E-6	2.4E-5
A1 (Closed seafront, keeping current water level)	<1	1	7.2E-7	1.4E-6
A2 (Closed seafront, rising water level)	<1	3	8.5E-7	6.9E-6
B1 (Closable seafront, same discharge distribution)	1	4	2.5E-6	9.1E-6
B2 (Closable seafront, changed discharge distribution	0	0	0.0	0.0

Table 6.13: Local Individual Risk (LIR) Hoeksche Waard following densification in 2100 and 2200.

	Expected annual victims in 2100	Expected annual casualties in 2200	LIR in 2100	LIR in 2200
Baseline	<1	<1	6.6E-6	2.3E-5
A1 (Closed seafront, keeping current water level)	<1	<1	5.4E-9	2.3E-8
A2 (Closed seafront, rising water level)	<1	<1	7.6E-8	1.5E-5
B1 (Closable seafront, same discharge distribution)	<1	<1	4.1E-6	1.8E-5
B2 (Closable seafront, changed discharge distribution	<1	<1	4.7E-7	1.8E-5

For the Noordereiland the baseline and alternative A2 and B1 result in a higher LIR than permitted.
For Vlaardingen and Hoeksche Waard the Local Individual Risk (LIR) is higher than the permitted value, only in 2200, with maximum of 2.3 times the norm for the baseline and 1.8 times with the alternatives implemented.
For all alternatives there is a decrease in LIR both for in 2100 and 2200 for all locations.
Because the acceptable LIR is set as a political decision, taking into account climate change effects, there could be a higher acceptable LIR set in the future (Van Alphen, 2016).

6.6. Societal risk

The reduction of flood risk by the alternatives will affect the estimated yearly fatalities, this does not only affect the local individual risk (LIR) but also the societal risk. Societal risk is defined as the probability of an event with multiple fatalities, in this context the event of a flooding where people drown.

Society weighs heavily on the prevention of large disasters with multiple fatalities, resulting in extremely high safety demands for airplanes and industrial installations.
The same holds for the event of a flooding, the dike norms are based on an economic optimum considering the maximum LIR set in the Netherlands but the dike could receive an even higher norm when a breach would mean a high casualty causing event (Van Alphen, 2016).

To discover if the societal risk of the Rhine-Meuse Estuary would be significantly impacted by the implementation of the alternatives a FN-curve is created.
The societal risk of an area is most often displayed in the form of an FN-curve; a curve showing the relation between the exceedance probabilities of an event with the corresponding fatalities it inflicts.
The formula of the FN-curve is given in Equation 6.1, taken from (Jonkman et al., 2011).

$$P(N \geq n) = P_f * e^{-\frac{(n-\xi)}{\sigma}} \; for \; n \geq \xi \tag{6.1}$$

Because the number of expected annual fatalities in the embanked areas is so close to zero for the baseline and alternatives, these have no signification share in the societal risk of the considered areas, making them not viable to display in a FN-curve.
The Noordereiland does have significant expected annual fatalities, although like described in the analyses of the section 6.5, these numbers would not be accepted by society and intermediary interventions would be inevitable.

Only the casualty estimations for the Noordereiland, following the baseline and with the implementation of alternative A2 or B1 are suitable to be converted to an FN-curve, see Figure 6.7.

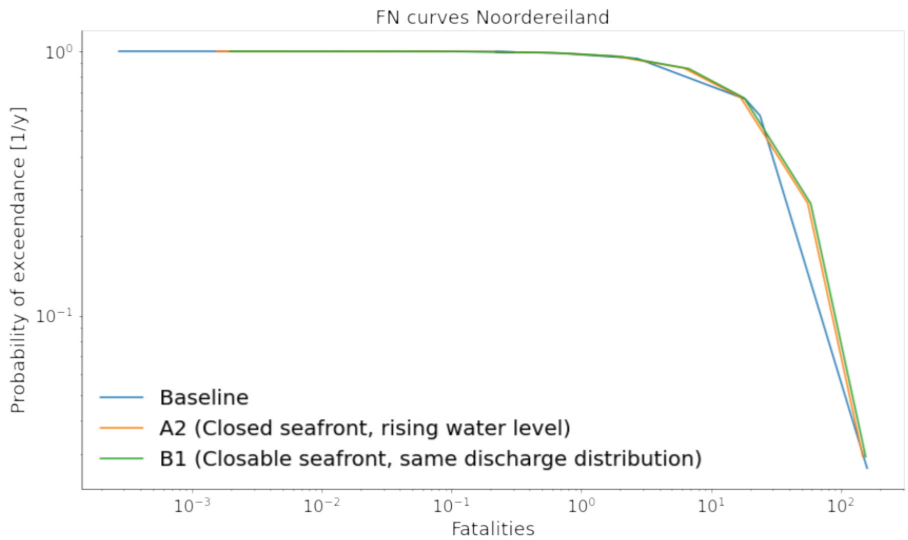


Figure 6.7: FN curve Noordereiland in the year 2200

No significant difference can be see by the implementation of any of these two alternatives, being in line with expectations by their flood risk reduction and reduction in expected annual fatalities as given in Table 6.11.
There can even be seen a small increase of the societal risk with the alternatives implemented compare to the baseline, this is most likely because of fitting error or rounding differences.

7

Influence of spatial planning on efficiency

The influence that different spatial planning strategies have on the efficiency of the alternatives will be discovered in this chapter. Spatial planning has a defining role for the exposure component of the risk formula given as Equation 2.2.
For the flood risk estimations given in chapter 6 only the densification spatial planning strategy was applied, in this chapter two other strategies will be introduced and their influence on the efficiency calculation determined, see Equation 1.1.

As provided in section 6.1, 367.100 dwellings will be distributed over the reference three locations in the Rhine-Meuse Estuary, done in the previous flood risk estimations by densification.
Densification is viewed as the most likely spatial planning strategy and is close to the current strategy that is applied in the Netherlands (Harbers et al., 2024; Rijken et al., 2016).
Still, in this chapter two other spatial planning strategies are explored being the moving to unembanked and the development of rural land.

Spatial planning strategies are only taken has having an influence on the exposure of floodings, in reality very large increases in exposure can even change the dike norm that protects these areas (subsection 2.5.2), this effect is not taken into account in this research.
Already outlined in subsection 6.1.1 an issuance level is set by the municipality of Rotterdam, all development in unembanked areas adheres to this issuance and this will be incorporated in the flood risk determinations. The calculations assume the plan capacity of 367.100 dwellings is developed within in the three locations before 2100, and the number of dwellings stay stabile until the year 2200; just as for densification.

