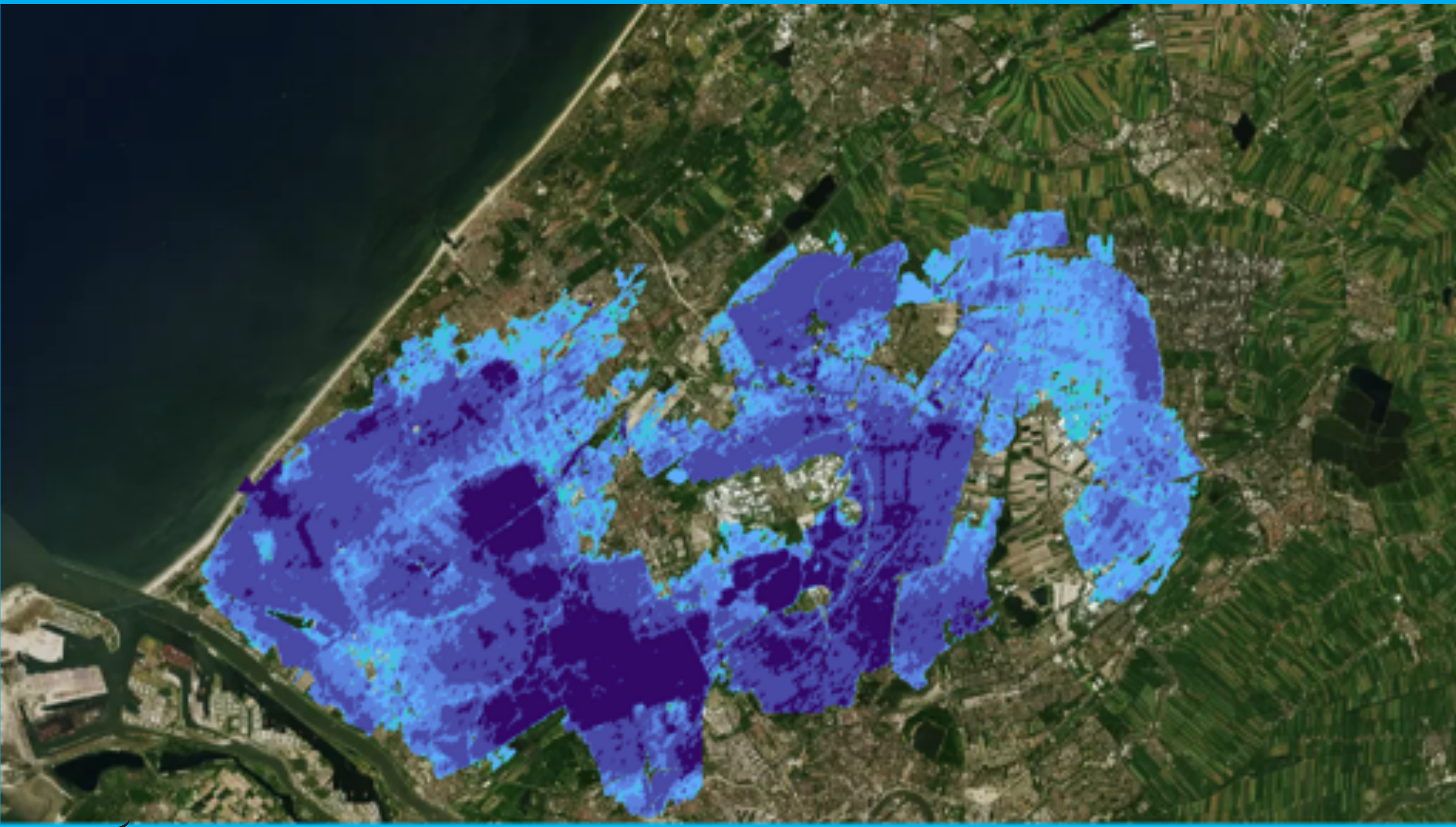
Assessment of changes in flood risk in South Holland due to sea level rise:

How can the dunes of dijkring 14 cope with sea level rise ?

M.W.(Marijn) Meyer Ranneft



TUDelft

Assessment of changes in flood risk in South Holland due to sea level rise:

How can the dunes of dijkring 14 cope with sea level rise ?

by

M.W.(Marijn) Meyer Ranneft

to obtain the degree of Master of Science
at the Delft University of Technology,

Student number:	4230248	
Thesis committee:	Prof. dr. ir. M. Kok,	TU Delft, supervisor
	Dr. ir. R. C. Lanzafame,	TU Delft
	Dr. ir. M. M. Rutten,	TU Delft
	Ir. M. Bos,	Royal HaskoningDHV

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

TU Delft

Preface

This thesis concludes two years of study on the degree of Hydraulic Engineering. During the several months of research the courses and trades of the specialisation of Flood Risk in the track Hydraulic Engineering were extensively used. Especially the economical optimisation of changes in flood risk that are faced in the Netherlands caught my attention during the courses. This resulted in a research in the influence of the sea level rise on the flood risk of South Holland.

Due to the climate change, sea level rise is currently a hot topic. When this thesis was written multiple articles were published and wild rumours spread that the Dutch children had to start learning German as the Netherlands would flood. However, all these researches and future planning were lacking a quantitative estimation of the current flood defences subjected to hydraulic boundary conditions that included sea level rise. Together with the chairmen of my graduation committee, Matthijs Kok, I concluded that missing piece was needed. In this research it was attempted to determine whether the strengthening the current flood defence system would result in sufficient safety and adequate flood risk. During this research it became clear that determining the possibility to keep protecting the Netherlands by strengthening the current flood defences was rather as PhD thesis then a Msc. thesis. The complexity and the amount of different estimations would not suit a research of several months. This led to a focus on the coastal South Holland area, especially on the dune flood defences.

When discussing the subject of this thesis I had the luck to come across my daily supervisor of Royal HaskoningDHV, Matthijs Bos. He was working on the development of the state of the art Global Flood Risk Tool of Royal HaskoningDHV. When we sat down and discussed the topic of my masters thesis it became clear that our shared interest in the influence of sea level rise on the flood risk would benefit my research significantly. Royal HaskoningDHV offered me a graduation internship and I had the possibility to do the research for them.

During this research I had the opportunity to work with the Delft3D D-Flow Beta software which is being developed by Deltares. This software is not yet available to the public, however I was allowed to use and test its functionality. Working with this software led to exciting new insights and frustrating unexpected errors. Besides the Delft3D D-Flow software Royal HaskoningDHV provided me with their state of the art Global Flood Risk Tool which allowed me to use cloud computing to estimated the damages imposed by the flooded area. This significantly reduced the computing time and resulted in a more flexible research.

I take pride in quantifying the influence of sea level rise on the flood risk of South Holland by using state of the art software. I've used lots of different software programs to extract and combine the information from land use, hydrodynamic simulations and economic optimisations. Countless hours were spend on writing code, learning to use the software and designing a hydrodynamic model. They were all working towards the final result.

I am thankful for those who helped me during this process. First of all I would like to thank the members of my thesis committee. Lots of thanks to Matthijs Kok who inspired me during his lectures on economic optimisation and provided me with this interesting subject. My sincerest gratitude to Matthijs Bos who extensively mentored me during the course of this research. He guided me while working at Royal HaskoningDHV, was always available when needed and took much of his own valuable time to personally assist me. I would like to thank Robert Lanzafame for helping me getting a thorough understanding of the subject and aiding me to answer the right questions. Martine Rutten brought me a lot of enthusiasm and gave me new insights on the matter. While only meeting a few times she pushed me to reflect on the research. Then I would like to thank Marcela Busnelli who provided me with hands on support during the design of the hydrodynamic model. Her hours of working together really accelerated the process.

Last but not least, I would like to thank the people that supported me during this graduation process. I am grateful for the support of my parents throughout my studies. Thankful to my colleagues' at the Nicolaas Maesstraat who highly contributed in taking pleasure in graduating during these strange times. Finally I would like to thank my girlfriend, Ileen, for the support and love during my entire studies.

M.W.(Marijn) Meyer Ranneft
Amsterdam, December 2020

Abstract

Economic risk due to a potential flood event is determined by combining the estimated damages and the probability of failure for many scenarios. In recent research of the IPCC (Intergovernmental Panel on Climate Change) it was stated that the sea level will rise more than expected due to climate change . This could influence the flood risk in coastal areas including the Netherlands. In this thesis the influences of the sea level rise on the flood risk for dijkring 14 will be evaluated.

Dijkring 14 is located in the coastal area of the Netherlands and contains Rotterdam, the Hague and parts of Utrecht and Amsterdam. It has 3.500.000 inhabitants, consists of an area of 224.000 acres and has the largest potential economic damages. The average elevation of the dijkring is one meter below NAP. The coastal area is protected by hydraulic structures and dunes which are both subjected to an increase of probability of failure due to sea level rise. In this thesis it is assessed if the protection of the coastal area by means of dunes is possible in case of an extreme sea level rise future scenario.

With an hydrodynamic flood simulation future flood events dominated by extreme sea level rise are simulated. The hydrodynamic flood simulation is executed by Delft3D Flow FM. In D-Flow FM the unsteady shallow water equations are solved based on the Navier Stokes equations. It solves in 2 dimensions with an average water depth per grid cell. This results in accurate water flow over land.

The hydrodynamic flood simulation is verified by comparing the result of the current scenario with the the widely accepted VNK2 model. The validation is executed based on a visual comparison, a inundation depth comparison and a comparison of the estimated damages. This assessment was done for three different breach locations and resulted in a reliable hydrodynamic flood simulation.

To estimate the damages that occur during a flood event that is simulated by the hydrodynamic simulation, the Global Flood Risk Tool was used. This tool combined the inundation depth, the land use map and the damage curves and created a damage map. This map represented the estimated damage per area which resulted in a total estimated damage per flood event.

Flood risk is determined by a combination of estimated damages and probability of failure. With the hydrodynamic simulation and the Global Flood Risk Tool, damages were estimated for three breach locations and five different future extreme sea level rise flood scenarios. This resulted in a damage estimation for sea level rise scenarios up to two meter rise. The probability of failure is estimated by means of the height that is needed to decrease the probability of failure by a factor ten.

Economic optimisation was used to determine the economically optimal probability of failure for each of the scenarios. With the economic optimisation, the cost and benefits of the investments needed to increase the the probability of failure are calculated. These optimal probability of failures were compared to the minimal required probabilities of the 'waterwet' of the Netherlands to determine if the investment is economically acceptable. For two of the three locations it became clear that investing in strengthening the dunes of the coastal area of dijkring 14 is economically acceptable. The third location resulted in a slightly smaller optimal probability of failure. When estimating for the whole coastal area of dijkring 14, it becomes clear the defending the dijkring against flood risk by use of the dunes is possible in future extreme sea level rise scenarios.

M.W.(Marijn) Meyer Ranneft
Delft, November 2020

Contents

List of Figures

List of Tables

1

Introduction

The ’watersnoodramp’ was the biggest flood in the recent history of the Netherlands. In the night of January 31st in 1953, a combination of an extreme storm surge and spring tide provided an extreme sea-level. At 03:00 am the dikes breached. The sea-level was +4,55m NAP at that point and the water flooded large parts of Zeeland (Watersnoodmuseum, 2020). The combination of the storm surge and the spring tide created over 150 breaches and caused a death rate of 1836 people and tens of thousands of animals. The dutch government created the ’Deltacommissie’, with one goal: to build a defence structure that ensures this won’t happen again(Rijkswaterstaat, 2020). They created the ’Deltawerken’. A famous flood defence system with storm surge barriers as the ’Maeslandkering’ and the ’Oosterscheldekering’ and dams as the ’Volkerakdam’ and the ’Haringvliet’. They also divided the Netherlands in 94 levee systems, ’Dijkringen’. Which had the goal to protect the hinterland if there would be a flood. Both the effort and the result of the ’Deltawerken’ are impressive but they are designed on the mean sea-level at that time. Unfortunately the sea-level is rising.

According to recent research of the IPCC (Intergovernmental Panel on Climate Change) our climate is changing. Temperatures are rising which causes the icecaps of both the North/South-Pole to melt. The melting ice means a rising water level overall(Masson-Delmotte et al., 2019). As the ice melts a whole variety of effects is changing, for example gravity forces from the ice and cold water circulation. These effects create gradients in the water level. Therefore the water level rise is difficult to predict. One thing is for certain though; The sea level will rise in the future and might rise a lot, see appendix **??**. As hundreds of scientists are discussing how, how much and when the sea-level will rise this thesis will not focus on a timeframe. It will determine whether the dunes of the Netherlands are to withstand sea-level rise. In a national research with over 1000 replicants, it becomes clear that over 75% of the Netherlands thinks that raising the dikes due to sea-level rise is not a luxury but a necessity(Thiel & Mol, 2020). This implies that people are willing to take action. At the same time not even 3% of the people states that they are willing to leave their residential area and move. Since the Netherlands is a low lying area the coastal defence structures are expected to become more relevant to support human activities. The sea-level rise will affect the probability of failure for those defence structures and therefore influence the flood risk itself. Flood risk is a function of the probability of failure for the flood defence and the consequence, either financial or individual risk. As the probability rises, the risk rises as well. By raising or strengthening the flood defences the probability decreases. This way the security against flood risk could be high enough.

1.1. Research questions

The background information and the problem description have led to the following main research question and sub-questions :

To what extent is it possible to keep protecting dijkring 14 by upgrading the dunes that are part of the current flood defence system, when taking into account extreme sea level rise scenarios of up to 2 meter?

- How can a hydrodynamic flood simulation be used to simulate reliable flood risk scenarios ?
- What is the influence of the sea level rise on the flood risk within dijkring 14?
- How can the dunes of the flood defence system be upgraded to the required safety level?

1.2. Report outline

Chapter	Content
Chapter 1	Introduction
Chapter 2	Dijkring 14
Chapter 3	Methods
Chapter 4	Case study set up
Chapter 5	Result case study
Chapter 6	Economic optimisation
Chapter 7	Conclusion and recommendations

Table 1.1: Outline of this thesis

In Chapter 1 *Introduction* the subject of this research is introduced, and the research questions to be answered in this thesis are given. The outline for the report is shown.

In Chapter 2 *Dijkring 14* the location of interest is evaluated. The vulnerable breach locations of the dijkring are located, the probabilities of failure are determined, the failure mode is elaborated and the possible damages are estimated. Furthermore current flood event scenarios for this dijkring are evaluated.

In Chapter 3 *Methods* the methods that are used to asses the flood risk in dijkring 14 are elaborated. Firstly general flood risk assessment is explained. Then the economical risk evaluation is clarified and finally the economical optimisation is specified

Chapter 4 *Case study set up* In this chapter the programs, models and assumption needed for the hydrodynamic flood simulation are explained. Further the translation from inundation depth to damage estimation is explained.

In Chapter 5 *Results case study* the case study is validated and when proven reliable extreme future flood scenarios are simulated. Damage estimations for each of the scenarios of all scenarios are given.

In Chapter 6 *Economical optimisation* The estimated damages that result from the case study are used to determine the risk. With this risk the optimal safety level of dunes is computed and compared to the minimal required safety level.

In Chapter 7 *Conclusion and recommendation* the conclusion of this research is given by answering both the main research question and the sub-questions. Furthermore recommendations for future research is given.

1.3. Methodology

Methodology is the combination of a planned time schedule and a work plan. In this work plan each step of the graduation research is described. In the flowchart these steps are categorised; *Preliminary, Main objective, Secondary objective, Optional.* The work plan consist of the here elaborated steps:

1.Background information A good thesis starts with a good research question. Besides a good research question, background information is needed, here some of the theoretical concepts that are needed for the research were collected. Besides theoretical background of damage calculation and risk estimation there was a information on the modelling software for the creation of the inundation/land use -map.

2. Define Location of interest The Netherlands is divided in 98 levee systems. A levee system is a flood protection system which consists of a levee, or levees, and associated structures, such as closure and drainage devices, which are constructed and operated in accordance with sound engineering practices. The combination of these structures enclose a system. This way the Netherlands is separated into different systems and therefore is better protected against a major flood. When modelling a inundation map and determine the damages by use of a land use map the computing power is limiting. For the purpose of this research one levee system is chosen to be modelled, evaluated and estimated. It is important to determine a levee system in which different solutions for the flood risk could be used.

3. Create Model To determine at which sea-level rise the risk grows faster than the investment possibilities different scenarios are needed. First the model should be defined. Delft 3D Flow FM with a breach in a dike is modelled. The flow velocity, flow rate and inundation depth are parameters of interest. Because the model could be run multiple times with different sea-level rise. The influence of these parameters on the damage curves could be evaluated.

4. Create Damage maps First a land use map is created. With GIS the land use is determined. When a flow process is created by the model and the damage curve is estimated based on the parameters from the model. The damage map could be created. By combining the flow model with a land use map, an inundation map could be created. The damage curve adds the economic value to this damage map. Because the flow-model is run with several scenarios the damage map for all different sea-level rises could be created.

5. Probability of failure Besides a larger damages the rise of the sea-level also influences the probability of failure. A mean sea level will causes a higher probability of failure. The new probabilities for each future flood scenario are taken into account in the estimated risk.

6. Economically optimising the safety level To evaluate the investment needed, a function of the flood risk and the investment costs dependent of lowering the probability of failure are optimised. This way the economically optimal safety level is determined. If this safety level is above the required safety level, the dunes are safe.

2

Dijkring 14

The Netherlands literally means "the lower countries" which refers to its low elevation and flat topography. Large proportions are below sea level and besides the coastal areas there are several major rivers flowing through the Netherlands. This creates an area prone to flooding of 60% of the country. Therefore it is of importance to protect against high river discharges and storm surges (Vergrouwe, 2010). The most recent disaster was the 'watersnoodramp' in 1953. The storm surge caused the government to appoint the Delta Commission to advise on the response. Besides the 'Deltawerken' they created the 'dijkringen'. These are levee systems to protect the citizens and the country against floods. These systems ensure a safety level dependent on economical consequences and individual risks. As can be seen in Figure 2.1, different autonomous systems are in place.

The research will focus on the economically largest and socially most impacted levee section of the Netherlands: 'Dijkring 14'. This levee section is located in South Holland and contains (parts) of the four largest cities in the Netherlands: Rotterdam, the Hague, the southern area of Amsterdam and the western side of Utrecht. Approximately 3.500.000 citizens live within the levee section and it has an area of over 224.000 acres(Ter Horst, 2012). The area is the beating heart of the dutch economy. Because of the economic aspect and the large amount of citizens it is one of the most important levee systems. The average elevation of land within this levee system is -1m below NAP. The lowest locations within dijkring 14 are Haarlemmermeerpolder, the Alexanderpolder and the Zuidplaspolder where surface is as low as -4 to -6 m below NAP. The lowest point of Europe, located at -6,76m below NAP, is located in dijkring 14, near Nieuwerkerk aan den IJssel. On the western side the levee section is protected by the dunes and the beach, from Hoek van Holland up to Ijmuiden. The eastern/ northern-boundary is the 'Amsterdam Rijnkanaal' and is protected by levee system 44. Therefore only cascade effect risks occur on the eastern/ northern-side. The southern side of the levee system consists of the 'Nieuwe Maas' and an c-category dike over land by Gouda all the way to Utrecht. See Figure (2.2)

Figure 2.1: Overview of the dijkringen in the Netherlands, Source: VNK2 (**?**)

Figure 2.2: Overview of dijkring 14, Source: VNK2 (**?**)

The levee system 14 Zuid-Holland is evaluated in VNK2(Vergrouwe, 2010). The probability of failure for the dike section is estimated to be 1/34.000 year for wave overtopping and overflow. The probabilities of both piping and inner strength are smaller and therefore less important. The failure probability of the dunes is 1/44.000 by dune erosion. The probability of failure for the hydraulic structures is estimated to be 1/12.000 for failure to close. The other failure modes are estimated to be zero. See Table 2.1 for the largest probability per flood defence category.

Flood defence	Failure mode	Probability of failure
Dike	Overflow and Overtopping	1 / 34.000
Dune	Dune Erosion	1 / 44.000
Hydraulic structure	Failure to close	1 / 12.000

Table 2.1: Probability of failure for the different failure modes in dijkring 14, Source: VNK2 (Vergrouwe, 2010)

For these flood events the consequences are as important as the probability probability of failure. As mentioned before dijkring 14 Zuid-Holland is an economic centre of the Netherlands and almost 3.5 million people have their home located within. As one would expect, the economic consequences could be catastrophic and the annual loss-of-life risks are tragic. It is estimated that 65% of the Dutch GDP is generated within the area (Vergrouwe, 2010). The estimated amount of fatalities closes in to the amount of the 'watersnoodramp', i.e. over one thousand, see Table 2.2. When combining the different flood risk scenarios the maximal economic damage could be determined (Van Schrojenstein Lantman, 2007). In this research this economic evaluation is the main component.

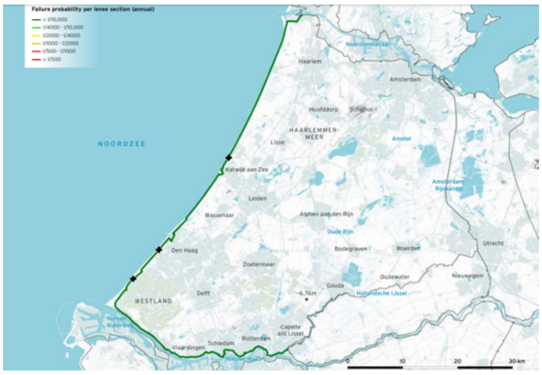


Figure 2.3: Most probable locations of coastal breaches

Flood risk	[-]
Annual probability of flooding	1 / 16.000
Annual economic risk	€ 0.3 million
Avg. losses /flood event	€ 4.7 billion
Max economic damage	€ 570 billion
Annual loss-of-life risk	1 / 10
Avg. no. of fatalities /flood event	1.500 people

Table 2.2: Flood risks for levee system 14 ’Zuid-Holland’ Source: VNK2

According tot the VNK2, a study of flood safety in the Netherlands, the main flood risk is due to the c-category dikes along the ’Hollandse Ijssel’ due to a breach in the ’Lekdijk’. Worse, half of the economic risk is determined by the cascade-effects that will issue if the ’Lekdijk’ breaches. When looking at fatalities almost half of the fatalities that are predicted will be because of a failure in the c-category dikes. Keeping this in mind it is discovered that the a-category flood defences, ’Nieuwe Maas’, ’Nieuwe Waterweg’ and the ’Noordzeekust’ barely influence the flood risk at this moment(Ter Horst, 2012).

In this thesis the economic influence of sea-level rise on these a-category dikes will be evaluated. Therefore it is important to first determine the coastal areas that are possible breach locations. Since sea level rise won’t happen overnight it is assumed that hydraulic structures will always be revised during planned reinforcement programs. This research will therefore focus on the the failure mode of dune erosion.

Failure mode of dunes The main probability of failure for the dunes is dune cut (duinafslag). In daily conditions the dunes are flood defences without a load from the sea. The sea water and the waves are not in contact with the dunes. The foot of the dune is the zone in which the gentle sloped beach changes in a steep dune. Often this transition is a gradual transition. Therefore the foot of the dune in the Netherlands is often based on height, NAP +3m. During a storm the storm surge, astronomical tides and high waves result in a sea water level that is higher than the foot of the dune and there is load on the dunes. The resistance of the dunes is dependent on the volume of sand that is in the dunes. This is determined by the cross section of the dunes. Besides the volume, the grain size is of importance. A larger grain results in a smaller dune cut.

The dunes are a dynamic flood defence due to waves, winds and tides. In regular circumstances sediment transport results in accretion and erosion of the dunes. To counteract structural erosion a coastal enforcement program is executed by Rijkswaterstaat. Part of this enforcement program is aimed at compensating the sea level rise. Neglecting the rise would result in a decrease of the safety level of the flood defence. During a storm the sea water level could rise above the foot of the dune by a combination of the storm surge and the astronomical tide. Sediment is transported into the sea and the dune talud becomes steeper until it becomes unstable. This will result in a dune cut, see Figure 2.4.

The sediment that is cut is transported into the sea and the process repeats. The sediment that is transported into sea settles in front of the dune. This sediment forms a bottom profile, this raised bed level results in the breaking of waves further from the dunes. Over time the new bottom profile becomes gentler and less wave impact is a load on the dune. If a dune is secure, the dune cutting process stops either because of the storm stops, or because there is an equilibrium in front of the dunes, see Figure 2.5. If the resistance of the the dune is inadequate, the flood defence will fail. A breach occurs and due to the astronomical tide this breach might grow into a tidal inlet.

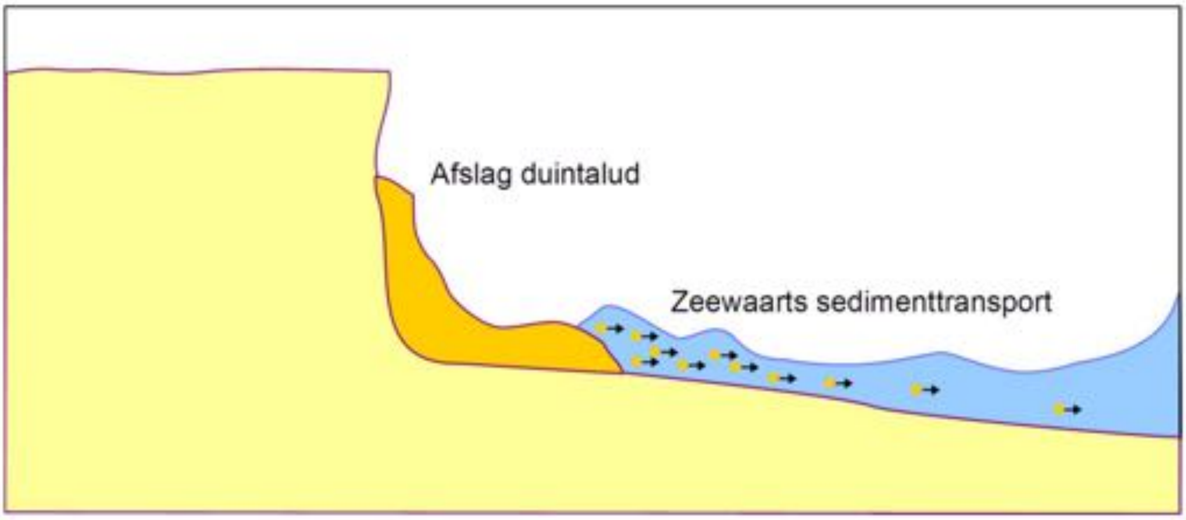


Figure 2.4: Process of failure of the dune by dune cut, Source: Technisch Rapport Duinsafslag

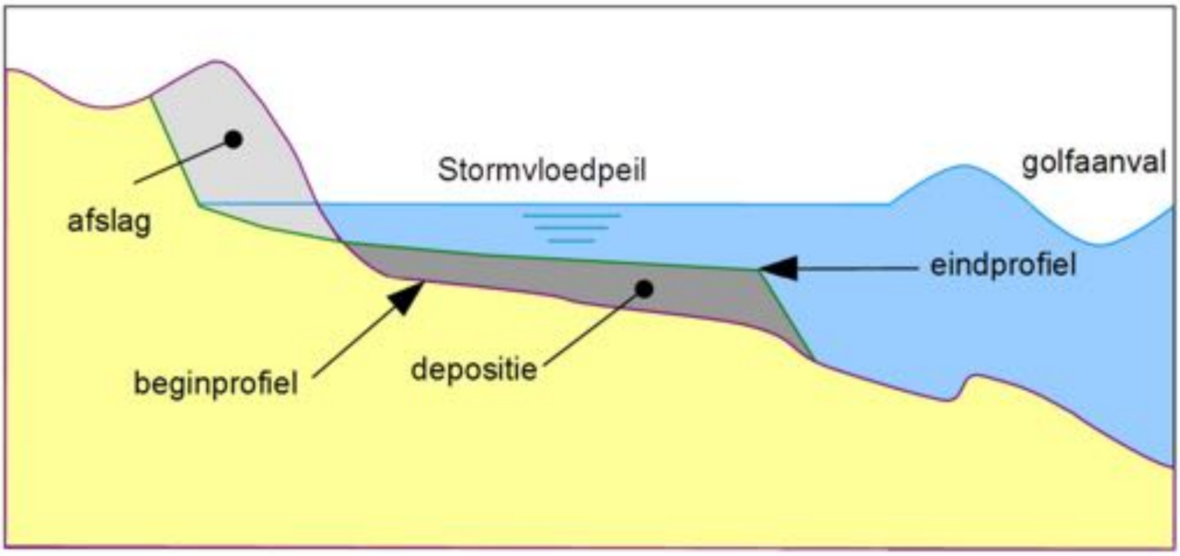


Figure 2.5: Profile of the dune before and after a storm, Source: Technisch Rapport Duinafslag

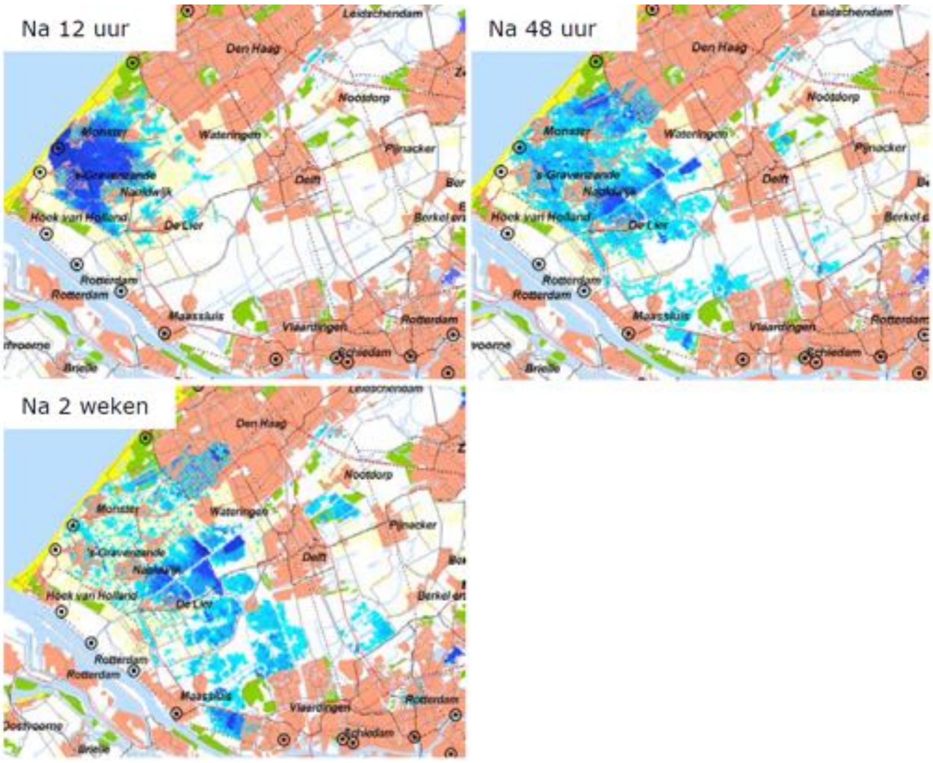
Breach locations In this section the three locations most probable to have failure modes, will be evaluated. In this evaluation there will be a more detailed review of the probability of failure. Besides an review of the probability of failure, the possible consequences based on the National Flood Risk Analysis for the Netherlands, VNK2 are evaluated. The overall characteristics for Dijkring 14 are mentioned in Table 2.2.

In the dijkring there are 13 separate ring elements. In Table 2.3 the predicted affected area is mentioned as well as the percentage of the total area within the levee system that is affected. In this thesis focus will be on Monster, Kijkduin and Noordwijk.

Nr	**Name**	**Affected area [km^2]**	**Percentage of levee system [%]**
8	Monster	151,7	6,8
9	Kijkduin	133,1	6
13	Noordwijk	330,9	14,9

Table 2.3: Flooded area per breach location at test depth + 2 decimal heights (estimated to be 2 meters). Source VNK2

Breach location: Monster Monster is a place within the ring element 8, Ter Heijde. If there would be a breach in this area the affected area will be between, the Hague, Hoek van Holland, and Vlaardingen (near Rotterdam). Delft, important for this university, and Vlaardingen will be safe but the southern part of the Hague and Wateringen will be flooded, see Figure 2.6. The maximum waterlevel with current sea level will be around 1,5m of water in Naaldwijk.


Na 12 uur

Na 48 uur

Na 2 weken

Figure 2.6: Predicted inundation maps for a breach at Monster at MSL, Source: VNK2 Dijkring 14

The breach location of Monster is evaluated due to the fact that the consequences could be severe. A very large area is prone to flooding with polders from The Hague up till Rotterdam. In these polders there is a lot of greenhouse agriculture, which has a significantly higher value than regular agriculture this could lead to disastrous damages. The estimated economical damages vary from €3,5 billion for current mean sea level to €5,3 billion and €7,2 billion with respectively 1D and 2D, decimal heights. In which D is the decimal height. The height for which the probability of failure increases a factor 10. One decimal height is estimated to be 1m of sea level rise.

Sea level	Affected people	Casualties	Estimated economical damage [Million €]
MSL	140.000	100-200	3.500
MSL + 1D	180.000	180-370	5.300
MSL + 2D	220.000	280-570	7.200

Table 2.4: Overview of expected damages and casualties based on predictions of VNK2 for flood in ring element 8 Monster. Source:VNK2

Breach location: Kijkduin A breach in ring element 9 Kijkduin would have severe consequences for the city The Hague. With a breach at the mean sea level a substantial area of south western the Hague will be flooded within several hours, see Figure 2.7 Higher water levels mean a larger inundation depth and a larger affected area in the city. Economical damages range from 2,7 billion Euro with the mean sea level to 7,6 billion Euro with a rise of two decimal heights.

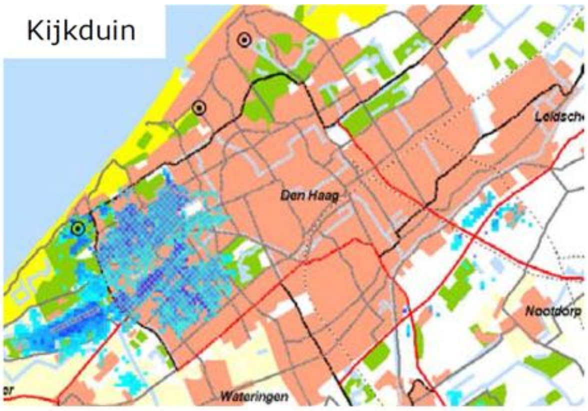


Figure 2.7: Predicted inundation map for a breach at Kijkduin at MSL after 24 hours, Source: VNK2

Sea level	Affected people	Casualties	Estimated economical damage [Million €]
MSL	120.000	100-200	2.700
MSL + 1D	180.000	240-490	4.700
MSL + 2D	280.000	320-650	7.600

Table 2.5: Overview of expected damages and casualties based on predictions of VNK2 for flood in ring element 9 Kijkduin. Source VNK2 Dijkring 14

Breach location: Noordwijk A breach near Noordwijk affects an area between Katwijk and Leiden up to Aalsmeer and Leidschendam. A breach with mean sea level mostly results in floods with a water depth of less than 1 meter. West of the Noordwijkerhout temporarily is flooded up to 2 meters. Most of the residential areas are dry, see Figure 2.8

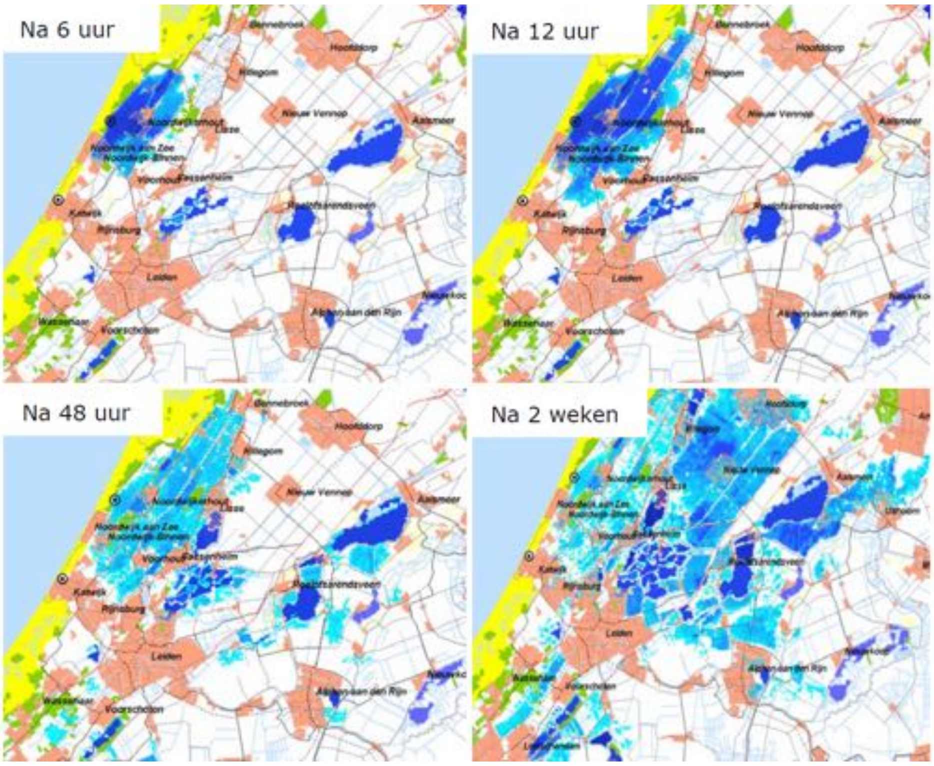


Figure 2.8: Predicted inundation map for a breach at Noordwijk at MSL, based on VNK2

When a breach occurs with higher seawater level multiple residential areas are within the flooded area. With a significant sea level rise of 2 decimal heights local water depths could be up to 2,5-3m. This is the reason why the seawater level is of large influence on the amount of casualties. At the same time the evacuation fraction is of large influence, this explains the large variation in casualties.

Sea level	**Affected people**	**Casualties**	**Estimated economical damage [Million €]**
MSL	80.000	80-160	1.800
MSL + 1D	140.000	250-490	3.200
MSL + 2D	220.000	520-1030	5.500

Table 2.6: Overview of expected damages and casualties based on predictions of VNK2 for flood in ring element 12 Noordwijk.Source: VNK2 Dijkring 14

3

Methods

In this chapter the methods that were used to asses the flood risk in dijkring 14 are elaborated. Firstly general flood risk assessment is explained. Then the economical risk evaluation is clarified and finally the economical optimisation is specified.

3.1. Risk Analysis

Everything in life has a certain level of risk. In engineering risk and safety are main components and are always taken into account. The formal meaning of risk according to Oxford dictionary is: 'the possibility that something unpleasant or unwelcome will happen.' If risk is evaluated based only on the possibility or probability, the consequence is left out of the equation. Therefore another definition is used in engineering: 'Risk is the probability of an undesired event multiplied by the consequences'.

Floodrisk is determined as the risk of flooding in a certain area. In hydraulic engineering the term risk is interpreted as probability of failure times consequences. The probability is often determined as the probability per time. In engineering most of the time the consequences are deducted to economic values and therefore risk is expressed in formula 3.1.

$$E(d) = p_i * d_i \tag{3.1}$$

With:

$$p_i = \text{Probability } [/\text{y}]$$
$$d_i = \text{Consequences}[\text{€}]$$
$$E(d) = \text{Economic risk } [\text{€}/\text{y}]$$

3.1.1. Flood risk assessment

Flood damages refers to different types of damage caused by flooding. It embraces all the damage on humans, their health and affects, public infrastructure, ecological systems and the cultural heritage. In flood damages there is differentiation based on direct damages and indirect damages. Direct damages are caused by the physical effects based on hydraulic conditions. Indirect damages occurs if the victims are outside of the flooded area. For example if a company is outside of the flooded area but is experiencing damages by loss of demand from the people inside the flooded area. Finally another distinction has to be made; tangible and intangible damage. Tangible damages are damages which can directly be priced in monetary terms, there is a market value. Intangible damages are damages which can't be priced because there is no market value.