7.1. Considered spatial planning strategies

The two spatial planning strategies that will be considered in this research, next to densification, are the following:

1. *Moving to unembanked*

   Moving to unembanked means that 70% of the plan capacity will move to the unembanked area being Noordereiland, 25% to Vlaardingen and 5% to Hoeksche Waard.
   Moving to unembanked could be considered counter-intuitive when viewed in the context of reduction of flood risk; Unembanked areas are per definition not explicitly defended against flooding.
   However, because of the limited available land for housing development, unembanked areas could be a region where housing development could take place in the (near) future.
   Some examples of planned development of unembanked areas are the Maasterras at Dordrecht and the development of the Rijnhaven in Rotterdam (Gemeente Dordrecht, n.d.; Gemeente Rotterdam, n.d.).
   As alternatives A1 and B2 immensely decrease hydraulic loading on the Noordereiland area it could be of great influence how many dwellings are present for their economic efficiency.

2. *Developing rural areas*

   Developing rural areas results in 15% of the plan capacity moving to the unembanked area, 15% to the city of Vlaardingen and 70% to the rural municipality of Hoeksche Waard.
   Rural land is defined as ”all population, housing, and territory not included within an urban area” (Department of Commerce, 2022).
   In the Netherlands a total of 54% of all land surface area is used for agricultural exploitation, making it an often discussed solution for the, able to develop, land shortage (Arcadis, 2024; CBS, 2020).
   Rural land has a relative low damage per area when flooded and thus can be interesting to see how housing development influences the exposure component and if this will significantly influence the efficiency of the alternatives.

The percentage wise distribution of the plan capacity over the different considered regions of the Rhine-Meuse estuary for both spatial planning strategies are given in Table 7.1.

Table 7.1: Distribution of plan capacity over three regions for both spatial planning strategies.

	Noordereiland	Vlaardingen	Hoeksche Waard
Moving to unembanked	70%	25%	5%
Developing rural areas	15%	15%	70%

7.2. Flood risk reduction considering spatial planning strategies

The spatial planning strategies will influence the exposure that each reference location has to flooding and with that the flood risk reduction of the alternatives.
To determine the flood risk reduction for the two introduced spatial planning strategies the exact same method is used as for the densification one, only now with the ratio of increase in dwellings being dependent on the different spatial planning strategies.
The alternatives' reduction in flood risk in 2200, as compared to the baseline, is given for the two introduced spatial planning scenarios in Table 7.2 and Table 7.3.

Table 7.2: Present value of the Estimated Annual Damage (EAD) reduction to baseline for alternatives in 2200 following moving to unembanked strategy.

	Reduction to baseline unembanked [M€]	Reduction to baseline embanked [M€]
A1 (Closed seafront, keeping current water level)	2000	19
A2 (Closed seafront, rising water level)	99	6
B1 (Closable seafront, same discharge distribution)	31	4
B2 (Closable seafront, changed discharge distribution)	2000	5

Table 7.3: Present value of the Estimated Annual Damage (EAD) reduction to baseline for alternatives in 2200 following developing rural strategy.

	Reduction to baseline unembanked [M€]	Reduction to baseline embanked [M€]
A1 (Closed seafront, keeping current water level)	555	245
A2 (Closed seafront, rising water level)	27	76
B1 (Closable seafront, same discharge distribution)	9	47
B2 (Closable seafront, changed discharge distribution)	556	55

As expected by moving the unembanked the flood risk reduction effect of the alternatives is larger than for the densification strategy. The embanked flood risk reduction part is larger than for densification, explained by the increase of dwellings, but still not significant compared to the unembanked part.
The effect of alternatives A1 and B2 is unchanged in being a high multitude of the A2 and B1 alternatives' effects.
The development of rural land results in the flood risk reduction for unembanked areas drastically decreasing as compared to the densification strategy. The added flood risk reduction for embanked areas does not compensate for this effect.

With the unembanked and embanked flood risk reduction being determined for both introduced spatial planning scenarios, these can be input in the economic efficiency equation as factor A and B (see Equation 1.1), resulting in the corresponding economic efficiency of the alternatives.

7.3. Efficiency considering spatial planning strategies

With the reduction in flood risk determined, for the two introduced spatial planning scenarios, the normalized efficiency of the alternatives can be determined, these are given in Table 7.4 and Table 7.5. The economic efficiency is determined in the same manner as for the densification strategy, using Equation 1.1 but now with the A and B factors (unembanked and embanked flood risk reduction) corresponding to the Table 7.2 and Table 7.3 figures. Normalization of the dike reinforcement cost reduction and cost of implementation the alternatives is also done in the exact same manner as for densification.

Table 7.4: Normalized efficiency determination corresponding to moving to unembanked strategy.

	Reinforcement cost reduction [M€]	Reduction in flood risk [M€]	Cost of alternative [M€]	Efficiency [-]
A1 (Closed seafront, keeping current water level)	233	2040	1655	1.37
A2 (Closed seafront, rising water level)	127	106	1511	0.15
B1 (Closable seafront, same discharge distribution)	60	35	1079	0.09
B2 (Closable seafront, changed discharge distribution)	223	2027	1511	1.49

Table 7.5: Normalized efficiency determination corresponding to moving to rural strategy.

	Reinforcement cost reduction [M€]	Reduction in flood risk [M€]	Cost of alternative [M€]	Efficiency [-]
A1 (Closed seafront, keeping current water level)	233	800	1655	0.62
A2 (Closed seafront, rising water level)	127	103	1511	0.15
B1 (Closable seafront, same discharge distribution)	60	56	1079	0.11
B2 (Closable seafront, changed discharge distribution)	223	611	1511	0.55

The spatial planning strategies have a significant impact on the efficiency of the alternatives.
Moving to unembanked increases the efficiency to being far above cost effective for alternatives A1 and B2. There is no significant change to the economic efficiency of alternatives A2 and B1, staying far below 1.0.
Developing rural land makes each alternative have an efficiency below 1.0 caused by the very large reduction in unembanked flood risk reduction, while only slightly increasing the embanked flood risk reduction effect.

The results show that spatial planning strategies have a significant impact on the economic efficiency of the alternatives, and this should be taken into account when decisions have to made about implementing, if any, which alternative.
This works the other way around as well, steering a specific spatial planning strategy to become the governing one for the Rhine-Meuse Estuary could have large impacts on the efficiency of the alternatives. This principle could be a part of the decision makers argumentation wether or not to implement a certain alternative or similar large scale hydraulic measures.
If steering inhabitants towards certain regions, as part of an argument to justify the implementation of an alternative, is possible or desired is outside the scope of this research.