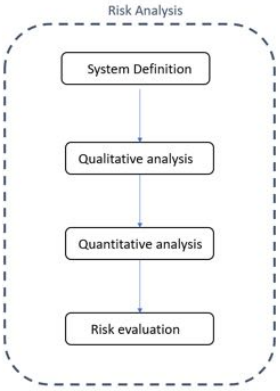


Figure 3.1: Risk Analysis overview by (Jonkman et al., 2016)

Risk is analysed by assessing the consequences and the probabilities of the event. Risk analyses are used to evaluate the risk and the acceptance in advance. It is used to determine whether a certain safety level threshold is reached, if additional measures for existing structures are needed. To translate the risks and the decisions based on these risks into technical specifications a quantification measure is needed (Voortman, Van Gelder, & Vrijling, 2003). These analyses are used to rationalise decision making in risk reductive matters. This could be used both in management or maintenance strategies or in civil structures to determine their dimensions. Besides creating a safety level threshold, a risk analyses could serve to gain information on the different failure mechanisms. Therefore it is a useful tool to communicate risks.

Risk analyses exist of different steps in a process. These steps are shown in Figure 3.1. The different steps of these analysis will be further elaborated in this chapter. Different sorts of analysis could be executed. A probabilistic risk analysis is based on quantitative risk for all known and undesired events, their probabilities and their consequences while a deterministic scenario analysis is done for a limited number of scenarios without considering its failure probabilistic. Scenario analysis is used in the Netherlands to evaluate disaster preparedness and the capability of emergency management. Detailed high impact and low probability scenarios might give an insight on effectiveness of actions or measures.

System definition In the first step of the risk analyses the scope and the objective of the system is defined. Normally the system is described by a input-output element in which the system will fail if there is no output. To analyse the whole system thoroughly, it is divided in subsystems and different components. This way the system will be schematised with different elements that have internal relations and show the whole system when combined. A system is in this situation a combination of boundary conditions that will determine the load based on the surroundings, physical components based on the situation within and users. Those users include people, organisations and operators all in different roles. Each of the users has its own risk aversion and therefore a different safety level threshold. Important is that for most systems, multiple events could have the same result. To gain insight it is therefore needed to have a complete overview.

Qualitative analysis In the second step of the risk analyses the system at risk will be described. All different failure mechanisms, scenarios and hazards are identified to get insight of the potential undesired events. The system has failed if the system or a part of it does not function as it is meant to. As mentioned above most systems have multiple events that could lead to failure. To determine the state of failure in civil engineering, the limit state is used. This is the state for which the structure or the system does not fulfill its design criteria(Delft Cluster, 2003). There are two types of limit state. The serviceability limit state, **SLS**, and the ultimate limit state, **ULS**. The serviceability limit state is met when the system temporary of partially doesn't function anymore. Within serviceability limit state there are two types. The reversible SLS for which the critical state is only reached during the load and the irreversible SLS is when the critical state is permanent. The ultimate limit state is met when a system fails or collapses. Therefore the whole system has to be rebuild. For a qualitative analysis it is important to find the different undesired events to determine their limit state. Many accidents happen due to that fact that identifying failure modes failed. To determine the different undesired events several qualitative techniques could be used. The failure modes and effects analysis **FMEA** is a qualitative approach that systematically identifies the failure modes of the subsystems in an overview. The FMEA is executed in the design phase to make sure that for each of the subsystems the safety levels are met, this way the total system is reliable. The FMEA could be executed either bottom-up or top-down. With the top-down method first the system is divided in different function blocks, within these blocks different components or subsystems have a function together. The undesired events and consequences are identified for each of the blocks. Then the importance of functioning of each of the blocks is ranked and the important blocks are evaluated. The bottom-up method is executed the other way around. The subsystems and components are evaluated and the analysis expands to the total system. To reduce work load the availability of data often determines at which level of subsystems it is valuable to start the analysis. Danger lies within analyses of high impact and low probability since the manageability of those scenarios might be unrealistic. The probability of the disaster should be taken into account in a cost-benefit/ cost-effectiveness analysis.

Quantitative analysis In the third step of the risk analysis the probabilities and the consequences of the above defined undesired events of the system are calculated. By means of either a economic or a individual risk determination the risk is quantified in risk number or a graph. To evaluate the probability of failure the earlier determined limit state is computed.

$$\begin{aligned} Z &= R - S \qquad (3.2)\\ Z &= \text{Limit state}\\ R &= \text{Resistance}\\ S &= \text{Load} \end{aligned}$$

When the probability is computed the consequences are quantified. Consequences are either evaluated economically, when the damage within the systems involves objects, or as individual risk if people are involved. When evaluating the economical consequences the indirect damages should also be taken into account. These are damages that are occurring outside the directly exposed area. Because some effects cannot be quantified and risk analysis are bound to take all impacts into account most evaluations are based on economic damages or life loss.

Risk evaluation The risk analysis gives insight on the probability of a unwanted event. In the risk evaluation it is determined whether or not the risk is acceptable. If the probability is too high, risk reduction measures can be used to reach the level of risk that is acceptable. To determine the acceptable level of risk different methods could be used. For loss of life safety standards could apply, for economic risk an economic optimization function applies. Both the different risk methods benefit from a cost and benefit analysis.

3.1.2. Flood risk in the Netherlands

Flood risk analysis To determine the flood risk in the Netherlands, the probability of failure of the flood event is analysed. The probability of the flooding is based on the extreme weather events such as storm surges for coastal areas and extreme rainfall for riverine areas. The probability depends, besides the load that is caused by these extreme events, also on the reliability of the flood defences. The extreme weather events cause hydraulic loads that might cause a failure to the flood defence. Examples of failure mechanisms are piping, macro instability, overtopping and dune cuts. For each of the dikes and dunes it is possible to determine the probability of failure but as one would expect it is possible that there are multiple failures or breaches. To get insight in the possibilities there are flood scenarios. The flood scenario determines based on the location and the characteristics of the breach what the consequences of a flood event would be. To create a flood scenario hydrodynamic models are used. This way different floods can be simulated. Their characteristics, flow velocity, inundation depth, flood pattern etc., are the input for the consequences. Consequences might be determined by impact tools and are mostly expressed in economic value or individual risk.

Flood risk management in the Netherlands In terms of risk it is inevitable that there is a chance of an undesired event happening. Therefore there is a threshold for which we have decided that the probability of failure is small enough to state it is safe. In flood risk management this threshold is determined. Since 2017 there is a safety standard in the Netherlands that is expressed in a minimal probability of failure of the flood defence. This threshold depends on the consequences of the flood event and therefore on the location in the Netherlands. In the Netherlands a multi-layer safety concept is used. This concept is based on three principles:

- Protection: Prevent floods by flood defences.
- Spacial planning: Reduce the consequences with land use planning
- Emergency management: Reduce the consequences with disaster relief (e.g. organizational preparations and rescue services).

To accomplish this concept the Netherlands is protected with dike rings. These are areas that are protected with a primary flood defence or higher ground. This way there is a first defence against the water for the area within the dike ring. Within the dike ring it is possible there are secondary or even tertiary flood defences that prevent flooding in more inhabited or valuable areas. This is partially protection but part of the spacial planning as well. This way the consequences of a flood event are reduced.

Flood risk evaluation in the Netherlands To execute a flood risk evaluation first the consequence of the flood has to be quantified. In case of a flooding event this is quantified in three ways: economic risk, individual risk and societal risk. This thesis focuses on the economic risk. Economic damage is not only determined by direct damage (the damage to infrastructure, housing or residents) but also by indirect damage. Indirect damage are damage that are caused by the flood event but happen outside of the affected area. This might be societal disruption or for example a company that can't export its shipment due to airport closure.

3.2. Economical Risk

To asses and model the direct economical damages of the flood three elements have to be evaluated. The flood characteristics, the land use and the local damage function. To determine the direct economical damage the use of the land per location is of importance. The area could be divided into categories of land use. All these categories are considered different types of land use that have their own damage category. Properties of these categories are estimated maximum economic value per square meter and a damage function. In this thesis the land use map is based on the data of the Centraal Bureau voor Statistiek and is used as an GIS map. This way the most recent land use could be retrieved and used.

3.2.1. Local damage estimation

The damage function determines what the level of economical damage is due to the flood conditions. Stage damage functions are used to relate the level of damage to flood conditions. Inundation depth is the most imported parameter but flow velocity and flood duration could be of influence as well. The general equation is given in 3.3

$$D_i = \sum_{i=1}^{m} \sum_{r}^{n} \alpha_i(h_r) * D_{max,i} * n_{i,r} \tag{3.3}$$

Where:

$D_{max,i}$ = Maximum damage for a land use category i [€]
i = Land use category [-]
r = Location of flooded area
m = Number of damage categories
n = Number of flooded locations
h_r = Hydraulic characteristics on certain location
$\alpha_i(h_r)$ = Stage damage function, expresses the fraction of maximum damage per i at location r
$n_{i,r}$ = Number of objects in land use category i at location r

This local damage function could be used to determine the damage for a certain location. In this thesis a model will be used to assess the damage for a dike ring. It is important to assign a land use value to every grid cell and define a local damage function for those grid cells. Then a damage map could be modelled. See Figure 3.2

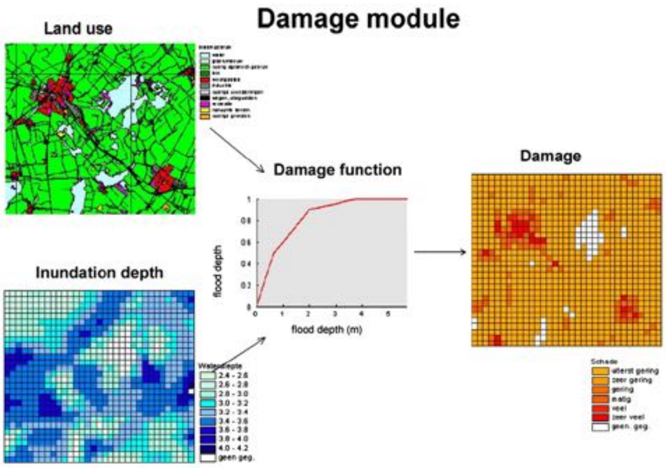


Figure 3.2: General approach for flood damage modelling (Jonkman et al., 2008)

Land use In the research of the thesis a flood is simulated to evaluate the consequences of the event. To simulate the damage of a flooding event, obviously a flood simulation is needed. Equally important is to gain insight in what exactly is flooded, therefore the land use map is needed. In the land use map that is create different categories are used to classify the land use in the area of interest. In a situation of a flood simulation the way in which the area is used is interesting to estimate the maximum damage. A residential area has a higher economical value than a forest. The categories that are represented are, residential areas, commercial use, recreation, agriculture, water, airports, railways, roads, nature reserves and greenhouses. Each class represents the buildings or a infrastructure in the area assigned on the map. To acquire the land use data, Bodemgebruik CBS2015 is used.

Flood characteristic from hydrodynamic model If a breach originates in a flood risk reduction structure water flows into the system. To assess the direct damages inundation depth, flow velocity and flow rate are the most important parameters. Duration and time of occurrence could also influence the damage significantly. (Jonkman et al., 2008) In this thesis Delft3D Flow FM will be used to model the breach three dimensional. This way all the parameters mentioned before could be extracted and used for the damage function. To simulate the flooding a hydrodynamic model is developed. The hydrodynamic model is simulated for different scenarios. Each scenario includes a sea level rise with a step of 0,5m. The results of these different simulation serve as flood characteristics that are input for the damage function are determined.

Damage estimation To determine the damages that would occur the 'Global Flood Risk Tool' of Royal Haskoning DHV is used. This tool combines the land use map and the inundation map of the flood that is simulated in D-Flow FM. To combine the inundation map and the land use map a damage function based on the water depth is needed. This damage function determines what percentage of the value is damaged by the flood at a certain water depth. As could be found in formula 3.3, the damage curves determines the estimated damage. These damage curves depend on the land use category and in our case multiple categories are combined. Therefore their damage function is combined.

3.2.2. Probability of failure

The probability of failure of a flood defence system can be calculated in two parts. The first part is the decomposing of the dijkring. A dijkring is generally composed of section that are averaged 750 m. These section are estimated to be statistically homogeneous sections and therefore they might differ in length. The dune sections for example might vary up to multiple kilometers. Hydraulic structures are a section on their own. Since this thesis focuses on the dune sections of the coastal area, the dunes are calculated.

Calculation of failure probability If the flood defence system does not retain the water it fails. This is determined by use of limit state function 3.1.1.

$$Z = R - S \tag{3.4}$$

Therefore failure occurs if $R < S$, thus $Z < 0$.

The probability of failure is then determined by:

$$P_f = P(Z < 0) = \int_0^\infty f_H(h) * F_R(h) dh \tag{3.5}$$

where:

$f_H(h)$ = probability density function of hydraulic load
$F_R(h)$ = cumulative distribution of resistance given hydraulic load

The probability of failure is determined on a section of the dijkring. Regularly there is a probability of failure for each failure mode. Since only the dunes are evaluated only one failure mode is evaluated, dune erosion.

3.2.3. Total risk estimation

The risk is a combination of the estimated damage and the probability of failure. In section 3.2.1 is explained how the local damages are estimated with use of the land use map and the inundation map combined by the 'Global Flood Risk Tool' with the use of formula 3.3. These estimated damages are used to determine the risk. In section 3.2.2 is explained how the probability of failure is determined. The estimated risk is calculated by

$$R = D * P_f \tag{3.6}$$

Where:

R = Risk that resulted from failure of a flood defence [€/y]
D = Estimated damages due to failure of the flood defence [€]
P_f = Probability of failure of the flood defence [1/y]

Hydraulic structures are build to reduce the risk of flooding over a long time. Besides economical influences as inflation economic growth could occur or a change in conditions. The sea-level could rise or the dike could lose strength on a larger time scale. (Eijgenraam, 2006) When the failure probability closes in to the maximal tolerable probability an intervention is implemented. Economical growth is taken into account as the tolerable probability is decreasing over time. To determine the risk more parameters are necessary. The probability of failure is evaluated in the next section. The growth rate and the discount rate are determined in this section.

Growth rate The rise of the sea level does not happen over night and the investments done to increase flood safety are for long term. Therefore it is of importance to expect that the damages will rise. Over time there will be economic growth, investments in Dijkring 14 and due to urbanisation more people will want to move to this area. All of these factors contribute to a larger economical value of dijkring 14 and therefore larger damages are bound to happen. To take the future growth into account the growth rate 'g' is used. This factor adds value to the expected damages by an expected growth rate per year. In this case $g = 0,019$ which is equal to 1,9% per year.

Discount rate As mentioned before the investments done to increase flood safety are for a long period of time. As the value of the dijkring may rise due to economic growth, the value of money decreases. To account for the devaluation of money the discount rate 'r' is used. The discount rate exist of two terms. The risk free interest rate. he risk-free rate represents the interest an investor would expect from an absolutely risk-free investment over a specified period of time. The real risk-free rate can be calculated by subtracting the current inflation rate from the yield of the Treasury bond matching your investment duration. Due to the fact that risk free investments are highly unlikely, this term is expected to be zero. The second term is the risk premium. An asset's risk premium is a form of compensation for investors. It represents payment to investors for tolerating the extra risk in a given investment over that of a risk-free asset. For example the investment in a flood defence that was never necessary. The risk premium for flood defences in the Netherlands is $r = 0,03$ this means that the premium is estimated at 3,0%

Hydraulic defences are designed to last for a long period of time. In this case the dunes do not have a design period but they are expected to defend the Netherlands for a long time. Therefore the damages need to be discounted for a unbound horizon. To transform 3.6 to unbound time horizon the following translation is needed.

$$\sum \frac{1}{(1+r)^i} \rightarrow \frac{(1+r)^i}{1-(1+r)^i} = \frac{1}{r} \tag{3.7}$$

Where:

$$r = \text{discount rate over time} i = \text{amount of years to discount for} \tag{3.8}$$

The same applies to the growth rate, this leads to the following equation for the risk

$$R = \frac{D * P_f}{r-g} \tag{3.9}$$

Where:

(3.10)

$$R = \text{Estimated risk for unbounded time horizon} D = \text{Estimated damages due to flood event} P_f = \text{Probability of failure of the flood d}$$

(3.11)

This risk determination is used to calculate the cost of increasing the safety level of the dunes. In this thesis three different locations are evaluated for five different scenarios. Each scenario has it's own estimated damages and there a risk determination is needed for each of the scenarios. This way it is possible to calculate the cost's and economically optimise the flood defence.

3.3. Economic Optimisation

Economic optimization is used to determine the level of safety for which the probability of failure and investment costs are optimal. In 1953 after the 'watersnoodramp' the economic optimization was developed by van Dantzig to derive the optimal dike for levee system 14 'Zuid Holland'(van Dantzig, 1956). It uses the costs of increasing the safety level (raising the dikes) and the decrease of the risk. Those costs are shown in formula 3.12. The flood risk that is used for the costs is determined before with formula 3.9.

$$C_t = I + R \tag{3.12}$$

Where:

$$C_{tot} = \text{Total costs estimated for a scenario}[€]$$
$$I = \text{Investment needed to minimise the costs}[€]$$
$$R = \text{Value of the risk for unbounded time horizon}[€]$$

To reduce the total cost there are two options: Reduce the risk by constructing a safer levee system or limit the damage by designing a flood resilient city. Since Dijkring 14 has a relatively short coast and a large potential economic damage the first option is chosen. The risk is reduced by building a safer system, therefore the investments are used to strengthen the flood defences to reduce the probability of failure. The investment becomes a function of probability. Since both the investment and the risk are dependent on the probability of failure the costs becomes a function of the probability of failure, see Figure 3.3

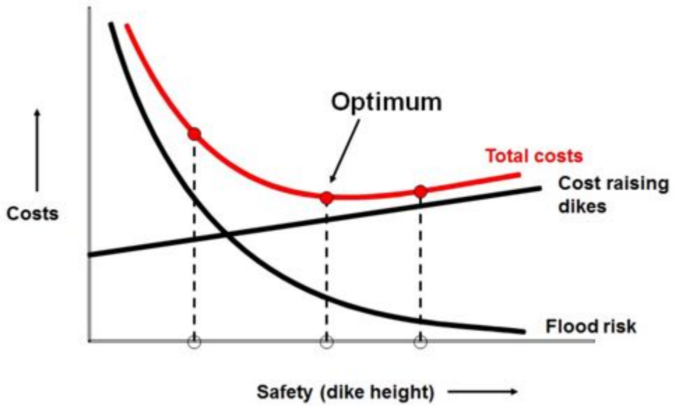


Figure 3.3: Economic optimization explained in a graph Source: Lecture Probabilistic design in hydraulic engineering by Prof. dr. ir. M. Kok

The economic optimum is found when the costs are minimal, if the differential is equal to zero, formula 3.13.

$$\frac{dC_t}{dP_f} = 0 \tag{3.13}$$

As could be seen in the figure above the approach is deducted to probability of failure and costs. Probability of failure in the case of van Dantzig was based on the probability of exceedance. it is shown in formula 3.14

$$P_f = P(h > H_d) = exp(-\frac{h_d - A}{B}) \tag{3.14}$$

Where:

$$h_d = \text{Height of dike [m]}$$
$$A, B = \text{Constants of the exponential distribution}$$

Since 'Veiligheid Nederland in Kaart' is published it became clear that the probability of failure is often not dependent on the probability of exceedance but on other failure modes. In this research the probability of failure will therefore not be probability of exceedance. Nevertheless the optimal probability of failure is determined based on costs and damages. It is shown in formula .

$$P_{f,opt} = \frac{I * B * r'}{D} \tag{3.15}$$

Where:

$$P_{f,opt} = \text{Optimal probability of failure [1/year]}$$
$$I = \text{Investment costs per m strengthening [€/m]}$$
$$B = \text{Constant of the exponential distribution in water level [m]}$$
$$r' = \text{reduced interest rate[-]}$$
$$D_i = \text{Damages in case of flood [€]}$$

As could be seen, higher consequences (a larger damage) lead to smaller optimal failure probability. Expected is that with sea level rise the consequences will increase as well as the probability of failure. Based on formula 3.15 an investment is needed to gain the optimal probability of failure. If the incremental investments are high this leads to a lower level of optimal safety.

Optimisation The economical optimisation is needed to determine the optimal level of safety that represents the lowest estimated costs. The costs that represent the safety of the dijkring are composed of the investment costs that are used to rise the safety of the flood defence and the risk that is determined by the estimated damages and the probability of failure. To optimise this process both the probability of failure, therefore the risk and the investment costs are dependent on same parameter. Since this thesis focuses on the strengthening of the dunes the investment cost and the probability of failure are dependent on the amount of sand that is added to the dunes. The investment costs are the costs to locate the amount of sand $'x'$ to the dunes. Therefore the costs of investment are determined by:

$$I(x) = I_0 * x \tag{3.16}$$

With:
x = amount of sand needed to increase the safety level is increased by 10.
I_0 = Investment costs for adding amount of x to the dunes.
$I(x)$ = Total investment costs dependent on amount of sand 'x'

The probability of failure decreases by adding the sand to the dunes. The amount of x is estimated to decrease the probability of failure by a factor 10. The amount of sand 'x' needed to decrease the probability of failure by factor 10 is estimated to stay equal. This estimation is valid due to the fact that it is expected that the probability will only decrease in the order of factor 10. The following function for the probability of failure is used:

$$P_f(x) = \frac{P_0}{10^x} \tag{3.14}$$

With:
x = Times the amount of sand 'x' is added to the dunes
$P_f(x)$ = probability of failure if safety level is increased with x
P_0 = probability of failure without investments

To optimise economically both these functions dependent on the times that the amount sand 'x' is added to the dunes to increase the safety level are used to calculate the costs by formula 6.3. If the costs are at an minimum the optimal safety level is reached, economically speaking.

$$R(x) = \frac{P_f(x) * D}{r - g} \tag{3.12}$$

with:
$R(x)$ = Risk dependent on the amount of times the safety level is increased.
P_f = Probability of failure dependent on the amount of times the safety level is increased.
D = Estimated damages per scenario for each location
r = Discount rate to create unbound time horizon
g = Growth rate to creat unbound time horizon

$$C(x) = I(x) + R(x) \tag{3.8}$$

with:
$C(x)$ = Costs dependent on the amount of times the safety level is increased.
$I(x)$ = Investments dependent on the amount of times the safety level is increased.
$R(x)$ = Risk dependent on the amount of times the safety level is increased.

When the economical optimum is determined the corresponding probability of failure is determined. This probability of failure should be below the minimal required level of safety. When the level is below it is determined that the investment is worth it. It is possible to evaluate for each of the scenarios is the current method of flood defences, with dunes is viable for the future with sea level rise.

4

Case Study set-up

As explained in the introduction the mean sea-level is rising due to climate change. The water level is an important factor for the failure function of a flood defences, as this influences the probability of failure (Jonkman, Schweckendiek, Jorissen, & van den Bos, 2017). At the same time a higher water level at sea influences the damage caused by a flood, because of higher inundation depths. A higher inundation depth causes more damage. Also the sea-level rise could cause a more rapid an violent flow into the dijkring which causes extra damage. As the flood risk is determined by the product of damage and probability of failure, the sea level rise leads to significant flood risk changes.

The current flood risk reduction system in the Netherlands is based on dunes, dikes and dams. To maintain a sufficient safety level, the dunes, dikes and dams are continuously maintained and upgraded. In this research thesis the change of the flood risk that is implied by the sea-level rise is evaluated.

Investments are needed to maintain the imposed safety level and limited the residual flood risk. These investments are cost effective as long as the investment is smaller or equal to change in the total risk. Due to the sea level rise the risk increases and therefore the investments that are needed increase as well.

In this chapter the case study used to execute the research of this thesis is explained. First the area of interest is analysed. Components of interest such as cities and geographic locations are defined, economic value is determined and the simulated flood pattern from previous research is analysed. Then several possible breach locations are extensively evaluated. In this evaluation the consequences of the flooding and the possible influence of higher sea level are elaborated. This way a verification study was possible once the flood model from the research was finished.

Furthermore the individual components of the flood model are explained. As a flood analysis exists of several steps each of them is elaborated. First the land use model is broken down to detail. This way it becomes clear which assumptions are needed, how the land use map is composed and with how much detail the different elements are evaluated. Second the hydrodynamic model which actually simulates the flood event is explained. This explanation includes the simulation of the breach, the determination of the grid size, the hydraulic boundary conditions and what flood characteristics are of influence. Finally the Global Flood Risk Tool is clarified. Here the inundation map and the land use map are combined by damage curves. With the use of this tool that calculated the damages it is possible to create damage maps to gain insight in the consequences of the flood event.

4.1. Land use map

In this research a flood was simulated to evaluate the consequences of the event. To simulate the damage of a flooding event, obviously a flood simulation was needed, equally important was to gain insight in what exactly is flooded. To gain this insight the land use map is needed. In the land use map that is created different categories are used to classify the land use in the area of interest. In a situation of a flood simulation the way in which the area is used is interesting to estimate the maximum damage. A residential area has a higher economical value than a forest. The categories that are represented are: residential areas, commercial use, recreation, agriculture, water, airports, railways, roads, nature reserves and greenhouses. Each class represents the buildings or a infrastructure in the area assigned on the map. To acquire the land use data, Bodemgebruik CBS2015 is used (**?**).

In this section the set up of the land use map that has been used in the Global Flood Risk Tool is revealed. Explained will be how the maximum damage is determined and the different categories are highlighted and further evaluated.

Valuation of categories Floods disrupts and damages the society in a variety of ways. As discussed in section 3.1.1 there is an individual risk with fatal consequences and there are economical consequences. In section 3.2 the economical damages are divided in direct and indirect damages. In Table 4.1 the different consequences are shown:

Category		**Tangible damages**	**Intangible damages**
Direct damages	Physical damage	Loss of capital (residences, vegetation, cars, industry infrastructure)	Casualties, ecosystems, pollution, loss of culture
	Interruption of business	Interruption of production (within flooded area)	Social disruption, emotional damages
Indirect damages		Interruption of production (outside flooded area)	Emotional damages, hindrance because of damages within flooded area

Table 4.1: Different economical consequences.

With a flood simulation it is possible to calculate the consequences of a flood in advance. The physical damage is mostly dependent on the flood characteristics while the interruption of business is mostly dependent on the time that the flood occurs. Therefore the determination of the damages is fundamentally different.

The physical damage is determined by the loss of the value or production capacity of an affected object of land use. To relate the damages to the flood characteristics the damage curves are used(**?**). Each category in the land use map has its own damage curve and and its own maximum damage. Direct physical damage is composed of:

- Damage to real estate and properties of the affected area.
- Damages to valuables as household effects, raw materials or harvest.
- Cost of repairs on machines, equipment.
- Loss of income due to unavailability of rental areas or comparable aspects.

Indirect damages are derived based on the loss of business due to reduced production capacity. It is dependent on the interchangeability of the production capacity to other companies or departments outside of the flood area. Estimated is that the indirect damages result in 50% of the direct damages, (Kind, 2011) This depends on the knowledge and available capacity as well as on the role in the supply chain. Duration of the flood and the reduced production capacity may be the most influential parameter.

Detail of land use map The detail of the map is defined by two different components. First is the resolution of the map in general. The resolution of the map determines the detail of the map. It depends on the cell sizes within the grid. This means that if there is a high resolution there is a high amount of cells in the grid. It is possible to ascribe each cell to a category. This means that with a high resolution the area of interest could be divided into different categories with high detail. High resolution therefore means highly detailed and therefore it is possible to gain more information on the area. Nevertheless a high resolution requires more computing power since there are more cells and therefore more calculations. This means that a trade-off is needed to determine how high the resolution should be. The land use map is composed of polygons and therefore a very detailed map is possible. Since the land use map will be combined with a inundation map created with a hydrodynamic model, a very detailed land use map will not add value. If one has a resolution of 1m x 1m and the other 10m x 10m, the highest resolution is lost when the two maps are combined. Since the computing time of the hydrodynamic model will be significantly larger than that of the land use map, the grid resolution of the hydrodynamic model is dominant. The grid resolution of the hydrodynamic model is

Categories:
Residential area
Commercial area
Recreational area
Semi built
Agriculture
Water
Greenhouses
Airport
Railway
Roads
Nature reserves

Table 4.2: The eleven categories used in the land use map

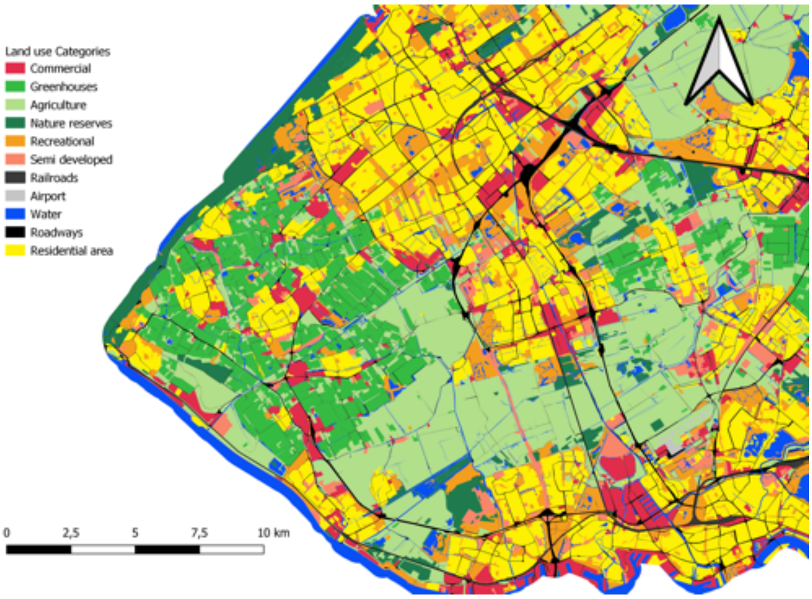


Figure 4.1: Example area of the land use map that is used for this research

37m x 99m. Therefore the land use map will be in categories that are easy to use on larger areas, i.e. residential area instead of houses, gardens, pavements etc.

The second component of influence for the detail is the amount of categories used. In reality every single house or property component has its own economical value, therefore there should be infinite categories to determine their maximum damage. When creating a land use map, a maximum of amount of categories is used to simplify the approximation. Even when simplifying the amount of categories might vary vastly. More categories will result in a more detailed calculation, but will require a lot more detailed information on each of the grid cells. Because of large variety of residential and commercial areas an estimation is used to average the value of the properties and gain an estimation of damage with a flood. This is done by combining the 26 categories of CBS grondgebruik into 11 different categories.

Determination of maximum values To determine the damage that could be done within a grid cell of a category first each of the categories should be analysed. It should be considered that the grid cell is an area in which there could be multiple properties. Therefore it is essential to value the used categories in a value per area. In case of a economical estimation this would be €/m^2. In this subsection the value of each of the land use categories is estimated. This estimation is elaborated and substantiated.

Commercial use To determine the damages to commercial enterprises, HIS-SSM of Deltares **?** in combination with the global depth damage functions of Huizinga, Meol, and Szewczyk (2017) is used. This registration is publicly accessible. The categorie is divided in different subcategories of which the most important are: Hostility services, Offices, Health, Industry, Education and Retail. As stated before the average damage to these commercial enterprises is valued on the area that is damaged by the flood. The value will be represented by the x,y coordinates of the authority. This could slightly differ from the x,y coordinates of the actual location. To reduce the amount of different used categories commercial use is a combination of the categories industry and office. Due to the fact that the detail of the land use map is smaller, a factor of 0,3 Huizinga et al. (2017) is needed for commercial use to translate from area of the business itself to commercially used area. The value per squared meter is estimated at €443.

Residential area The damage to residential areas, just as for the commercial area, is based on the HIS-SSM. In reality their are different forms of residential areas. People might live above stores or there could be multiple addresses in one building. This distinction is based on 2 separate residential situations. The first is single-family housing. This includes farms, bungalows and other possibilities. The second is apartments. Consisting of ground floor apartments, first floor apartments and second or higher floor apartments. To determine the damage on household effects each apartment is granted its own contents value. Due to the fact that the detail of the land use map is smaller, a factor of 0,2 is needed for residential area to translate from area of houses itself to residential area including gardens and pavements,(Huizinga et al., 2017). The value per squared meter is estimated at €212.

Infrastructure For this category the Nationaal Wegen Bestand Wegen(NWBW) is used,(*Documenten :: Nationaal Wegenbestand*, n.d.). In the NWBW the different roadways are divided in three categories. The sections highway and motorway are especially distinguished and the other roads are combined in the third category. This is based on a topographical map of top10nl,(*TOPNL Basis Registratie Topografie- PDOK*, n.d.). The distinction is based on the responsible authority. The highway is the responsibility of the nation. The motorways are the responsibility of the province and the other roads are maintained by the municipality and the regional water authorities. To reduce the amount of use categories all these subcategories are combined and valued at one price per squared meter. This estimation is valued at €109 in 2020.

The category railroads is composed of two subcategories. These are distinguished by the fact whether or not they are electrified or non electrified railroads. It is based on the file of the spoorbaanaandeel of the Basisregistratie Topografie (BRT),(*Basisregistratie Overheid - Spoorbaan deel*, n.d.). The attribute of electrification determines the value of the railroad. Civil constructions such as bridges or tunnels are left out of the valuation. As mentioned before are these subcategories are combined to a single category railroads which is estimated to be worth €353 per square meter in 2020.

The airport is determined based on the CBS land use map. Its value is estimated to be €155 per square meter in 2020.

Agriculture, Recreation and greenhouses The green categories are based on the CBS land use map that is created in 2008 and regularly updated. The value of these area categories are dependent on seasonal influences. Nevertheless to estimate the value they have been set to a fixed value. The distinction between agriculture and greenhouses is based on the fact that values of the categories varied to much to combine. The values for agriculture are estimated at €2 per square meter while greenhouse category is estimated at €52 per square meter. To price recreation an estimation of €108 is made. This estimation is based mostly on the value of sports.

Use category	Estimated maximal value
Residential	€212
Commercial	€433
Recreational	€108
Semi developed	€13
Agriculture	€2
Water	-
Greenhouses	€52
Airport	€155
Railroads	€353
Roadways	€109
Nature reserve	€11

Table 4.3: Overview of the maximal estimated damage per squared meter area Source: HIS-SSM

4.2. Hydrodynamic model

To simulate the flooding a hydrodynamic model is developed. The hydrodynamic model is simulated to model sea level rise with steps of 0,5m. The results of these different hydrodynamic simulations are used as flood characteristics for the damage function. In this section the input parameters and assumptions and the software are discussed.

Software for flood simulation There are different software packages that are able to simulate a storm event at sea. This storm event results in a breach and this results in a flood. De Bruijn, Slager, Piek, Riedstra, and Slomp (n.d.) made an overview of the strengths of each of the packages. To simulate a flood in a large area a 1D2D is needed. This leaves SOBEK-1D2D, D-FLow Flexible Mesh and 3Di. Finally 2D simulation is used since it is about overland flow due to dune breach. To determine whether the model is comparable, the base scenarios are compared to the VNK2. Therefore breaches are at Kijkduin, Noordwijk and Monster.

In this study D-Flow Flexible Mesh is used to simulate the flood. D-Flow FM is part of the Delft 3D Flexible Mesh Suite, developed by Deltares. D-Flow FM will be the successor of Delft3D Flow and SOBEK. The user is able to apply finer resolutions and is free to use a flexible combination of an unstructured grid. With triangles, hexagons or other polygons it has more freedom at locations that need more detail. The polygons are either in Cartesian or in spherical coordinates and 1D and 2D grids can be combined (*Delft3D-FLOW Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments User Manual Hydro-Morphodynamics permission from the publisher: Deltares*, 2011). This is the reason why D-Flow FM can improve the accuracy and compute it efficient.

In D-Flow FM the unsteady shallow water equations are solved based on the Navier Stokes equations. It is solved in either 3 dimensions or in 2 dimension with an average of the depth. Delft3D Flow FM is part of the Flexible mesh suite which is in development. The graphical user interface is already working but in the beta version not all functions are up and running yet. For example in this thesis the maximum water depth and the maximum flow velocity are needed. For this study D-Flow FM version HMWQ 1.6.1.47098 is used.

Expected Results In VNK2 and different reconnaissance studies flooding for the whole of the Netherlands are simulated. Part of the aim of this thesis is to determine damages in case of different scenarios, a hydrodynamic model will be helpful. With the new software a 3D hydrodynamic model with an curved-linear grid will lead to new insights. The detail that could be reached is beyond previous models. To determine whether the model is comparable, the base scenarios are compared to the VNK2. Therefore breaches are at Kijkduin, Noordwijk and Monster.

4.2.1. Model resolution

The resolution of the model determines the detail in which the flood simulation will run. The cell sizes determine the resolution, therefore a higher resolution means a higher number of cells and thus smaller area per unit for the cell. This higher detail leads to more detailed floods but also more cells for which the calculations need to be done. The calculation time increases exponential as cell sizes decrease since the number of cells exponential. This means that a larger matrix has to be solved by the kernel and respectively a longer computation.

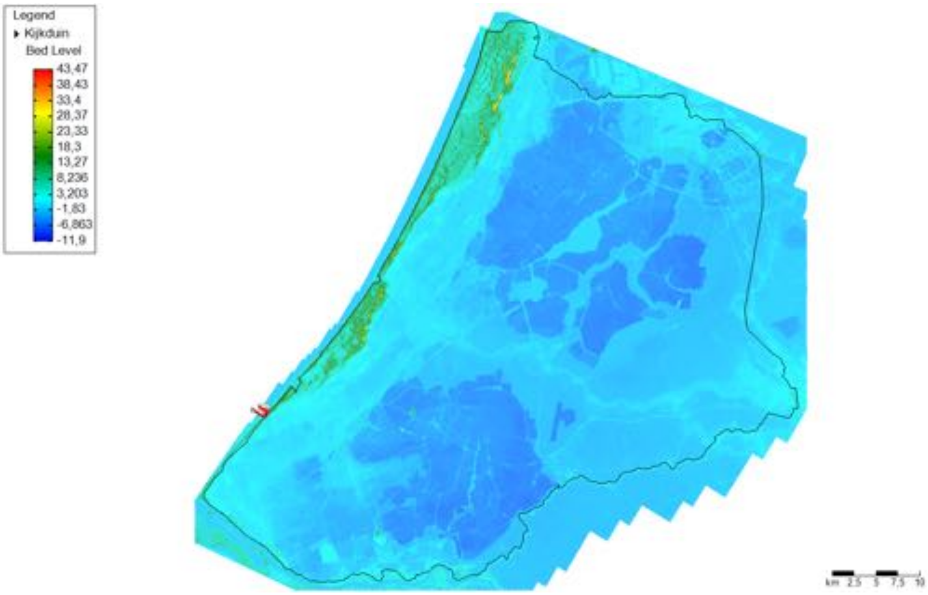


Figure 4.2: Elevation used in the hydrodynamic model based on AHN3

Besides a larger computation time, the limit of the courant condition is more likely to be reached with smaller grid cells. The courant condition is used to compute the maximum time step of the model. Therefore a to small grid cell will limit the model even tough it would result in the most detailed flood simulation. Since the area of interest is relatively large, dijkring 14 has an area of 225.700 hectares, the number of grid cells grows large fast and the computation time is very large. Because of this large area the file size of the bed level, the unstructured grid and the final flood simulation are enormous and partially because the GUI is in beta phase and partially because a computer with Intel i5 processor was used, the GUI of D-Flow FM would crash if files are too big. As mentioned before different breaches need to be evaluated and the area of interest is large. This led to a curvi-linear grid with size varying of 33-37m to 93-99m. The size of this grid is large enough to have a detailed flood over land and have a doable computation time. Smaller grid will be more detailed but might not lead to significant difference of water level in the long run. The grid is larger than the dijkring. Because the elevation that is used marks the boundaries of the dijkring. This way it is possible to simulate the flood without cut off boundaries. Cascade effects would show if they would develop during the flood event.