8

Well founded comparison alternatives

Now all results are determined they can be gathered in a single table, to have a complete and well founded comparison of the alternatives, see Table 8.1.
This table gives a complete picture of the most important economic and non-economic effects the implementation of the alternatives will have compared to the baseline.
The baseline is the strategy of only reinforcing dikes to keep within norm and not implement the alternatives at all, equal to the current strategy applied in the Netherlands.
The economic efficiency of the implementation of the alternatives is determined by the four factors A,B,C and D given in Equation 8.1.

$$Economic\,efficiency\,of\,alternative = \frac{A+B+C}{D} \tag{8.1}$$

Where:

$$A = reduction\,of\,flooding\,probability\,and\,effect\,of\,unembanked\,areas\;[€]$$
$$B = reduction\,of\,flooding\,effect\,of\,embanked\,areas\;[€]$$
$$C = reduction\,of\,dike\,reinforcement\,costs\;[€]$$
$$D = added\,cost\,of\,alternative\,system\,measures\;[€]$$

In the numerator are the three economic benefits the alternatives have on flood risk reduction, in estimated annual damage (EAD), and the reduction in cost of necessary dike reinforcements, all in comparison to the baseline.
In the denominator is the cost of the implementation of the alternative, based on the implementation in the year 2100.
All economic factors and non-economic indicators are calculated up to the year 2200, the economic factors are all made to present value with a discount rate of 1.6%.

Table 8.1 shows, for each spatial planning strategy, the economic factors that will result in the economic efficiency of the alternatives.
The non-economic factors considered; the dike reinforcement land use reduction and the amount of averted dike reinforcements, are given in the bottom two rows for each alternative.
The reduction in dike reinforcement cost and the cost of implementation of the alternatives, are not dependent on the spatial planning strategies, they are normalized like described in subsection 6.4.2.

Table 8.1: Complete comparison of all alternatives normalized economic factors (in M€), economic efficiency and non-economic indicators, for each spatial planning strategy.

		A1 (Closed seafront, keeping current water level)	A2 (Closed seafront, rising water level)	B1 (Closable seafront, same discharge distribution)	B2 (Closable seafront, changed discharge distribution)
Spatial planning strategies	Densification	A = 1512 B = 9 C = 233 D = 1655 Econ.Eff. = 1.06	A = 74 B = 4 C = 127 D = 1511 Econ.Eff. = 0.14	A = 23 B = 3 C = 60 D = 1079 Econ.Eff. = 0.08	A = 1512 B = 4 C = 223 D = 1511 Econ.Eff. = 1.15
	Move to unembanked	A = 2021 B = 19 C = 233 D = 1655 Econ.Eff. = 1.37	A = 99 B = 6 C = 127 D = 1511 Econ.Eff. = 0.15	A = 31 B = 4 C = 60 D = 1079 Econ.Eff. = 0.09	A = 2022 B = 5 C = 223 D = 1511 Econ.Eff. = 1.49
	Develop rural land	A = 555 B = 245 C = 233 D = 1655 Econ.Eff. = 0.62	A = 27 B = 76 C = 127 D = 1511 Econ.Eff. = 0.15	A = 9 B = 47 C = 60 D = 1079 Econ.Eff. = 0.11	A = 556 B = 55 C = 223 D = 1511 Econ.Eff. = 0.55
Non-economic indicators	Land use reduction	1.5 km^2	0.6 km^2	0.8 km^2	1.2 km^2
	Averted reinforcements	1183	612	447	1042

Factor A (flood risk reduction unembanked)
Alternative A1 and B2 have the most unembanked flood risk reduction, alternative A2 and B1 significantly less.
For spatial planning strategies densification, and the move to unembanked, the unembanked flood risk reduction alone is enough to make alternative A1 and B2 economically efficient.
The unembanked flood risk reduction is by far the largest factor in the efficiency determination for each alternative.

Factor B (flood risk reduction embanked)
The flood risk reduction for embanked areas is not significant for any of the alternatives.
However, in the develop rural land spatial strategy the flood risk reduction for embanked areas is at least a factor 10 higher than in the other two spatial planning strategies.
This is for a large part because the applied method for flood risk determination only takes into account outside water level and not flooding duration or intensity.

Factor C (dike reinforcement cost reduction)
Alternative A1 and B2 reduce the normalized dike reinforcement cost by more than 200 million euros.
Alternative A2 doesn't exceed a cost of reduction 127 million euros, B1 about half that.

Factor D (cost of implementation measure)
Alternative A1, A2 and B2 cost around a normalized 1.5 billion euros to implement, B1 is significantly cheaper with a cost of around 1 billion, this is not enough to justify the difference in beneficial effects.

Economic efficiency
A1 and B2 have a economic efficiency that is above 1.0 for the densification and move to unembanked spatial planning strategies, meaning that if these spatial planning strategies are to be implemented, these alternatives would be cost effective.
A2 and B1 are for none of the spatial planning strategies cost effective, they both have a economic efficiency far below 1.0.

The influence of spatial planning on a alternatives' efficiency is massive: A1 goes from 1.06 to 1.37 if densification is replaced by moving to unembanked, a 29.2% increase.
Alternative B2 goes from 1.15 to 1.49 if densification is replaced by moving to unembanked, a 29.6% increase.
This effect mainly comes from the influence of spatial planning on the flood risk reduction effect of unembanked areas.
The spatial planning strategy of developing rural land lowers the flood risk reduction of all alternatives so significantly that none of the alternatives are cost efficient.

Land use reduction
Land use reduction of dike reinforcements is higher for alternative A1 and B2 than A2 and B1.
This is mainly because of the reduction in hydraulic loading that the lower Rhine-Meuse Estuary experiences when A1 and B2 are implemented.
The surface area of land saved could be used for development of housing, commercial properties, nature additions or recreational areas, all just behind the dike bodies.

Averted dike reinforcements
The amount of averted dike reinforcements is significant for all alternatives.
Especially for the nearby residents of dikes this would mean the prevention of large amounts of nuisance, if they have to be reinforced up to three times less until the year 2200.
For locations where dike reinforcements are exceptionally difficult to execute, like historic city centers, this reduction in the amount of reinforcement operations could be a deciding factor for which alternative has the preference.

9

Discussion

Alternative A1 (Closed seafront, keeping current water level) and B2 (Closable seafront, changed discharge distribution) are the only alternatives that can be considered cost effective with a economic efficiency of 1.06 and 1.15 respectively, for the most likely spatial planning strategy: densification.
Their efficiency is even higher with the move to unembanked spatial planning strategy.
Alternative A2 (Closed seafront, rising water level) and B1 (Closable seafront, same discharge distribution) have a cost efficiency lower than 0.2 for all spatial planning strategies.
The spatial planning strategy of developing rural land makes all alternatives have a economic efficiency lower than 1.0.