4.2.2. Elevation model

The elevation of the area of interest serves as the bed level of the flood simulation. Therefore the elevation of the area is the determining parameter in where the water flows and thus what the water level will be. Since it is a coastal area, in general it should flow from east to west, unfortunately there are lots of polders in this area and large parts of dijkring 14 are below sea level. Therefore the water will flow into the area.

The elevation is based on AHN3, 'Actueel Hoogtebestand Nederland 3'*AHN Viewer | AHN* (n.d.), which is data that is gathered by laser altimetry in the Netherlands. The AHN3 is the elevation of the area. Buildings, infrastructure and vegetation are taken out, this leaves us with terrain elevation. Since the area of the grid cell is determined before and is 99m by 39 meters it is unnecessary to take a resolution of the elevation that is significantly higher as the resolution of the grid cells. This because the curvi-linear grid in which the elevation will be part will only take the corner values of the grid cells. This means that the values of the terrain elevation are interpolated to an average value, that way there is always a value at the corner values of the grid cells. A resolution of 30 by 30 meters is taken of the AHN, a higher resolution would mean larger files and therefore a slower process. The detailed area that would be created with a higher resolution elevation map would be lost in translation to the grid cells. To make this simulation work, the dikes or flood defences of the dijkring should have a value that could retain water. To make sure the dijkring functions as a dijkring the boundaries are checked and corrected by hand if necessary.

4.2.3. Breach locations

In VNK2 different breach scenarios of dijkring 14 are evaluated. Since it is a large dijkring and the research of this thesis is especially focused on the sea level rise, the breach simulations in this thesis are those of dune breaches. In VNK2 different dune breaches are evaluated but certain defences had significantly higher probability of failure. To verify the simulation with VNK2, the same breach locations are taken in; Monster, Kijkduin, and Noordwijk. All these breaches are dune cut based. Since sea level rise won't happen overnight it is assumed that hydraulic structures will always be revised during planned reinforcement programs. Therefore the breach location will be part of a dune failure.

Breach formation To compute the breach growth there are different possibilities. Within the D-Flow FM software the Verheij-Van der Knaap (2002) and van der Knaap (2000) (*Delft3D flexible Mesh suite 1D/2D/3D Modelling suite for integral water solutions User Manual D-Flow Flexible Mesh*, n.d.) formula are possible. In this paragraph they are both assessed and the breach formation is determined. Both the formulas are to be evaluated in two separated phases. **Phase 1:** During phase 1 the breach level, for a constant initial breach width, is lowering. From the initial crest height to the minimal crest level. This is called the 'lowering' phase. **Phase 2:** When phase 1 is finished and the breach has reached the minimal crest level, phase 2 starts. In this phase the breach grows only in width. In this phase do the two formulas differ. The Verheij- van der Knaap increases the width of the breach based on the water level jump. If flow velocity through the beach is larger than the critical flow velocity sediment will erode and the breach will widen. The van der Knaap formula is bases the breach width as a function of time and is based on a maximal breach width. Hence the Verheij-van der Knaap is used:

Phase 1

for: $T_{start} \leq t \leq T_{start} + t_{phase1}$

$$B(t) = B_0 \tag{4.1}$$

$$z(t) = z_{crest} - \frac{t - T_{start}}{t_{phase1}} * (z_{crest} - z_{min} \tag{4.2}$$

Where:

T_{start} = The time when initial breach starts [s]

$T_{start} + t_{phase1}$ = Time when maximum breach depth is reached, phase 1 ends [s]

$z(t)$ = Crest level of the dam breach as a function of t [m]

z_{crest} = Initial crest level [m]

z_{min} = Minimal crest level of breach [m]

Phase 2

for: $t > T_{start} + t_{phase1}$

$$B(t_{i+1}) = B(t_i) + \frac{\Delta t}{3600} * \frac{\delta B}{\delta t}_{t_{i+1}} z(t) = z_{min} \tag{4.3}$$

With:

$$\frac{\delta B}{\delta t}_{t_{i+1}} = \frac{0.052}{ln(10)} * \frac{(g * (h_{up} - max(h_{down}, z_{min})))^{\frac{3}{2}}}{u_c^2} \tag{4.4}$$

Where:

g = Acceleration due to gravity $[m/s^2$

h_{up} = Water level upstream of breach [m]

h_{down} = Water level downstream of breach [m]

u_c = Constant critical flow [m/s]

(4.5)

Hydraulic boundary conditions The hydraulic boundary conditions are the conditions that determine the load on the flood defences and describe the simulated storm event. These conditions are suggested to be the maximal load. They therefore represent a storm surge that is equal to a storm surge that would occur once per return period. In this thesis the maximum load is evaluated and therefore the storm surge with a frequency of 1/ 10.000 is used. The hydraulic boundary conditions are determined by Rijkswaterstaat for the purpose of the Botlek adaptation project at the Port of Rotterdam. (Boersen et al., 2017). The point of reference is assumed to rise with the sea level rise. The wave that is used is based on the statistical maximum storm surge that is determined by Rijkswaterstaat, see Figure 4.3.

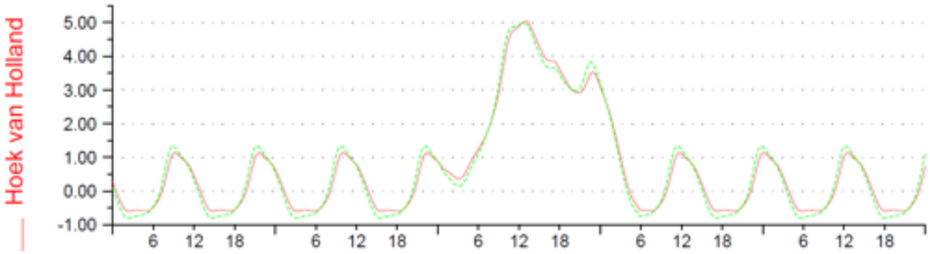


Figure 4.3: Estimated maximal storm surge load with return period R= 1/10.000 in 2015, Source: Boersen et al. (2017)

As mentioned before will the influence of sea level rise only influence the height of the whole tidal cycle, this is shown in Figure 4.4 and 4.5. These storm surges have the same pattern and are just raised by respectively 0,35m and 0,85m. Rijkswaterstaat based these rises on the sea level rise projections for 2050 and 2100. Because of this earlier research, for this research the length, height and form of this storm surge is used with larger sea level rise. In this thesis the current sea level, + 0,5m, + 1m, + 1,5m, + 2m, + 2,5m are simulated.

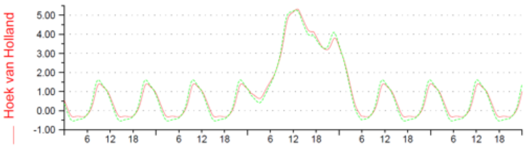


Figure 4.4: R= 1/10.000 in 2050 Source: (Boersen et al., 2017)

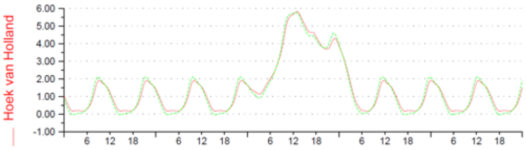


Figure 4.5: R= 1/10.000 in 2100 Source: (Boersen et al., 2017)

In the flood simulation a longer period than only the storm surge is simulated. Since the water that is on land will spread over time. To ensure the load of the storm surge is equal to the estimated load the regular tide pattern is extended. The final storm surge used in the flexible mesh model is 4.6

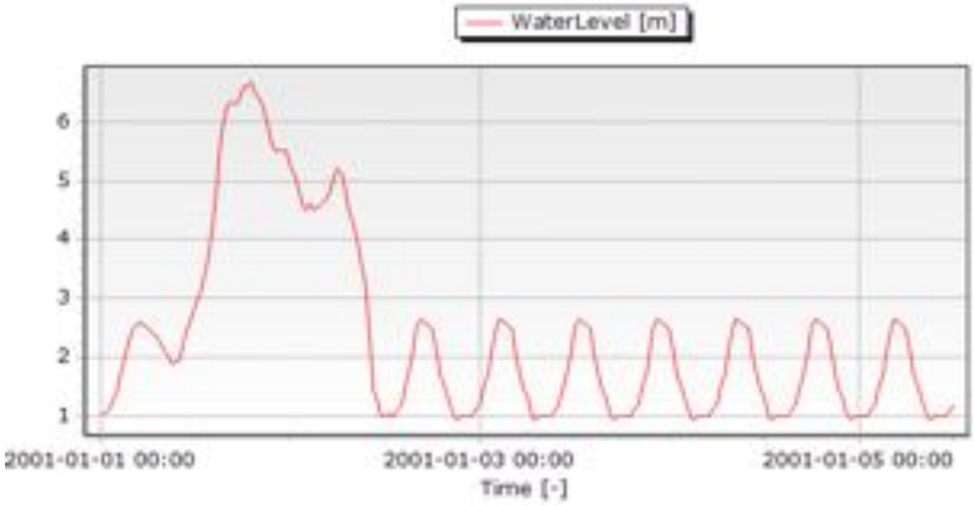


Figure 4.6: Storm surge used in research. R=1/10.000 2020, with on the y axis the sea level and on the x axis time of 5 days.

4.2.4. Model and grid generation

Grid generation In this thesis a simulation of dijkring 14 is run with a resolution of 39m by 99m. The grid is made within the RGF Grid generator. The grid is a curvi-linear grid. It is created by splines that are curved besides the dijkring. Then a grid could be build. This way the orthogonality and the smoothness of the grid started great. Then the grid was refined, this lead to more cells but still orthogonality and smoothness well within range. By deleting the cells that were out of range an fitting grid area is created. The process of refining, removing and orthogonalising is repeated until the grid cells were detailed enough to simulate the flow. If the grid cells would have been refined further the computing time would be too large. The area that is simulated is the area within the flood defences of the dijkring 14 area. Since the flood defences are well recorded in the elevation of the model, the edges of the grid are outside of the dijkring area. This way the dikes have their limited heights and if the scenario would be such that if the water is flowing out of the dijkring this would be visible in the simulation.

Fixed weirs To model the breaches a dune cut is simulated. Therefore the elevation of the dune is is corrected to sealevel. Instead of the elevation a fixed weir is added. The fixed weir can be varied in height and will overflow. The fixed weirs are added in the GUI and have the maximum width that is determined by the Verheij- van der Knaap formula mentioned in 4.2.3. Since it will function as a breach the width and the height of the fixed weir will vary over time. Because the GUI is still a beta version, the flexible weir is added by an additional function. The weirs are located at the breach locations between the dunes that are mentioned before, see Figure 4.7.

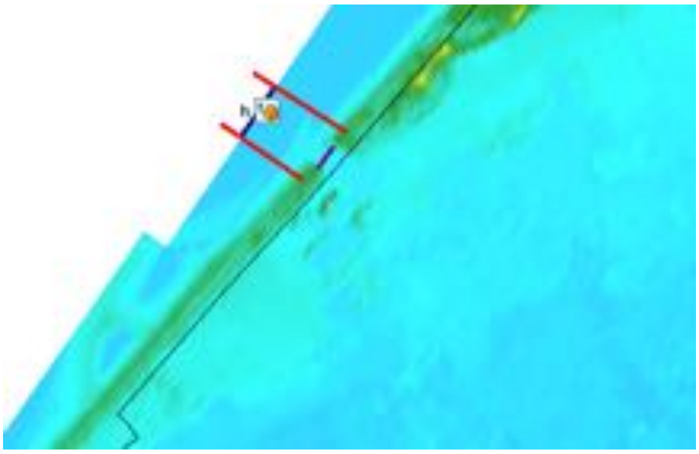


Figure 4.7: Detailed image of the breach location

Thin dams To minimize the chance of mistakes in the simulation thin dams are added just beside the boundary conditions that will simulate the maximum storm surge. The thin dams stretch from the edge of the grid to the dunes and retain the water, this way the boundary condition applies only on the breach, the fixed weir, and the dunes located right besides the fixed weir. Without the thin dams, either the entire western edge of the grid would have to be a boundary condition, or the entire coast would have to fill up, before the breach would occur. With the thin dams local breaches can be simulated. The thin dams are visible in Figure 4.7 in red. They retain the water within and are a modelling trick to speed up the simulation process. In case of multiple local flood event, multiple boundary conditions, breaches and thin dams are applied to create the same effect.

4.2.5. Damage estimation

To determine the damages that would occur because of the flood the ' Global Flood Risk Tool' of Royal Haskoning DHV is used. This tool combines the land use map and the inundation map of the flood that is simulated in D-Flow FM. To combine the inundation map and the land use map a damage function based on the water depth is needed. This damage function determines what percentage of the value is damaged by the flood at a certain water depth. As could be found in formula 3.3, the damage curves determines the estimated damage.

$$D_i = \sum_{i=1}^{m} \sum_{r}^{n} \alpha_i(h_r) * D_{max,i} * n_{i,r} \tag{4.6}$$

These damage curves depend on the land use category and in our case multiple categories are combined. Therefore their damage function is combined.

Damage functions determine how much of damage is inflicted on the area of interest. The function is based on the hydraulic characteristics of the floods and the most influential characteristic is the inundation depth. Since the damage function is different for each land use category the most important ones are evaluated in appendix B.

Overview damage curves To determine the damage that is imposed due to a flood event these damage curves need to be combined with an inundation depth. This is done by the Global Flood Risk Tool of Royal HaskoningDHV. The different damage curves that are being used in this research thesis are in Figure 4.8. These damage curves are based on historical data from coastal floods. The different damage curves are further evaluated in appendix B

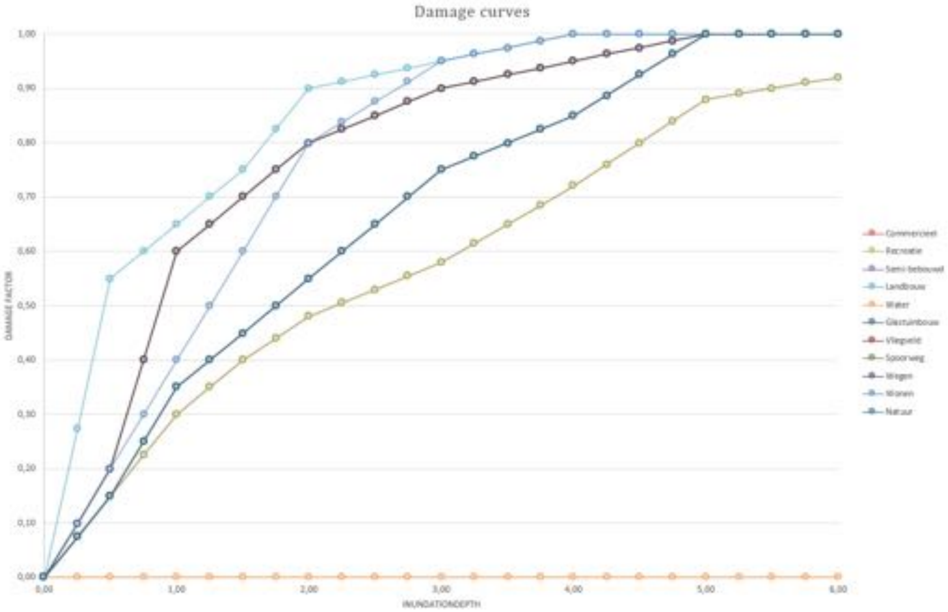


Figure 4.8: Damage functions used in the Global Flood Risk Tool.

4.2.6. Functionality of Global Flood Risk Tool

The global flood risk tool combines the inundation maps and the land use map by means of the damage curves. It is combined in a damage map which indicates the damage in € per squared meter. In Figure 4.9 such a damage map is shown. In the tool the damage map is integrated and the total damage is determined. This way for each of the scenarios the total damage can be evaluated. The economic optimization is then executed to determine whether or not the investment in rising the flood defences is feasible.

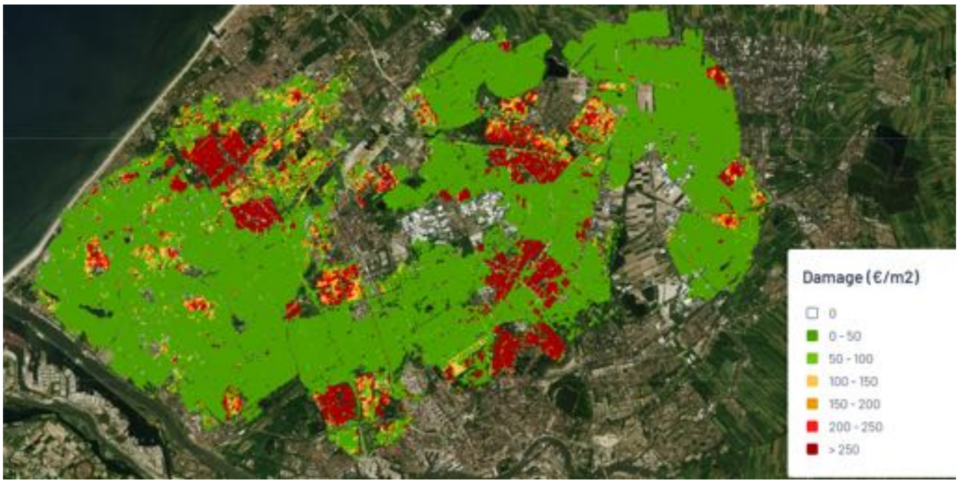


Figure 4.9: Example of the damage map

5

Result of case study

In chapter 4 it is explained how the case study was set up and which assumptions were made. In this chapter the result of the case study is analysed and the flood events are verified. The chapter starts with the validation of the simulated flood events, in section 5.1. The simulated events for current situation are compared to previous acknowledged simulations such as VNK. If the results are verified the other flood scenario simulations are evaluated. These are used to estimate the damage by a flood event. For each of the breach locations different scenarios were evaluated to predict the damage that would be caused by a flood event in case of sea level rise.

5.1. Validation of flood event

In this thesis, the goal is to determine the influence of the sea level rise on the flood risk of the Netherlands. Chosen is to do a case study of the largest and most valuable Dijkring of the country. In the case study different flood scenarios are simulated to determine the consequences of various flood events. Before using the different simulations as a tool to predict consequences, the simulations have to be validated. This validation is executed by comparing the flood simulation of the current sea level with other flood simulations. In the Netherlands one of the foremost known flood simulations is the VNK2. To determine the similarity of the simulations three characteristics are studied. The first is the pattern in which the flood event expands, in both simulations the water should be in the same places. The second is the flood depth, comparable flood depths are necessary to have an equal flood event. Finally the damages are compared.

5.1.1. Flood pattern

To determine the equality of the flood pattern, each of the three scenarios is evaluated individually. The inundation map of the simulation is compared to the inundation map of the VNK2. Since the VNK2 inundation maps are not created by a hydrodynamic flood simulation the flood pattern is not coherent. There are several patches without a connection to the main flood component. This is one of the reasons that explains the difference of the flood patterns. Besides the different simulation methods the differences can be explained by different grid sizes, slightly different breach locations and the resolution of the bed elevation. In this section the key elements of the flood patterns are compared based on optical comparison. To assess the flood pattern each of the flood simulations is divided in 4 quarters to assess more precise.

Kijkduin The breach location of Kijkduin is evaluated due to the fact that the consequences could be severe. A major city, The Hague, is located close to the breach location and part of that city is flood prone. Besides the consequences, the probability of failure in this dune area is relatively large.

When comparing the inundation of the hydrodynamic simulation and the VNK2 optically, the first major difference is the size of the area that is flooded. The size of the area in the hydrodynamic model is significantly larger, see Figure 5.2. This is explained by the fact that the hydrodynamic model simulates five days. This means that even when the simulated flood event is over, the water that is already on land will be divided over a larger area, as it takes time to flow.