This study demonstrates a significant influence of spatial planning strategies on the efficiency of large scale flood risk reduction measures (the alternatives).
The flood risk reduction of unembanked areas has by far the largest positive influence on the efficiency of an alternative. This reduction is the highest for the A1 and B2 alternatives, making these the only two cost effective alternatives.
Dike reinforcement cost reduction is significant and accounts for a maximum of around 1/7 of the cost of implementation of the alternatives.
The cost difference between the alternatives is not large enough to overcome the difference of their benefits.

This is a continuation on the alternatives' impact on hydraulic loading for the Rhine-Meuse Estuary, calculated for the research program Knowledge Program Sea level Rise track 4.
This study provides new insight into the relationship between spatial planning strategies and in what manner, and to what extent, they influence the economic efficiency of implementing measures.
The alternatives' dike reinforcement cost reduction hasn't been explored further than linear approximations, now with the use of OKADER the effect of the alternatives are calculated with more precision.
The number of averted dike reductions, where these would take place and corresponding land use reduction has not been researched before this study for the considered alternatives.
The relation between hydraulic loading reductions and their impact on averted dike reinforcements and land use reduction is now made clear.

The findings of this research show that only the strategies A1 and B2 from Knowledge Program Sea level Rise track 4 are worth exploring further if economic efficiency is considered. The influence of spatial planning on the efficiency of large scale system level measures hasn't been researched before, now that is determined that the effect of spatial planning is significant, this should be a well considered factor in future research on this subject.
This research is entirely based on already existing data sets; hydraulic loading and cost of implementing the alternatives are based on the strategies from Knowledge program track 2 and 4, flood damage estimations are based on existing LIWO scenarios.
This leads to some constraints in the methodological choices by the input data quantity, quality, and availability.

The hydraulic loading data is determined for the Very Extreme climate scenario making it impossible to consider other, less extreme climate scenarios and how this will influence the effeminacy fo the alternates.
The hydraulic loading data is structured in such a way that only two of the three available OKADER failure modes for dike sections can be considered in the calculations of the dike reinforcement demand. The available two being macro stability and piping; overtopping is not taken in to account and thus leads to a blind spot in how this failure mode would influence the outcomes of OKADER.

The LIWO scenarios that are available are not evenly distributed over the Rhine-Meuse Estuary and for unembanked areas often not available at all. This constraint in data leads to the methodological choice to schematize the Rhine-Meuse Estuary in three locations and use these as reference for the flood risk estimations.
The schematization leads to the need for a normalization of the dike reinforcement cost reduction and the cost of implementation of the alternatives. This normalization is a direct factor on the efficiency determination and could skew the economic efficiency of the alternatives.

The determination of flood risk reduction is done by utilizing a damage curve based on the extrapolation of available LIWO scenarios, extrapolated based on outside water level.
By not taking into account the duration and intensity of flooding for this extrapolation the result of flooding reduction of embanked areas are expected to be underestimated.
Also the flood risk reduction determination method does not take into account second order effects like indirect damages because of flooding and the value of the land saved which could be a large factor.

Finally, the non-economic factors like averted dike reinforcements and dike reinforcement land use reduction are not explored further while these effects could have a large impact on decision makers' preferences of which alternative, if any, to implement. Averted dike reinforcements and land use reduction could have massive impact on the feasibility of dike reinforcement projects especially in historic regions and with nearby protected nature.
The non-economic factors of the alternatives that are not considered in this research like salt intrusion and feasibility of the alternatives' measures construction could also be important decision steering factors.

10

Conclusion and recommendations

10.1. Conclusion

The main question of this research is: *how do the proposed flood risk management alternatives compare in terms of economic efficiency across various spatial planning scenarios for the Rhine-Meuse estuary?*

The alternatives are the implementation of large scale hydraulic interventions on the Rhine-Meuse Estuary water system. The economic efficiency of an alternative is determined by its economic benefit, compared to the baseline (to only reinforce dikes), divided by the cost of its implementation.
Because the alternatives' flood risk reduction is not determined for the whole Rhine-Meuse Estuary the dike reinforcement cost reduction, and cost of implementation of the alternatives, are normalized when the efficiency is considered.

The main question is answered by considering the answers to the following sub questions:

- *What is the future hydraulic loading of the Rhine-Meuse Estuary because of climate change and what is the alternatives influence on it?*

  The future hydraulic loading is given as water level frequency curves, following the very extreme climate scenario that is considered in Knowledge Program Sea Level Rise track 2.
  As a result of sea level rise and higher peak river discharges a significant increase in hydraulic loading is predicted, especially for the lower Rhine-Meuse Estuary.
  The alternatives A1 (Closed seafront, keeping current water level) and B2 (Closable seafront, changed discharge distribution) lower the hydraulic loading drastically especially for the Rotterdam area along the Nieuwe Maas, alternatives A2 (Closed seafront, rising water level) and B1 (Closable seafront, same discharge distribution) have less significant hydraulic impact.

- *What is the impact of an alternative on the necessary future dike reinforcement costs?*

  Alternative A1 and B2 have the highest cost reduction for dike reinforcement, being 970 and 930 million euros respectively, in present value until 2200.
  Alternatives A2 and B1 have considerable lower impact on dike reinforcement cost, resulting in a reduction of 530 and 250 million euros.
  All reduction in dike reinforcement cost is caused by the reduction of hydraulic loading as an effect of the implementation of the alternatives, the majority of the cost reduction is for the dike sections in the lower Rhine-Meuse Estuary especially along the Lek and Nieuwe Maas rivers.

- *How many dike reinforcement instances are averted by implementing the alternatives and how much land use is avoided?*

  Alternative A1 and B2 avert the highest amount of dike reinforcements being 1183 and 1042 respectively until 2200. Alternatives A2 and B1 avert about half that; 612 and 447 dike reinforcements are averted by implementing these alternatives.
  Within the Rhine-Meuse Estuary, 1100 dike sections are considered; on average every single dike section has one reinforcement instance less than the baseline would have for A1 and B2.
  This amount of dike reinforcements averted as a result of the alternatives is significant, especially because of the challenges that dike reinforcements operations have like protected historic areas and existing nature protection laws.
  The reduction of hydraulic loading as an effect of the alternatives leads to the following reduction in land use; 1.5 and 1.2 squared kilometer for alternative A1 and B2 respectively, 0.6 and 0.8 squared kilometer of land use is avoided by implementing A2 and B1.
  Most averted dike reinforcements and land use reduction will be in the lower Rhine-Meuse Estuary, where the alternatives' hydraulic loading reduction is the largest.