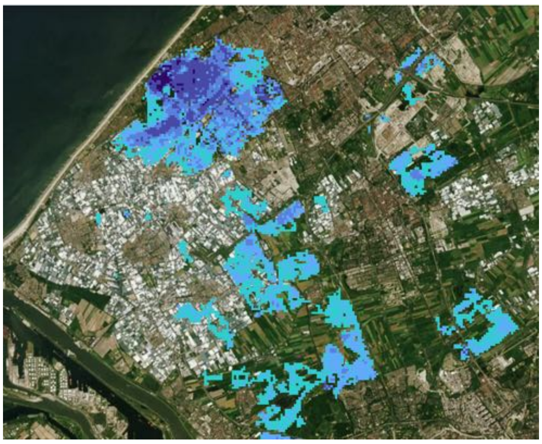


Figure 5.1: Inundation based on VNK2

Figure 5.2: Inundation based on hydrodynamic simulation

When taking a closer look at the flooded area similarities and differences are brought to light. Therefore in this optical analysis a close up is analysed. The image is divided into quarters. Each of the quarters is compared.

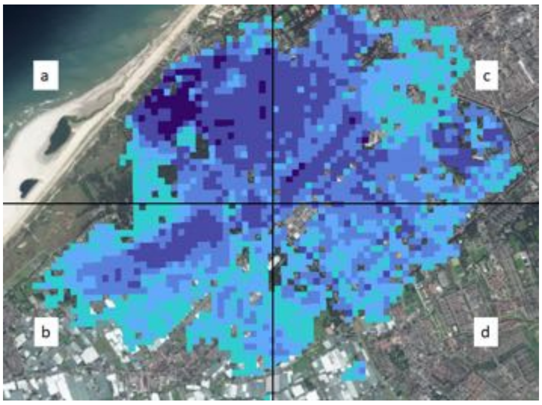


Figure 5.3: Inundation based on VNK2

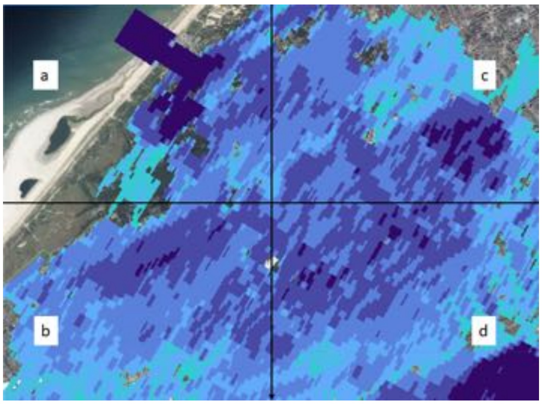


Figure 5.4: Inundation based on hydrodynamic simulation

Quarter a: It becomes clear that a slightly different breach location is used. The breach location in the simulation is based on the lowest part of the dunes within the sector with the highest probability of failure. Furthermore the shape of the flood in quarter a is very similar. The higher inundations are located at the same areas and the same areas are being dry. The inundation of the VNK seems to be higher. This will be further evaluated at the inundation depth comparison.

Quarter b: In quarter b the larger flooded area of the simulated inundation is clearly visible. As mentioned before this is because the hydrodynamic simulation lasted longer and the water had more time to flow. This could also explain why the overall inundation depth of the hydrodynamic simulation is larger in quarter b. Besides the size and overall depth of the flooded area it is visible that the area that has the largest inundation depth is situated at the same location with the same shape for both the simulations.

Quarter c: Quarter c seems very equal in both simulations. In the top left and far right area of the hydrodynamic simulation map, the water has extended to a larger area as a result of the longer period of time this simulation has run. The shape of larger inundation depths are very similar for both the inundation maps.

Quarter d: It becomes clear that the extension of the flooded area is in the south eastern direction. Apparently the water accumulates in the area in the bottom right corner of quarter d of the hydrodynamic simulation. This is because the elevation of that area is significantly lower. Furthermore there is similarity in the shape of the inundation depth of the map of VNK2 and the higher inundated area of the map of the hydrodynamic simulation. This can also be explained by the fact that there is lower elevation. Therefore the water will flow there first. Over time more water will flow there and it will extend to a larger area, hence the almost entirely flooded quarter d in the hydrodynamic simulation map.

Concluding, based on the optical comparison of the inundation maps, of the VNK and from the hydrodynamic simulation, it is clear that the flood pattern is similar. Even tough there is a larger flooded area with the hydrodynamic simulation the pattern is similar. The flood pattern of the hydrodynamic Kijkduin simulation is therefore validated.

Noordwijk The breach location of Noordwijk has a relatively large probability of failure. Behind the dunes a large polder is situated and therefore a large area is flood prone. Flooding of the national airport Schiphol would lead to large damages.

When comparing the inundation of the hydrodynamic simulation and the VNK2 optically, the first major difference is the size of the area that is flooded. The size of the area in the hydrodynamic model is significantly larger, see Figure 5.6.

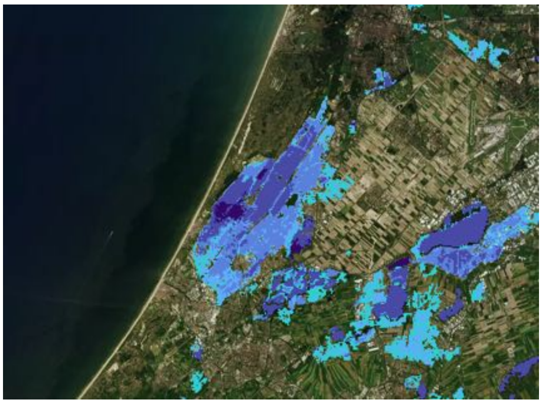


Figure 5.5: Inundation based on VNK2

Figure 5.6: Inundation based on hydrodynamic simulation

When taking a closer look at the flooded area similarities and differences are brought to light.

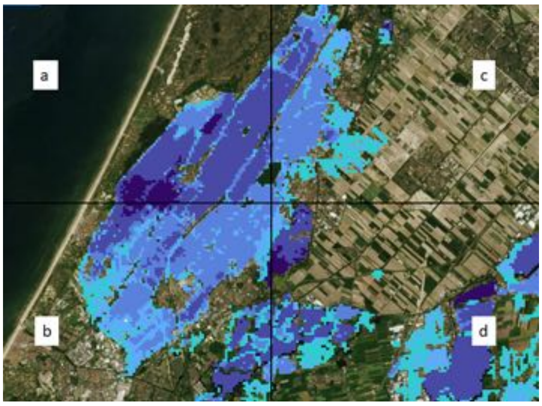


Figure 5.7: Inundation based on VNK2

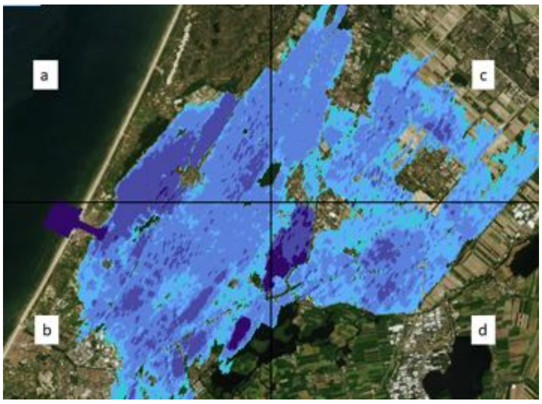


Figure 5.8: Inundation based on hydrodynamic simulation

Quarter a: Clearly a slightly different breach location is used. The breach location in the simulation is based on the lowest part of the dunes within the sector with the highest probability of failure. This different location is the reason for the extremely high inundation depths in the bottom of quarter a of the VNK2 inundation map. Furthermore the shape of the flood in quarter a is very similar. The boundaries of the flooded area are located at the same location. The inundation of the VNK2 seems to be higher. This will be further evaluated at the inundation depth comparison.

Quarter b: In quarter b it is visible that the area that is flooded in the hydrodynamic simulation is slightly larger than the area of VNK2. The left boundary is equal and the follows the same shape up to the canal. In the hydrodynamic simulation the flooded area expands past the canal and the inundation depth leading up to the canal is larger. In the middle and the right side of quarter b of the VNK2 inundation map there is a dry area. This is slightly flooded in the hydrodynamic simulation. This could be explained due to a larger simulation time. Furthermore the shape and location of the areas in which there is a deeper inundation are similar at both simulations.
Quarter c: It becomes clear that the extension of the flooded area is in the north eastern direction. When comparing the left side of the quarter the flood pattern is very similar. The location and shape of the flooded area is equal. Apparently the water extends in eastern direction as for both quarter c and quarter d the flooded area extends. The low inundation depth is a signal that this is due to a longer simulation period.

Quarter d: Quarter d is very different for the hydrodynamic simulation and the VNK2. At the top left is the only similarity. This is in both simulations the area for which the largest inundation depth is reached. The shape and location is identical. When observing the rest of the quarter there seem no similarities. In the VNK2 inundation map it is clear that the flooded areas are located close to water bodies. The flooded areas are not connected. The hydrodynamic simulation simulates the flow of water for each grid cell. The flooded area is therefore always connected. When evaluating the flooded area of the hydrodynamic simulation it is clear that a large agricultural area is flooded extra. This is due to a longer simulation period.

Concluding, based on the optical comparison of the inundation maps, of the VNK2 and from the hydrodynamic simulation, it is clear that the flood pattern is similar. Even tough there is a larger flooded area with the hydrodynamic simulation the pattern is similar. The larger area is explained by the longer duration of the flood simulation. The flood pattern of the hydrodynamic Noordwijk simulation is therefore validated.

Monster at The breach location of Monster the consequences could be severe. A very large area is prone to flooding with polders from the Hague up till Rotterdam. In these polders there is a lot of greenhouse agriculture which has a significantly higher value than regular agriculture, this could lead to disastrous damages.

When comparing the inundation of the hydrodynamic simulation and the VNK2 optically, the first major difference is the size of the area that is flooded. The size of the area in the hydrodynamic model is significantly larger, see Figure 5.10.

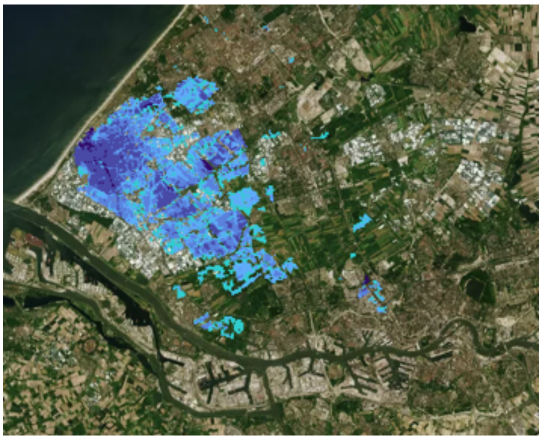


Figure 5.9: Inundation based on VNK2

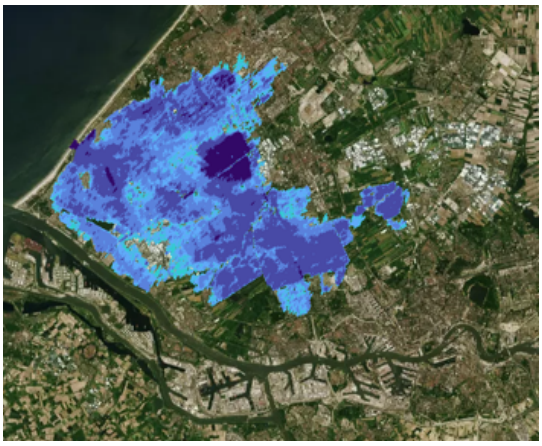


Figure 5.10: Inundation based on hydrodynamic simulation

When taking a closer look at the flooded area similarities and differences are brought to light.

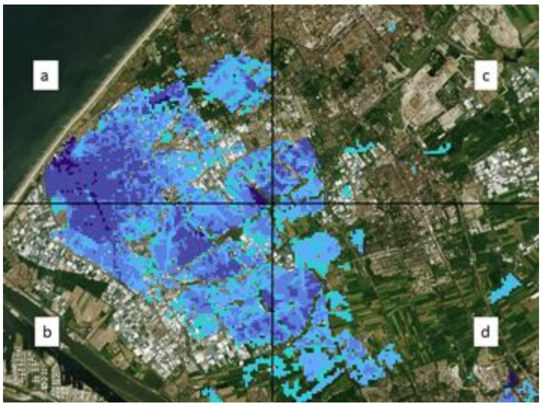


Figure 5.11: Inundation based on VNK2

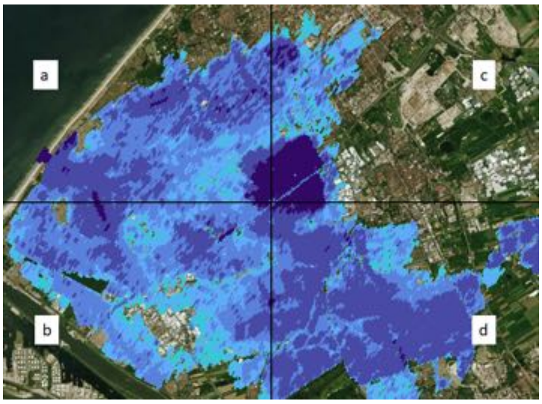


Figure 5.12: Inundation based on hydrodynamic simulation

Quarter a: When comparing the VNK2 and the hydrodynamic simulation it becomes clear that the breach location is almost at the same location. Furthermore, the shape and location of the larger inundation depths is similar which implies as similar flood. When comparing the top right area of quarter the flooded area is larger. Another important detail is in the bottom left corner: In the VNK2 simulation there is a clear dike visible that draws the edge of the flooded area. In the hydrodynamic simulation the dike is flooded near the dune. This is of large influence when evaluating 'b'. Furthermore, in the bottom right there is a very large inundation depth in the hydrodynamic simulation that is not there in the VNK2 simulation. This will be further evaluated at the inundation depth comparison.
Quarter b: In quarter b it is visible that the area that is flooded in the hydrodynamic simulation is larger than the area of VNK2 simulation. The left boundary of the VNK2 simulation follows a dike, while in the hydrodynamic simulation, the area after that dike becomes flooded. This results in a larger flooded area. The shape and size of the area with a larger inundation depth is similar.
Quarter c: First thing that is noted when comparing the third quarter is the very high inundated area at the bottom left side of the hydrodynamic simulated inundation map. It has a similar shape to the flooded area of the VNK2 simulation but is clearly different in inundation depth. The water is accumulated in that area. This is the same location as in the Kijkduin breach. This means that due to the longer duration of the simulation more water accumulates and therefore a larger inundation depth occurs. Furthermore there is additional flooded area at the top left corner. This flows in from 'a' and is also due to a longer duration of the simulation.
Quarter d: Quarter d is very different for the hydrodynamic simulation and the VNK2. The flooded area at the left side of the quarter has for both the simulation the same shape. Due to the duration of the simulation the inundation depth of the hydrodynamic simulation is significantly larger. This is also the cause of the extension of the flooded area in eastern direction.The relatively large inundation depth of the flooded area this far from the breach is explained by the low elevation of this area. The elevation of the area varies up to -3 meter NAP.

Concluding, based on the optical comparison of the inundation maps, of the VNK2 and from the hydrodynamic simulation, it is clear that the flood pattern is similar. Even tough there is a larger flooded area with the hydrodynamic simulation the pattern is similar. Major difference is explained by the fact that in the hydrodynamic simulation the water flows past the dike. This, in combination, explains the larger area that is flooded in the hydrodynamic flood simulation. When investigating the dike in the elevation model and the flow velocity map it seems that the water flows over the dike in the dunes. This might be explained by a slightly different breach location. Since this could happen it is taken into account and therefore; the flood pattern of the hydrodynamic Monster simulation is validated.

5.1.2. Flood depth

To validate the hydrodynamic simulation, the pattern of the flood has been discussed in 5.1.1. To determine whether or not the inundation depth of the simulations is comparable, QGIS is used. With this GIS tool it is possible to do calculations on raster (GeoTiff) files. To compare them only the area that is flooded in both the simulations, in this case mostly the VNK2 simulation, are beings used. Then the inundation depth of the hydrodynamic simulation is subtracted of the VNK2 simulation. This leaves the difference between the inundation depths at each location. This means that when there is a red colour, or negative Δ inundation, the inundation of the hydrodynamic simulation is larger. In a perfect scenario the difference is close to zero. Each of the breach locations is evaluated and determined whether the simulation is good.

Kijkduin In the flood pattern comparison the flooded area of the hydrodynamic simulation was larger. Besides a larger flooded area some inundation depths appeared larger, see 5.4.

When comparing the inundation depths of the hydrodynamic simulation and the VNK2, it clealy visible that the western part, close to the breach, is comparable, see Figure 5.13. Towards the edges of the flooded area of the comparison the colour becomes more red. Because of the longer duration which led to a larger flooded area, more water has passed that point. One of the most highlighted areas are very close to dunes at the breach. This can be explained by the fact that the breaches are at a slightly different location. The breach location in the hydrodynamic simulation is based on the lowest part of the dunes within the sector with the highest probability of failure. The other is in the centre of the picture. This can be explained that at that location the water is accumulated, see Figure 5.4. Since the duration of the hydrodynamic simulation was longer there was more time and water to accumulate.

Figure 5.13: Map to indicate the difference between the inundation depths of the hydrodynamic simulation and the VNK2 for a breach in the dunes at Kijkduin.

Concluding, the core area of the comparison shows similar inundation depths and due to the duration of the hydrodynamic simulation and the larger flood area the edges of the comparison are diverging slightly. With an maximum at the center of the map. Tough the edges are slightly red, the core proves that the simulation have a similar inundation depth and therefore the hydrodynamic simulation of the flood at breach location Kijkduin is validated with respect to inundation depth.

Noordwijk As mentioned before the breach location at Noordwijk is evaluated due to the probability of failure being relatively high. In the flood pattern comparison it became clear that due to a longer duration of the simulation the flooded area of the hydrodynamic simulation was slightly larger. Besides a larger flooded area some inundation depths appeared similar, see 5.8.

When comparing the inundation depths of the hydrodynamic simulation and the VNK2, it becomes clear that the entire area that is flooded in both simulations, is comparable, see Figure 5.13. Almost the entire area is close to white which indicates that the difference between the inundation depth of the two simulations is similar. First thing that catches the eye is again a red area at the breach area. This can be explained by the fact that the breach location was slightly different. Notable is the light grey area in the middle. This means that the VNK2 simulation has a larger inundation depth. The reason that this happened is that in the hydrodynamic simulation the water expended in a eastern direction instead of north, see Figure 5.7. The small difference might be because the flow of water was less stowed and therefore the inundation depth was smaller. Towards the edges of the flooded area of the comparison the colour becomes more red. This is due to the fact that the hydrodynamic simulation had a longer duration which led to larger flooded area and therefore more water has passed that point. Despite these small differences the inundation depth is still comparable.

Figure 5.14: Map to indicate the difference between the inundation depths of the hydrodynamic simulation and the VNK2 for a breach in the dunes at Noordwijk.

Concluding, the comparison shows similar inundation depths and due to the duration of the hydrodynamic simulation and the larger flood area the edges on the eastern and southern side of the comparison are diverging slightly. Tough the eastern and southern edges are slightly red, the core proves that the simulation have a similar inundation depth and therefore the hydrodynamic simulation of the flood at breach location Noordwijk is validated with respect to inundation depth.

Monster As mentioned before the breach location at Monster is evaluated due to the large financial damages. In the flood pattern comparison it became clear that due to a longer duration of the simulation the flooded area of the hydrodynamic simulation was larger. Besides a larger flooded area some inundation depths appeared larger, see Figure 5.12. The largest difference was due to the dike that was passed close to the breach location in the hydrodynamic simulation but retained the water in the VNK2 simulation. In this comparison only the areas that were flooded in both scenarios are evaluated.

When comparing the inundation depths of the hydrodynamic simulation and the VNK2, the first thing to draw your attention is the dark red area in the center, see Figure 5.15. This area has a large inundation depth in the hydrodynamic simulation. Water is accumulated there and there is a low elevation height. Due to the fact that the duration of the simulation is larger there is time for the water to flow here. In the VNK2 simulation the area is barely flooded. This explains the large difference. Furthermore the core of the flooded area is very similar. The edges of the flooded area are turning red. This is due to the fact that the duration is longer, the flooded area significantly larger and the water will flow passed these areas in the hydrodynamic simulation see Figure 5.12.