- *To what extend do the proposed alternatives reduce flood risk of unembanked areas?*

  Alternative A1 and B2 reduce the unembanked flood risk the most, both reduce the flood risk with 1512 million euros of Estimated Annual Damage (EAD) until 2200 compared to the baseline.
  Alternatives A2 and B1 have no significant impact with 74 and 23 million euros of EAD reduction respectively.

- *To what extend do the proposed alternatives reduce flood risk of embanked areas?*

  None of the alternatives result in significant flood risk reduction for the embanked areas.
  Both the alternatives A2 and B2 reduce flood risk with 4 million euros EAD, alternatives A1 and B1 reduce the flood risk of embanked areas with 9 and 3 million euros EAD respectively.

- *What is the normalized economic efficiency of the alternatives?*

  The economic efficiency of the alternatives, considering the most likely densification spatial planning strategy, is 1.06 and 1.15 for alternative A1 and B2 respectively.
  For alternatives A2 and B1 the economic efficiency is considerably lower being 0.14 and 0.8.

- *How will different spatial planning strategies affect the economic efficiency of the alternatives?*

  There is a significant impact of the spatial planning strategies on the economic efficiency of the alternatives.
  The impact is especially impactful for the alternatives A1 and B2 moving to a efficiency of 1.37 and 1.49 respectively if the move to unembanked spatial planing strategy is applied.
  The development of rural land spatial planning strategy has a negative impact on the efficiency of these two alternatives specifically, both becoming lower than 1.0 with 0.62 and 0.55 for A1 and B2 respectively.
  The economic efficiency of the alternatives A2 and B1 are largely unchanged between the spatial planning strategies and stays around 0.1.
  Almost all of the influence of the spatial planning strategies have on the economic efficiency is caused by the difference in the unembanked flood risk reduction.

Finally to conclude, the answer to the main question can be given: *how do the proposed flood risk management alternatives compare in terms of economic efficiency across various spatial planning scenarios for the Rhine-Meuse estuary?*

For the most likely spatial planning strategy, densification, alternatives A1 (Closed seafront, keeping current water level) and B2 (Closable seafront, changed discharge distribution) are the most efficient with an economic efficiency of 1.06 and 1.15 respectively.
Alternatives A2 (Closed seafront, rising water level) and B1 (Closable seafront, same discharge distribution) have an economic efficiency far below 1.0 at 0.14 and 0.08.
If the spatial planning strategy would become moving to unembanked areas, alternatives A1 and B2 are even more efficient with an economic efficiency of 1.37 and 1.49 respectively, A2 and B1 are far below 1.0 at 0.15 and 0.09.
For the spatial planning strategy of developing rural land, the alternatives' economic efficiency is below 1.0 for all alternatives, with A1 and B2 having 0.62 and 0.55 respectively.
Alternatives A2 and B1 result in an economic efficiency of 0.15 and 0.09, equal with the unembanked strategy.
Alternatives A1 and B2 are cost effective, with an economic efficiency above 1.0, this holds only for the densification and move to unembanked spatial planning strategies.

General conclusion by this research are that the protection of unembanked regions are extremely important beneficial effects of large scale hydraulic measures, being the largest beneficial factor to economic efficiency.
The hydraulic loading reduction, that large scale hydraulic measures result in, has significant impact on dike reinforcement needs and leads to a reduction in the amount, economic cost, and lands use of dike reinforcements to keep dikes up to norm.
Spatial planning, in the form of dwelling distribution, has significant influence on the economic efficiency of large scale hydraulic measures. The distribution of dwellings dictates, for a large part, the exposure component of flood risk and thus on the measures' resulting flood risk reduction.

10.2. Recommendations

Based on the efficiency of the alternatives only the A1 (Closed seafront, keeping current water level) and B2 (Closable seafront, changed discharge distribution) alternatives from Knowledge Program Sea Level Rise track 4 should be considered as viable strategies for the high water protection of the Rhine-Meuse Estuary.
Spatial planning is an important factor for the economic efficiency of an alternative and should be a well considered factor in all following research and decision making challenges.

The flood risk reduction of the alternatives is extremely important for their economic efficiency. The option to specifically relieve the unembanked areas from the hydraulic loading increase is expected to be very cost efficient, this would be a separate alternative with some elements from A1 and B2 implemented, and could include local measures like local flood barriers along the rivers.

Recent initiatives like "Water en bodem sturend" are focused on lowering, or minimally increasing, the exposure to areas that are relatively vulnerable to flooding, and advise on developing housing and economic activities in already well protected areas. This research shows that contrary to that, this will most likely lower the economic efficiency of future large scale hydraulic measures. If the implementation of large scale hydraulic measures is seriously considered, their protection of highly vulnerable areas could be an argument to still develop these areas. Such a decision would be highly consequential, possibly controversial, and make the implementation of hydraulic measures necessary after such a decision has resulted in the development of highly vulnerable areas.

Because the normalization of the Rhine-Meuse Estuary wide effects is so detrimental for the determination of the economic efficiency of an alternative this should be be improved.
The normalization is necessary because not all flood reduction effects of the alternatives could be determined with the current method and quantity and quality of the LIWO scenarios.
Developing a method where all flood risk reduction effects can be determined would reduce uncertainty in the results and remove the need of the normalization step.

The dike reinforcement calculations are done using OKADER considering failure modes macro stability and piping but does not consider overtopping, how large the impact of including this failure mode is should be investigated.
Only the very extreme climate scenario is considered for all hydraulic loading, a more likely climate scenario should be investigated as well to see how this will influence the efficiency.
The spatial planning scenarios would introduce very high population density increases in all considered areas, how realistic this would be considering components like technical feasibility, nature protection laws and national and regional politics should be investigated.

The non-economic effects, averted number of dike reinforcements and land use reduction, could be very important, especially on local level. These effects should be taken into account when comparing alternatives, avoided reinforcements in an historic city center could be viewed, on local level, even more important than the total economic efficiency.
Also, the nuisance factor of the reinforcements, possible secondary damages to nearby structures, complying to nature protection laws, and the loss of usable land could be deciding factors in the choice whether or not to implement an alternative.

With the method to determine the economic efficiency of large scale hydraulic interventions now developed, it can be applied to other alternatives as well. The other two directions from the Knowledge Program Sea Level Rise track 4; ”Accommodate” and ”Advance”, could be analyzed with the same method, and their economic efficiency compared to the each other and to the alternatives from direction ”Protection”.

Final recommendation is to include not only the water level for the flooding effects estimations but also the longevity of the outside water level. This could be of large influence on the embanked areas specifically and some alternatives could even increase flooding damages, compared to the baseline, because of longevity of the outside water level being higher.

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A

Delta Works

Figure A.1: Delta Works with year of construction (IenW, 2024a)

B

Hydraulic loading Vlaardingen

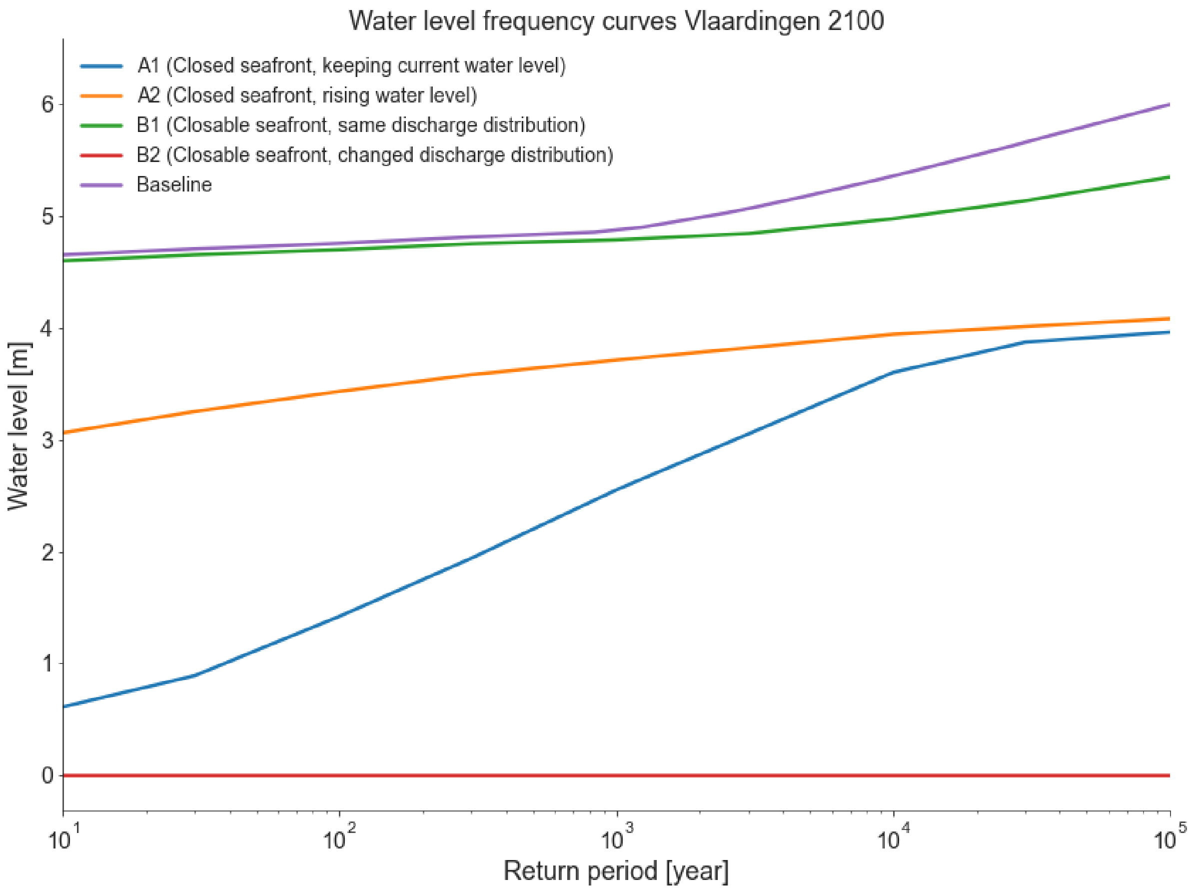

Figure B.1: Hydraulic loading for Vlaardingen in 2100 for baseline and alternatives.

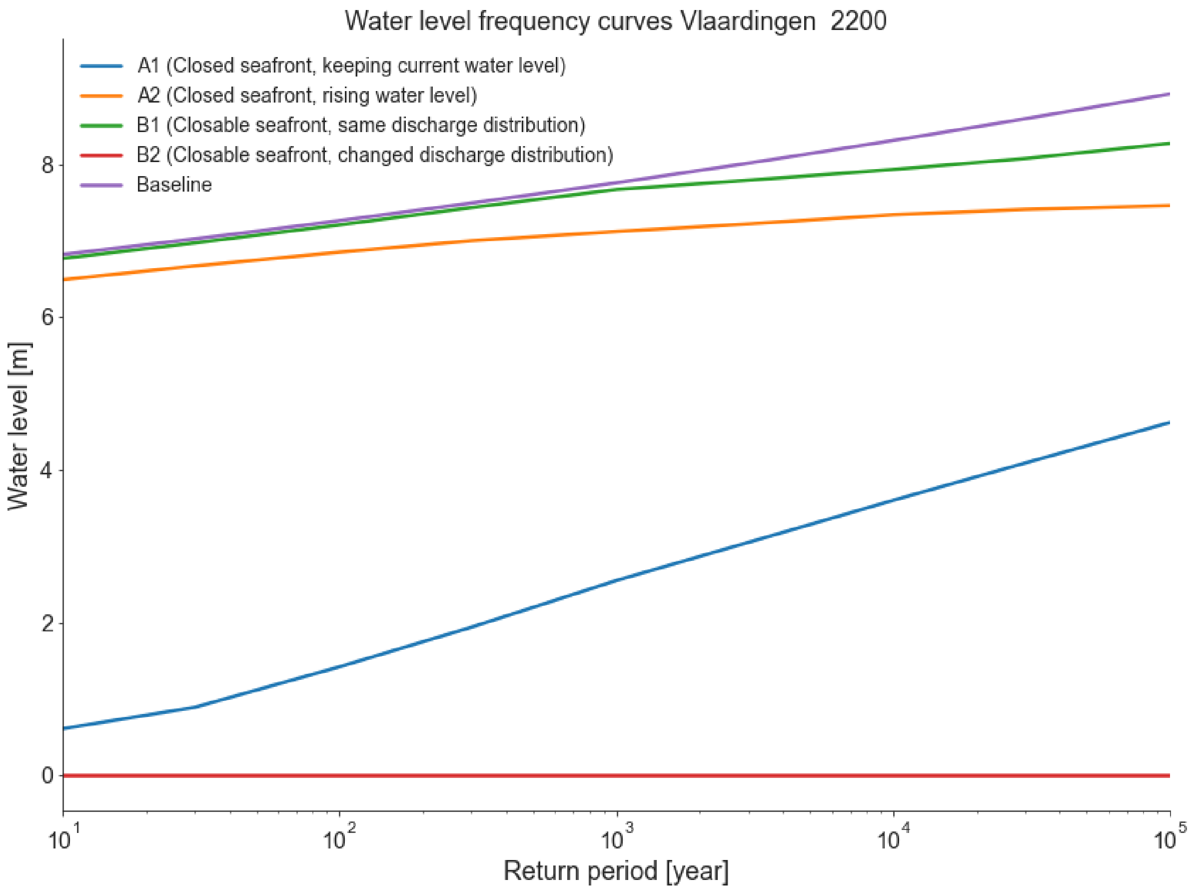

Figure B.2: Hydraulic loading for Vlaardingen in 2200 for baseline and alternatives.