Figure 5.15: Map to indicate the difference between the inundation depths of the hydrodynamic simulation and the VNK2 for a breach in the dunes at Monster.

Concluding, the core area of the comparison shows similar inundation depths and due to the duration of the hydrodynamic simulation and the larger flood area the edges of the comparison are diverging slightly. With an maximum at the center of the map. Tough the edges are slightly red, the core proves that the simulation have a similar inundation depth and therefore the hydrodynamic simulation of the flood at breach location Monster is validated with respect to inundation depth.

5.1.3. Estimated damages

In the sections above it is concluded that for each of the three breaches a similar flood event is simulated. This led to the conclusion that the flood event is validated and that other, future scenarios will be trustworthy. The thesis is about the evaluation of the risk of flooding and therefore the estimated damages are of large influence. This means that it is of large importance that the estimated damages are validated as well. To validate the estimated damages not only the hydrodynamic simulation needs to be accurate, but also the land use map and the damage curves are of influence.

Therefore the estimated damages are validated in two different ways. The first is to see if there is a resemblance between the VNK2 flood simulation that is publicly available via LIWO, and used to validate the hydrodynamic simulation above, and the hydrodynamic simulation. This is a flood simulation with a relative short duration. This is the reason that a relatively small area is flooded. To compare the flood events. In QGIS the areas of flooding are made equal, part of the hydrodynamic simulation is left out. This comparison is of interesed because of the fact that The second method of validation is by comparing the estimated damages of the hydrodynamic simulation with the estimated damages of the VNK2 report. These damages are based on the total direct damage that will occur and the duration of the simulation is up to two weeks.

Kijkduin As mentioned before the breach location at Kijkduin is evaluated due to the consequences being severe. In the flood pattern comparison it became clear that due to a longer duration of the simulation the flooded area of the hydrodynamic simulation was larger. Besides a larger flooded area the inundation depths are larger, see Figure 5.13.

When comparing the estimated damages, two different comparisons are done. First the VNK2 simulation is compared to the

The second comparison is based on the estimated damages of the hydrodynamic simulation and the estimated damages of a flood event according to VNK2(). The estimated damages of the flood event in VNK2 are based on the direct damages that would occur if a breach happens. These are all the damages because the duration of the simulation is up to two weeks. This means that in this simulation the water has a long time to flow. Therefore simply applying the damage curves and the land use map used for the damage estimation of this thesis on the inundation depths used above would not suffice. As stated in 2 the damages that is estimated if a breach occurs at Kijkduin is €2.700 Million. This is compared to the damages that are estimated with the hydrodynamic simulation, see Figure 5.16

Figure 5.16: Map to indicate the estimated damages per square meter based on the hydrodynamic simulation for a breach in the dunes at Kijkduin.

In the figure above the estimated damage per square meter is presented. This is based on the land use map and the damage curves mentioned in 4.1. They are combined with the flood event of the hydrodynamic simulation, see Figure 5.2. With use of the Global Flood Risk Tool the estimated damage map is created and a total of € 2.148 Million of damages is estimated. This is slightly lower as the damages estimated with VNK2. This difference is explained by the fact that the hydrodynamic simulation runs for 5 days and the VNK2 estimation is based on over two weeks. This leaves time for the water to flow and expand the affected area.

The area that is damaged is therefore larger which results in a larger damage.

Concluding, estimated damage of the hydrodynamic simulation is in the same order of magnitude as the estimated damages of the VNK2. The simulation serves a slight underestimation of the damages due to a shorter duration of the simulation time. Therefore the estimated damages are validated if it is kept in mind that they serve as a minimal estimation.

Noordwijk As mentioned before the breach location at Noordwijk is evaluated due to the probability of failure being relatively high. In the flood pattern comparison it became clear that due to a longer duration of the simulation the flooded area of the hydrodynamic simulation was slightly larger. Besides a larger flooded area, the inundation depths are similar, see 5.8.

To validate the estimated damages, the hydrodynamic simulation is compared twice.

The second comparison is based on the estimated damages of the hydrodynamic simulation and the estimated damages of a flood event according to VNK2(Vergrouwe, 2010). The estimated damages of the flood event in VNK2 are based on the direct damages that would occur if a breach happens. The duration of the VNK2 flood event is based on two weeks, see Figure 2.8. This means that in this simulation the water has a longer time to flow. This results in a larger flooded area. The damages that are estimated by the VNK2 have a total value of € 1.800 Million. These damages are compared to the estimated damages of the hydrodynamic simulation, see Figure 2.8.

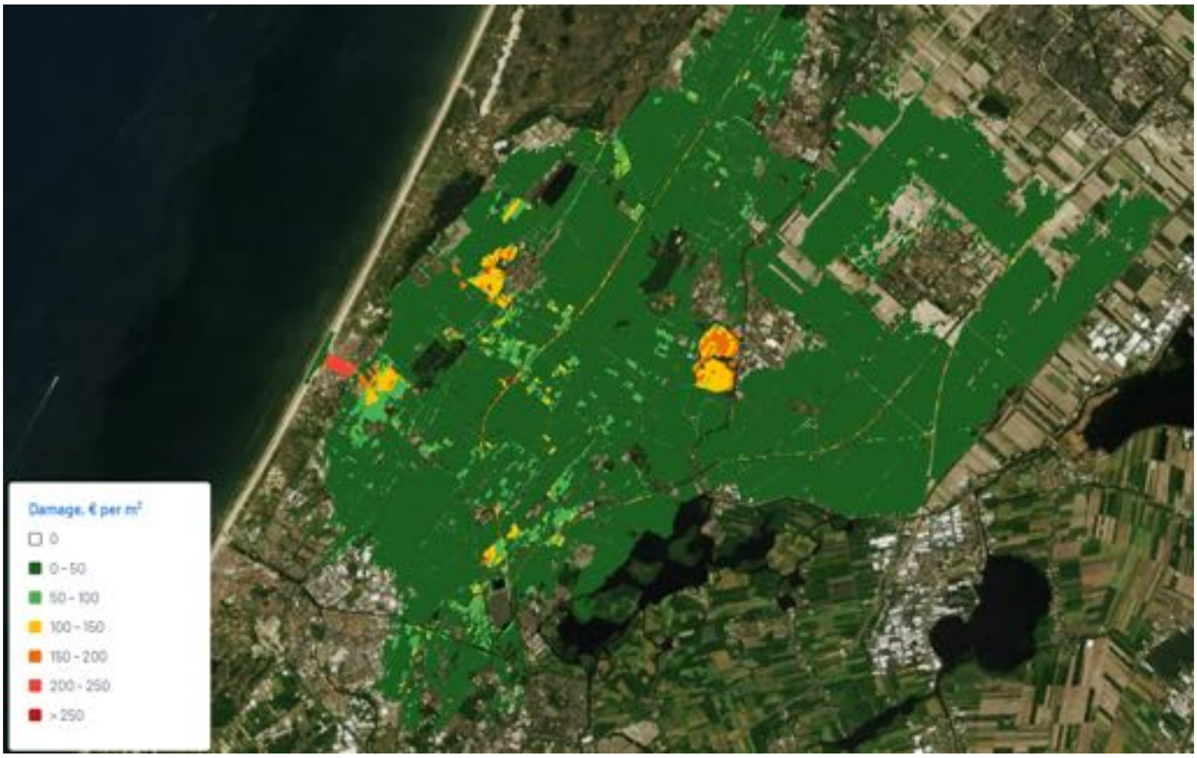


Figure 5.17: Map to indicate the estimated damages per square meter based on the hydrodynamic simulation for a breach in the dunes at Noordwijk.

In the figure above the estimated damage per square meter is presented. This is based on the land use map and the damage curves mentioned in 4.1. They are combined with the flood event of the hydrodynamic simulation, see Figure 5.6. With use of the Global Flood Risk Tool the estimated damage map is created and a total of € 1.367 Million of damages is estimated. This is slightly lower as the damages estimated with VNK2. This difference is explained by the fact that the hydrodynamic simulation runs for 5 days and the VNK2 estimation is based on over two weeks. This leaves time for the water to flow and expand the affected area. The area that is damaged is therefore larger which results in a larger damage.

Concluding, estimated damage of the hydrodynamic simulation is in the same order of magnitude as the estimated damages of the VNK2. The simulation serves a slight underestimation of the damages due to a shorter duration of the simulation time. Therefore the estimated damages are validated if it is kept in mind that they serve as a minimal estimation.

Monster As mentioned before the breach location at Monster is evaluated due to the large financial damages. In the flood pattern comparison it became clear that due to a longer duration of the simulation the flooded area of the hydrodynamic simulation was larger. Besides a larger flooded area some inundation depths appeared larger, see 5.12. The largest difference was due to the dike that was passed close to the breach location in the hydrodynamic simulation but retained the water in the VNK2 simulation.

To validate the estimated damages, the hydrodynamic simulation is compared twice.

The second comparison is based on the estimated damages of the hydrodynamic simulation and the estimated damages of a flood event according to VNK2(). The estimated damages of the flood event in VNK2 are based on the direct damages that would occur if a breach happens. The duration of the VNK2 flood event is based on two weeks, see Figure 2.6. This means that in this simulation the water has a longer time to flow. This results in a larger flooded area. The damages that are estimated by the VNK2 have a total value of € 3.500 Million. These damages are compared to the estimated damages of the hydrodynamic simulation, see Figure 2.6.

Figure 5.18: Map to indicate the estimated damages per square meter based on the hydrodynamic simulation for a breach in the dunes at Monster.

In the hydrodynamic simulation is the area south of a dike flooded due to an overflow close to the breach. This results in an extra flooded area in the hydrodynamic simulation. In the figure above the estimated damage per square meter is presented. This is based on the land use map and the damage curves mentioned in 4.1. They are combined with the flood event of the hydrodynamic simulation, see Figure 5.10. With use of the Global Flood Risk Tool the estimated damage map is created and a total of € 3.365 Million of damages is estimated. This is slightly lower as the damages estimated with VNK2. This difference is explained by the fact that the hydrodynamic simulation runs for 5 days and the VNK2 estimation is based on over two weeks. This leaves time for the water to flow and expand the affected area. Because of the extra flooded area south of the dike this difference is small and therefore the estimated damages are close.

Concluding, estimated damage of the hydrodynamic simulation is in the same order of magnitude as the estimated damages of the VNK2. The simulation serves a slight underestimation of the damages due to a shorter duration of the simulation time. Therefore the estimated damages are validated if it is kept in mind that they serve as a minimal estimation.

Validation In this section,the hydrodynamic simulation is compared to the VNK2 simulation. The hydrodynamic simulation was validated based on three different components. The flood pattern, the inundation depth and the estimated damages. For each of the breach locations all three of the components were validated and therefore the hydrodynamic simulation is validated, see table 5.1. This means that the hydrodynamic simulation produces trustworthy flood simulations. With the simulations it is possible to simulate other future scenarios. These scenarios are based on sea level rise and will result in estimated damages for future scenarios with a higher sea level.

	Kijkduin	**Noordwijk**	**Monster**
VNK2 estimation [€ Million]	2.700	1.800	3.500
Hydrodynamic simulation [€ Million]	2.148	1.367	3.365
Hydrodynamic simulations * β	2.578	1640	4038
VNK2/HS [-]	1,31	1,23	1,04

Table 5.1: Overview of the estimated damages of the VNK2 simulation and the hydrodynamic simulations.

As can be seen in table 5.1 the hydrodynamic simulation is underestimating the estimated damages. As mentioned before this is due to the fact that the VNK2 damage estimation is based on a flood simulation of two weeks and the hydrodynamic simulation is based on 5 days. To compensate for the this longer duration and estimate the total damages, a conservative calibration factor of $\beta = 1,2$ is applied. This helps to approach the total estimated damages of a flood event.

5.1.4. Future scenarios

In the previous section the hydrodynamic simulation is validated. That means that the flood simulations that are done with the hydrodynamic model are validated and that future scenarios can be created. With these scenarios sea level rise can be simulated. In this section sea level rise up to two meters will be simulated in different scenarios. To simulate sea level rise four different scenarios are evaluated. Each scenario has half a meter of sea level rise. The water level is therefore NAP +0.5m, NAP +1.0m, NAP +1.5m and NAP +2.0m. The hydraulic boundary conditions are equal. The hydraulic boundary condition is equal to the scenario that is validated. They represent a storm surge that is equal to a storm surge that would occur once per return period. In this thesis the maximum load is evaluated and therefore the storm surge with a return period of 1/ 10.000 is used. The hydraulic boundary conditions are based on a report of the Rijkswaterstaat. (**?**). In this case the hydraulic boundary conditions are sea dominated. The point of reference is assumed to rise with the sea level rise. The wave that is used is based on the statistical maximum storm surge that is determined by Rijkswaterstaat, see Figure 4.3. Each of the breach locations will be evaluated and the estimated damages are determined.

Kijkduin The breach location of Kijkduin is evaluated due to the fact that the consequences could be severe. A major city, The Hague, is located close to the breach location and part of that city is flood prone. Besides the consequences is the probability of failure in this dune area relatively large. In the scenario without sea level rise, the southern part of the Hague is flooded and the flooded area expanded in a South Eastern direction. With a large polder this area is highly flood prone. Since there is a large area of greenhouse agriculture south of the Hague this might be of large influence on the estimated damages. Th second large city Rotterdam is allocated directly on the other side of the polders. If Rotterdam is flooded the estimated damages of this single breach flood event rise exponentially.

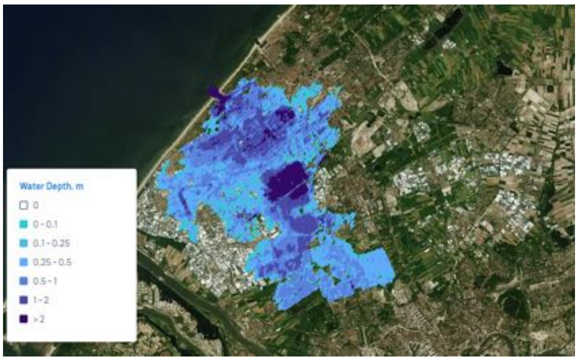


Figure 5.19: Inundation map of a flood event with a breach at Kijkduin. Based on a hydrodynamic simulation with a scenario of 0.5m sea level rise

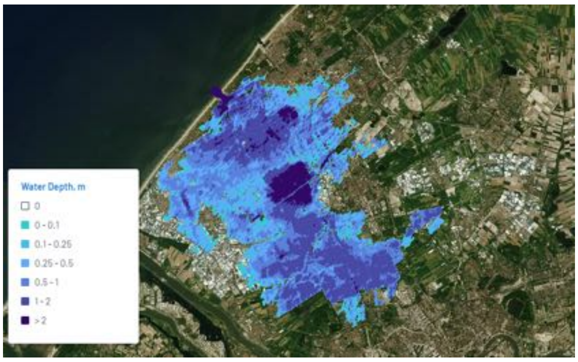


Figure 5.20: Inundation map of a flood event with a breach at Kijkduin. Based on a hydrodynamic simulation with a scenario of 1.0m sea level rise

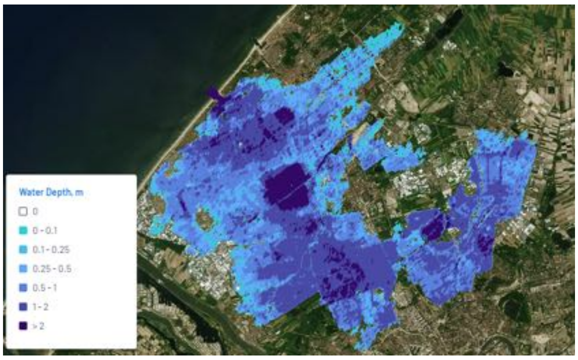


Figure 5.21: Inundation map of a flood event with a breach at Kijkduin. Based on a hydrodynamic simulation with a scenario of 1.5m sea level rise

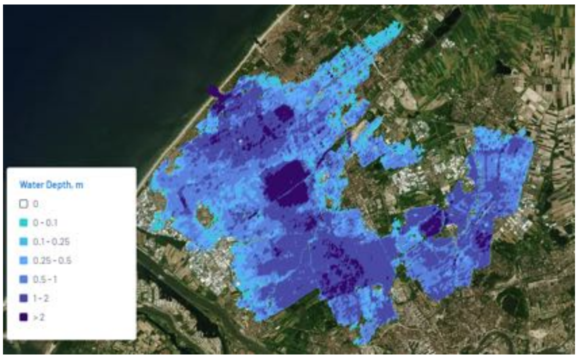


Figure 5.22: Inundation map of a flood event with a breach at Kijkduin. Based on a hydrodynamic simulation with a scenario of 2.0m sea level rise

In the Figures 5.19 to 5.22 each future scenario of the breach at Kijkduin is shown. As each the sea level rises, the inundation depth and the flooded area grow. The first note of importance is that the southern area of the Hague has a significantly higher inundation depth. Since this is a residential area, this could lead to increasing of the estimated damages. The second difference is that the flooded area expands north, due to the northern growth a large part of the Hague is affected extra. Because of the relatively low inundation depth this would not result in a significant increase of the estimated damages. The third and most eye catching result of the sea level rise is the enormous area of the polders, reaching from Schipluiden to Berkel en Rodenijs and even up north to Zoetermeer, that is flooded in the scenario with 2m sea level rise. Most of this area is composed by argiculture and will not contribute significantly to the damages. Unfortunately, part of Schiedam, the north of Rotterdam and Berkel en Rodenijs are affected as well. These are residential areas and these are of large impact on the estimated damages.

With the use of the Global Flood Risk Tool it was possible to estimate the damages of these flood events. The land use map that was mentioned before, see Figure 4.1 is used as a base map. Then the inundation map was combined with the damage curves to determine the ratio of damage. For each of those single breach flood event, the damages are shown in table 5.2

Scenario Kijkduin	Estimated damages [€Million]
NAP	2.578
NAP +0,5	3.340
NAP +1,0	4.316
NAP +1,5	5.743
NAP +2,0	8.102

Table 5.2: Estimated damages for different sea level rise scenarios for single breach flood event at Kijkduin.

Noordwijk The breach location of Noordwijk is evaluated due to the fact that the probability of failure is relatively large. Behind the dunes a large polder is situated and therefore a large area is flood prone. Flooding of the national airport Schiphol could lead to large indirect damages. In the scenario without sea level rise, the flooded area is mostly composed of agriculture. Some smaller residential areas as Nieuw-Vennep, Lisse are slightly flood prone but are outside of the affected area. With a large polder on the northern side, that area is highly flood prone. If residential areas such as Hoofddorp north of the polder or the northern area of Leiden flood, the estimated damage will increase.