C

Hydraulic loading Hoeksche Waard

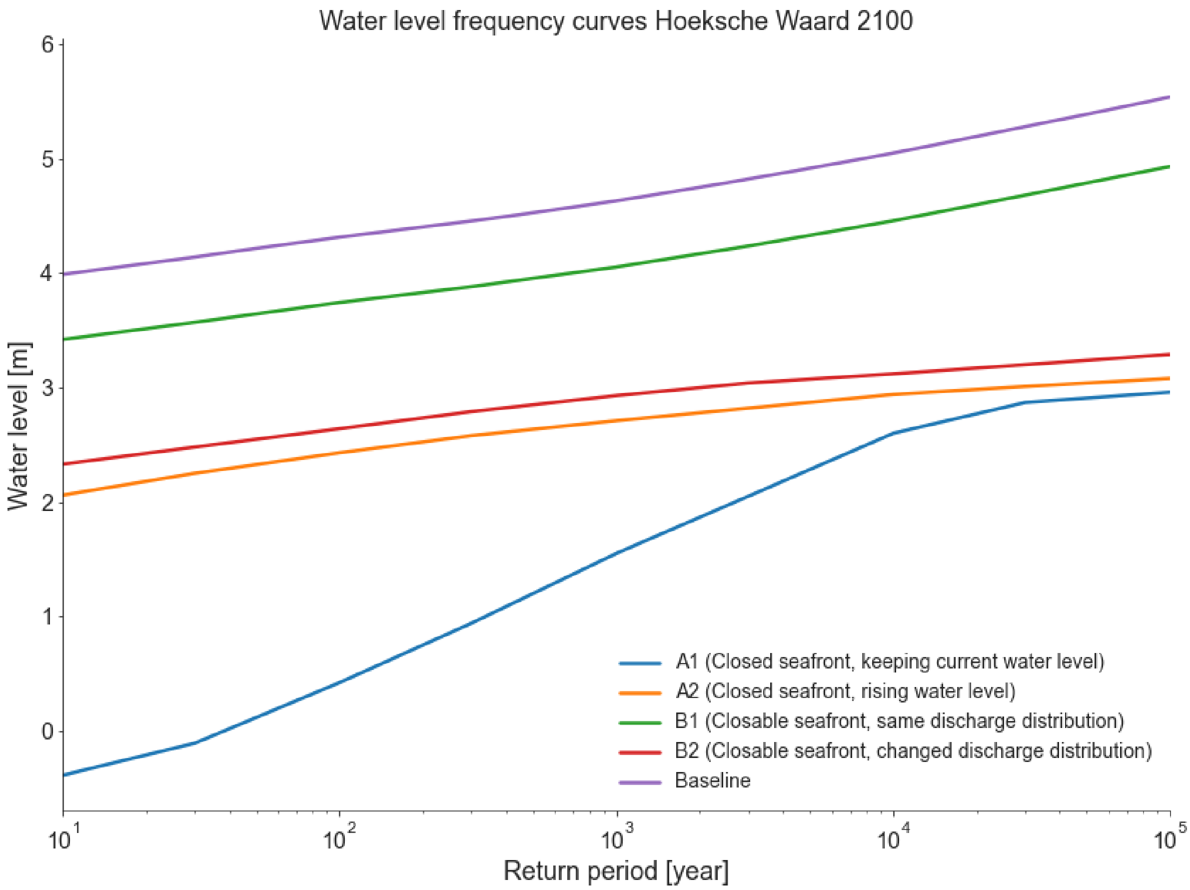

Figure C.1: Hydraulic loading for Hoeksche Waard in 2100 for baseline and alternatives.

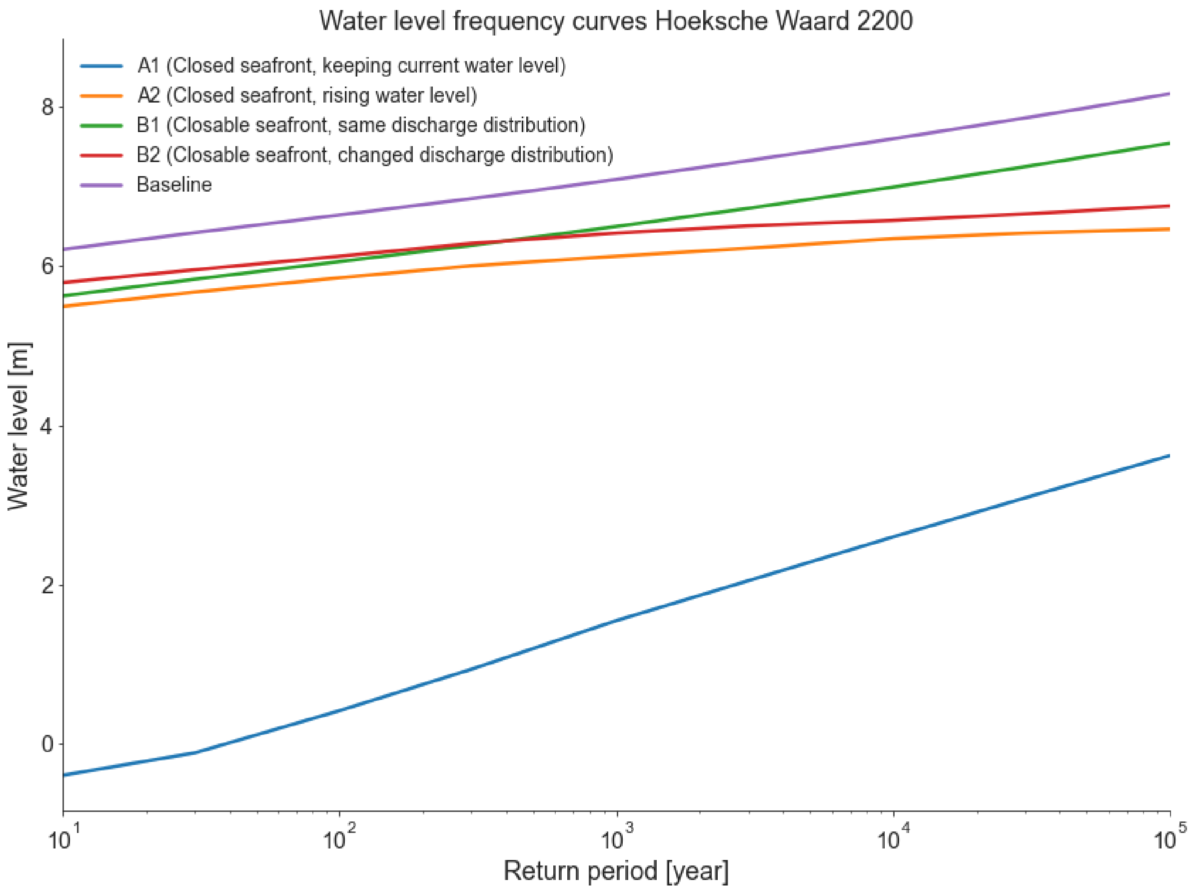

Figure C.2: Hydraulic loading for Hoeksche Waard in 2200 for baseline and alternatives.

D

Alternatives' hydraulic loading reduction

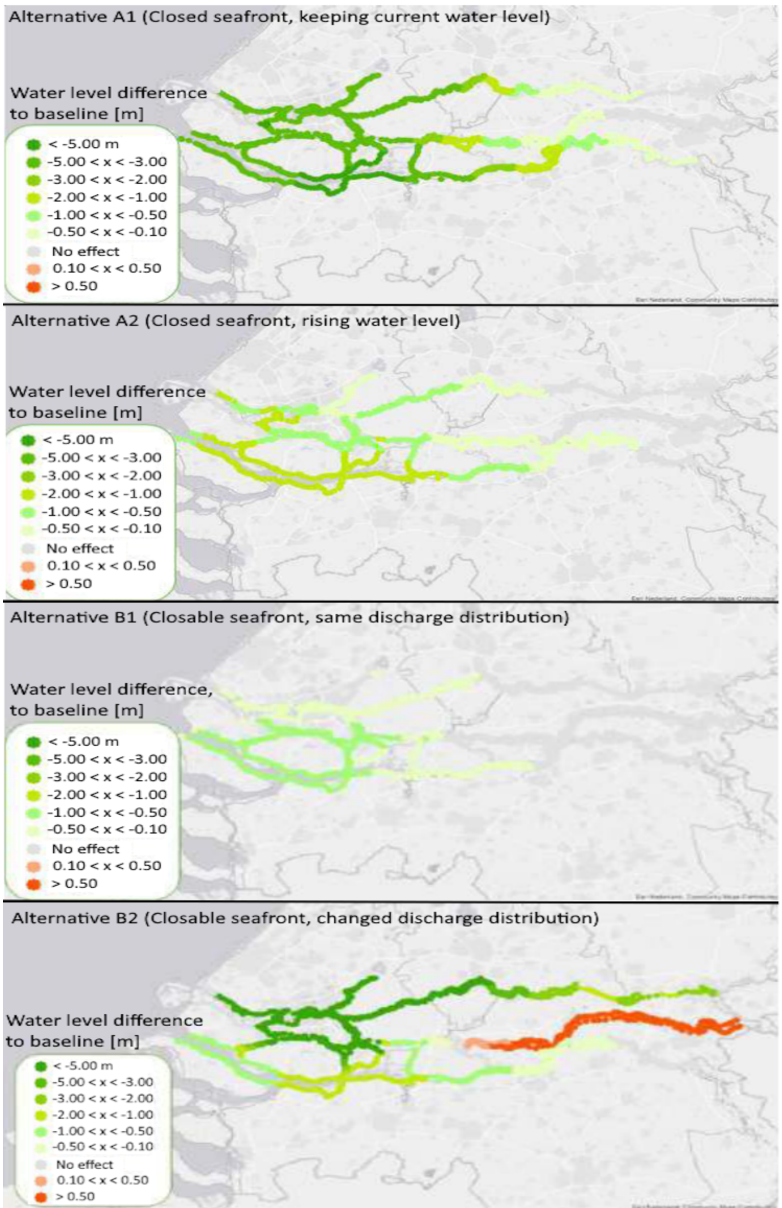

Figure D.1: Difference in water level, corresponding to 10.000 year return period, between baseline and alternatives for the whole Rhine-Meuse Estuary in the year 2200, adapted from van der Biezen et al. (2024).

E

LIWO parameters

LIWO parameters for the Noordereiland flood risk estimations are given in table Table E.1.

Table E.1: LIWO parameters for the Noordereiland flood risk estimations (IenW, 2024b; Royal HaskoningDHV, 2018).

Parameter	Used for the Noordereiland scenario
Project	Waterveiligheid buitendijks, Werken aan waterveiligheid in het Rotterdamse buitendijks stedelijk gebied
Method	Standaard methode Schade en slachtoffers als gevolg van overstromingen (Slager & Wagenaar, 2017)
Creation date	Between 01-2018 and 04-2022
Outside water type	Large river
Modeling software	GlobalFloodRiskTool
Model resolution	5 m
Stability local dikes	Yes
Method for casualties	Risico Applicatie Buitendijks (RAB)
Damage curves	Standaard methode Schade en slachtoffers als gevolg van overstromingen

LIWO parameters for the Vlaardingen flood risk estimations are given in table Table E.2.

Table E.2: LIWO parameters for the Vlaardingen flood risk estimations (IenW, 2024b; Jongejan, 2010).

Parameter	Used for the Vlaardingen scenario
Project	Onderzoek compartimenterende keringen
Method	Equal as used for VNK2 (Jongejan, 2010)
Creation date	14-01-2015
Outside water type	Large river
Modeling software	Sobek 2.13.002
Model resolution	100 m
Stability local dikes	Yes
Method for casualties	Standaard methode Schade en slachtoffers als gevolg van overstromingen
Damage curves	Standaard methode Schade en slachtoffers als gevolg van overstromingen

LIWO parameters for the Hoeksche Waard flood risk estimations are given in table Table E.3.

Table E.3: LIWO parameters for the Hoeksche Waard flood risk estimations (IenW, 2024b).

Parameter	Used for the Hoeksche Waard scenario
Project	Nut en noodzaak compartimenteringskeringen
Method	Equal as used for VNK2 (de Groot, 2014)
Creation date	Between 11-2013 and 04-2019
Outside water type	Large river
Modeling software	SOBEK 2.13.002
Model resolution	50 m
Stability local dikes	No
Method for casulties	Standaard methode Schade en slachtoffers als gevolg van overstromingen
Damage curves	Standaard methode Schade en slachtoffers als gevolg van overstromingen