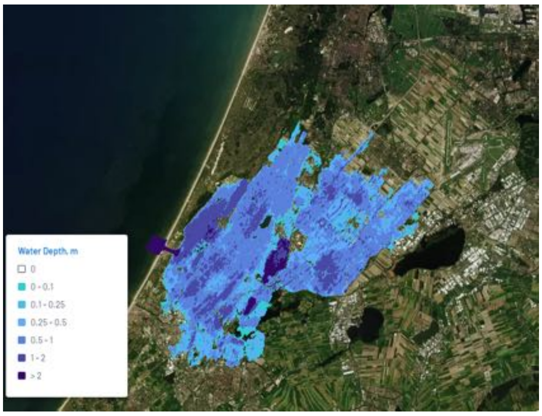


Figure 5.23: Inundation map of a flood event with a breach at Noordwijk. Based on a hydrodynamic simulation with a scenario of 0.5m sea level rise

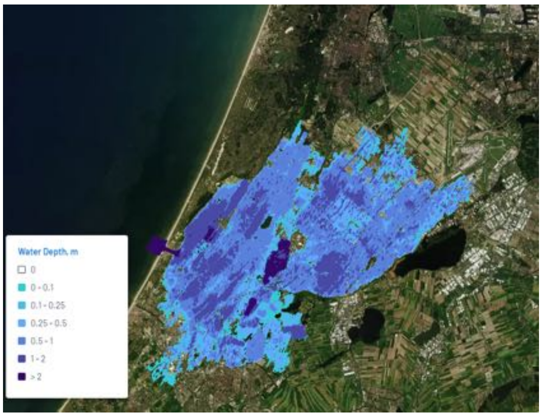


Figure 5.24: Inundation map of a flood event with a breach at Noordwijk. Based on a hydrodynamic simulation with a scenario of 1.0m sea level rise

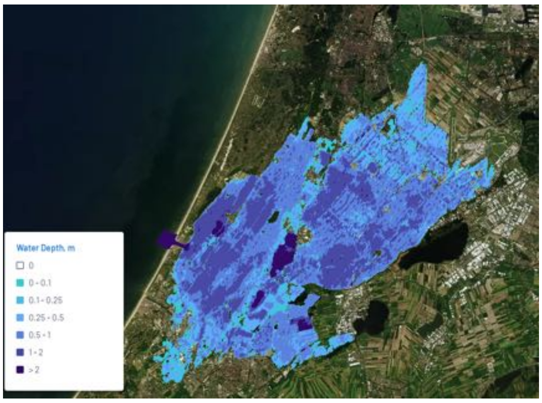


Figure 5.25: Inundation map of a flood event with a breach at Noordwijk. Based on a hydrodynamic simulation with a scenario of 1.5m sea level rise

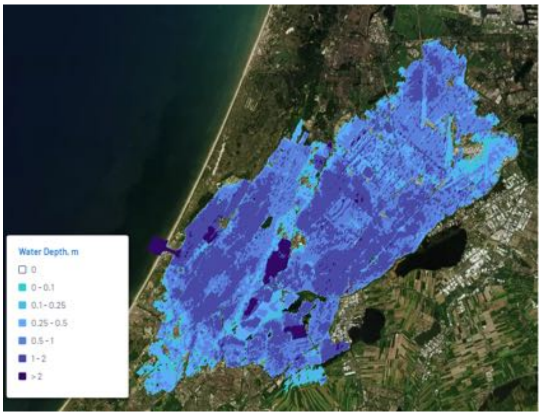


Figure 5.26: Inundation map of a flood event with a breach at Noordwijk. Based on a hydrodynamic simulation with a scenario of 2.0m sea level rise

In the Figures 5.23 to 5.26 each future scenario of the breach at Noordwijk is shown. As the sea level rises, the inundation depth and the flooded area grow. The first note of importance is that the area directly behind the dunes has a significantly higher inundation depth. For the residential areas of Noordwijk, Voorhout, Sassenheim and Lisse, this leads to increasing of the estimated damages. The second difference is that the flooded area expands slightly south, due to the southern growth a part of Oegstgeest and northern Leiden is affected extra. Despite the relatively low inundation depth this would result in a significant increase of the estimated damages. The third note of importance is that residential areas of Nieuw-Vennep and Hoofddorp are flooded with the expansion of the flooded area North. Because of the residential nature of these areas the rise expected damages is severe. The last and most eye catching result of the sea level rise is the enormous area of the polders, reaching all the way North up to Schiphol is flooded in the scenario with 2m sea level rise. Most of this area is composed by agriculture and will not contribute significantly to the damages.Fortunately, Schiphol only has low inundation depths. Schiphol is of large impact on the estimated damages, both direct and indirect.

With the use of the Global Flood Risk Tool it was possible to estimate the damages of these flood events. The land use map that was mentioned before, see Figure 4.1 is used as a base map. Then the inundation map was combined with the damage curves to determine the ratio of damage. For each of those single breach flood event, the damages are shown in Table 5.3

Scenario Noordwijk	Estimated damages [€Million]
NAP	1.640
NAP +0,5	2.273
NAP +1,0	3.160
NAP +1,5	4.295
NAP +2,0	5.674

Table 5.3: Estimated damages for different sea level rise scenarios for single breach flood event at Noordwijk.

Monster The breach location of Monster is evaluated due to the fact that the consequences could be severe. A very large area is prone to flooding with polders from the Hague up till Rotterdam. In these polders there is a lot of greenhouse agriculture which has a significantly higher value as regular agriculture this could lead to disastrous damages.

In the scenario without sea level rise, the area with greenhouse agriculture is mostly flooded. Some smaller residential areas as 's-Gravenzande, Naaldwijk, de Lier, Wateringen and southern the Hague are flooded. This causes large estimated damages already. With a large polder between the Hague, Rotterdam, and north in the direction of Zoetermeer and Leiden, a large area is highly flood prone. If mayor residential areas such as the Hague, Rotterdam or Zoetermeer flood. The estimated damage will exponentially increase.

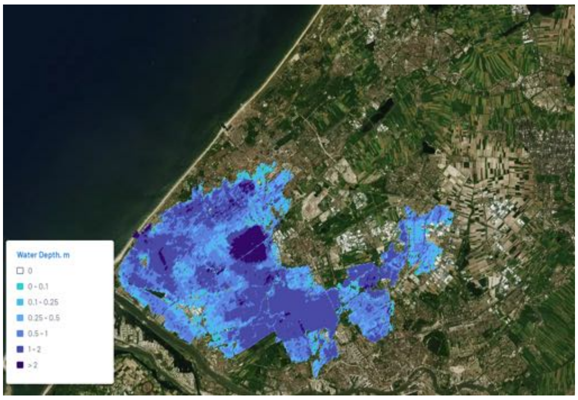


Figure 5.27: Inundation map of a flood event with a breach at Monster. Based on a hydrodynamic simulation with a scenario of 0.5m sea level rise

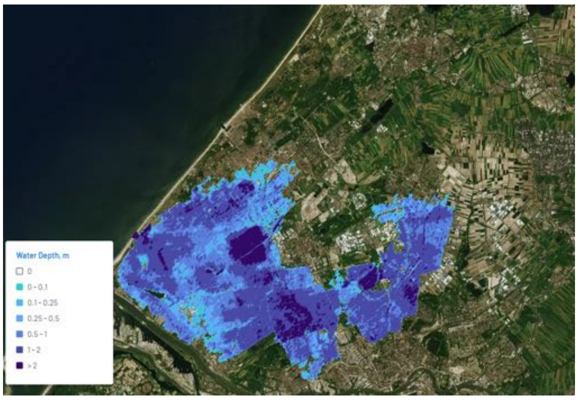


Figure 5.28: Inundation map of a flood event with a breach at Monster. Based on a hydrodynamic simulation with a scenario of 1.0m sea level rise

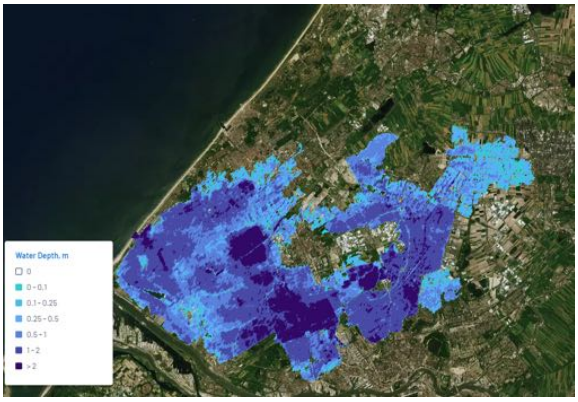


Figure 5.29: Inundation map of a flood event with a breach at Monster. Based on a hydrodynamic simulation with a scenario of 1.5m sea level rise

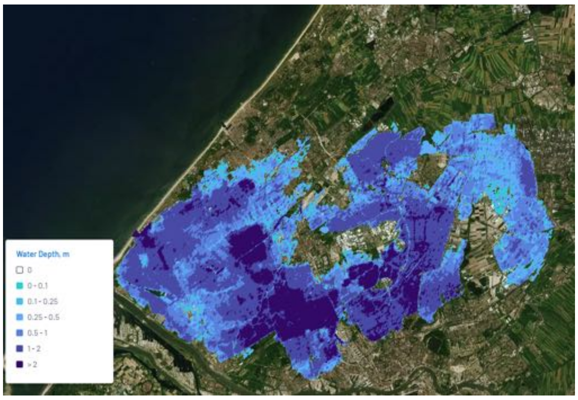


Figure 5.30: Inundation map of a flood event with a breach at Monster. Based on a hydrodynamic simulation with a scenario of 2.0m sea level rise

In the Figures 5.27 to 5.30 each future scenario of the breach at Monster is shown. As the sea level rises, the inundation depth and the flooded area grow. The first note of importance is that the area directly behind the dunes has a significantly higher inundation depth. For the residential areas of 's-Gravenzande, Naaldwijk, de Lier and Wateringen, this leads to increasing of the estimated damages. The second difference is that the flooded area in the polder has a a rise in the height of the inundation depth. Due to the low value of agriculture area this does not have serious influence on the total estimated damages. Part of Schiedam and part of Northern Rotterdam are flooded due to the sea level rise. This is of large impact on the estimated damages. The fourth note of importance is that residential areas of Berkel en Rodenijs and Zoetermeer are flooded with the expansion of the flooded area North. Because of the residential nature of these areas the rise of expected damages is severe. The last and most eye catching result of the sea level rise is the enormous area of the polders, reaching all the way Northeast beyond Zoetermeer is flooded in the scenario with 2m sea level rise. Most of this area is composed by argiculture and will not contribute significantly to the damages. Finally the Rotterdam/the Hague airport is flooded.This airport is of impact on the estimated damages, both direct and indirect.

With the use of the Global Flood Risk Tool it was possible to estimate the damages of these flood events. The land use map that was mentioned before, see Figure 4.1 is used as a base map. Then the inundation map was combined with the damage curves to determine the ratio of damage. For each of those single breach flood event, the damages are shown in table 5.4

Scenario Monster	Estimated damages [€Million]
NAP	4.038
NAP +0,5	5.416
NAP +1,0	7.768
NAP +1,5	10.190
NAP +2,0	12.974

Table 5.4: Estimated damages for different sea level rise scenarios for single breach flood event at Monster.

Overview of estimated direct damages In this section the different future scenarios are evaluated for each breach location. The damages for each of the single breach flood events are estimated and these are the expected damages in case a breach would happen. In this paragraph an overview of all the estimated damages is given.

Scenario	E D Kijkduin [€Million]	E D Noordwijk [€Million]	E D Monster [€Million]
NAP	2.578	1.640	4.038
NAP +0,5	3.340	2.273	5.416
NAP +1,0	4.316	3.160	7.768
NAP +1,5	5.743	4.295	10.190
NAP +2,0	8.102	5.674	12.974

Table 5.5: Overview of the estimated direct damages for different sea level rise scenario for each of the breach locations.

Indirect damages Indirect damages are damages that are caused by the flood event but happen outside of the affected area. This might be societal disruption or for example a company that can't export its shipment due to airport closure. To estimate the indirect damages half of the value of the direct damages can be used (Kind, 2011) therefore the additional indirect damages are shown in table 5.6

Scenario	E D Kijkduin [€Million]	E D Noordwijk [€Million]	E D Monster [€Million]
NAP	1.289	0.870	2.019
NAP +0,5	1.670	1.136	2.708
NAP +1,0	2.158	1.580	3.384
NAP +1,5	2.872	2.148	5.095
NAP +2,0	4.051	2.837	6.487

Table 5.6: Overview of the estimated indirect damages for different sea level rise scenario for each of the breach locations.

6

Economic optimisation

In this chapter the economical optimisation is executed. First the risk is estimated. This is a product of the estimated damages and the probability of failure combined with a grow and discount rate. Then the investments are computed for each location to determine how much is needed to create safety. Finally the economical optimisation is executed for each scenario at each location. This way it is possible to determine that even in a scenario with a large sea level rise ,it is possible to defend against flooding by using the flood defences that are already installed.

6.1. Estimated risk

As explained in chapter 3.2, risk is a combination of the probability of failure and the estimated damages. In this section the risk is estimated for each scenario at the different locations. First the damages that are estimated in chapter 5 are given in an overview. Together with these damages is an estimation of the growth rate and the discount rate. This way it is possible to discount the damages for an unbounded horizon. Then the probability of failure is determined for each of the scenarios. These probabilities are crucial to determine the risk.

6.1.1. Estimated damages

The damages that are estimated in chapter 5 are shown in Table 5.5 and also shown below. These damages are estimated based on the damage curves that are discussed in section 4. These are used with the results of the hydrodynamic flood simulation that is executed to predict the flood events of the different scenarios. By combining the damage curves and the flood simulation a damage estimation is done. These damages will be used in the determination of the risk.

Scenario	**E D Kijkduin [€Million]**	**E D Noordwijk [€Million]**	**E D Monster [€Million]**
NAP	2.578	1.640	4.038
NAP +0,5	3.340	2.273	5.416
NAP +1,0	4.316	3.160	7.768
NAP +1,5	5.743	4.295	10.190
NAP +2,0	8.102	5.674	12.974

Table 6.1: Overview of the estimated direct damages for different sea level rise scenario for each of the breach locations.

Additionally the estimated indirect costs are added. These are shown in the following table:

Scenario	E D Kijkduin [€Million]	E D Noordwijk [€Million]	E D Monster [€Million]
NAP	1.289	0.870	2.019
NAP +0,5	1.670	1.136	2.708
NAP +1,0	2.158	1.580	3.384
NAP +1,5	2.872	2.148	5.095
NAP +2,0	4.051	2.837	6.487

Table 6.2: Overview of the estimated indirect damages for different sea level rise scenario for each of the breach locations.

Risk is calculated by the following formula:

$$R = \sum * \frac{1}{(1+r)^i} * D * (1+g)^i * P_f \tag{6.1}$$

With:

R = Estimated risk
r = discount rate
i = year
D = estimated damages
P_f = Probability of failure
g = grow rate

6.1.2. Probability of failure

The probability of failure of a flood defence system can be calculated in two parts. The first part is the decomposing of the dijkring. A dijkring is generally composed of sections that are averaged 750 m. These sections are estimated to be statistically homogeneous sections and therefore they might differ in length. The dune sections for example might vary up to multiple kilometers. Hydraulic structures are a section on their own. Since this thesis focuses on the dune sections of the coastal area, the dunes are calculated. The probability of failure is determined on a section of the dijkring. Regularly there is a probability of failure for each failure mode. Since only the dunes are evaluated only one failure mode is evaluated, the dune cut.

Failure probability of flood defence systems The flood defence systems consist of different elements. These elements are connected in a series system, which means that failure occurs if one of the elements fail. The probability of failure of the system is therefore equal to the probability of one or more sections. Because this research only focuses on the evaluation of the dunes, the hydraulic structures are assumed to have a failure probability of close to zero. Correlations in the space domain are taken into account when combining the failure probabilities. Since the flood defences system is a series system the system fails if one element fails. This leads to a lower limit of the failure probability and an upper limit. These are the lowest and the highest failure probability. In a series system the lower limit is equal to the maximum failure probability of each of the elements. This corresponds to the situation in which failure of elements is entirely dependent. The upper limit of the failure probability in a serial system equals the sum of the failure probabilities of the elements (Jonkman et al., 2017). If the failures are independent and the probabilities are small the probability of failure for the whole system is close to the upper limit. In reality the failure probability will be between those two scenarios. First each of the scenarios will be treated individually and therefore independent. Finally the entire system is taken into account. Breach locations at Monster and Kijkduin are then taken dependent since they are in the same dune section and Noordwijk is treated independent. The probability of failure was determined by VNK2 at the different locations. To determine the probability of failure first a cross section of the dunes was created based on the AHN3 and the JarKus measurements. With this cross section a volume of sand per meter of dunes is determined. These volumes combined with the estimated median grain size determine the probability of failure for each of the dune section.

Noordwijk The dune section of Noordwijk streches from IJmuiden to Scheveningen. The area located at Noordwijk has the smallest cross section and therefore has the largest probability of failure. As can be seen in Figure 6.1 the breach of the first dune section is higher at the Noordwijk location. Based on the research of Ditlevsen Vuik and van Balen (n.d.) the probability of failure for the Noordwijk location is $P_f = 1/33000$, .

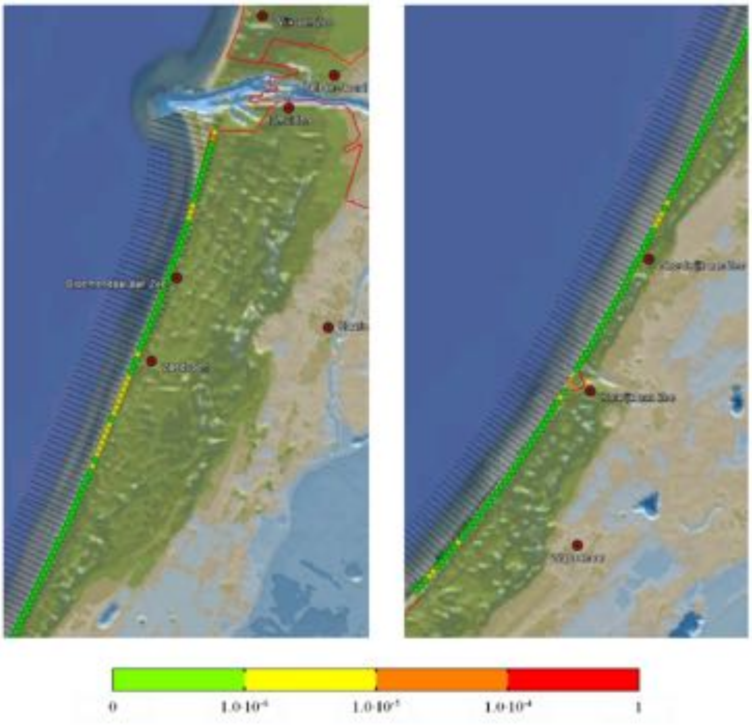


Figure 6.1: Probability of failure per section per year for the first dune of Noordwijk. Source: Overstromingskansen voor de Nederlandse kust

Kijkduin and Monster The dune section of Kijkduin and Monster streches from Hoek van Holland to Scheveningen. As can be seen in Figure 6.2 the breach of the first dune section is higher at the Noordwijk location. Based on the research of Ditlevsen the probability of failure for the locations of Kijkduin and Monster is $P_f = 1/150000$, (Vuik & van Balen, n.d.).

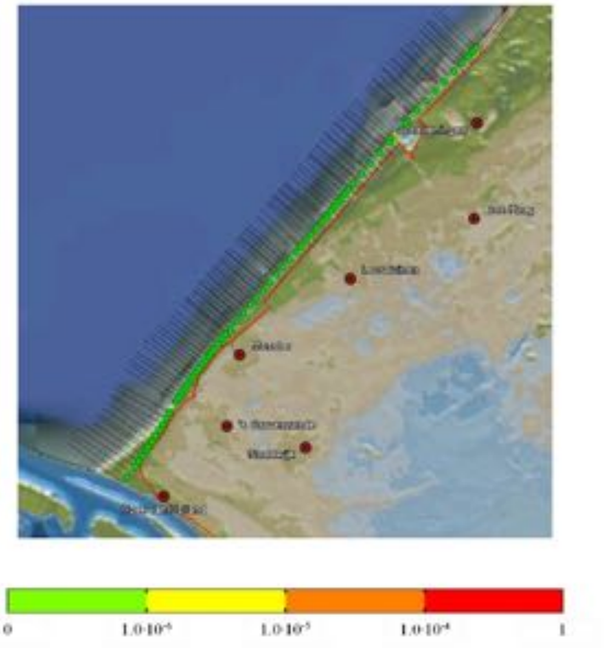


Figure 6.2: Probability of failure per section per year for the first dunes of Kijkduin and Monster. Source: Overstromingskansen voor de Nederlandse kust

For future scenarios an estimation had to be made of the probability of failure of these locations without strengthening. This estimation is done based on the increased probability of failure per meter sea level rise. Based on the VNK2 calculations and the estimated damages it was chosen that the probability of failure increases with a factor 10 per meter sea level rise.

6.2. Estimated investments

6.2.1. Investments for dune strengthening

Dune reinforcement Nourishment of the dunes is necessary if the volume of the dune is insufficient to deal with the erosion occurring with the design storm. If the erosion is too large, a breach will occur. This breach leaves the hinterland exposed. In this case the existing dunes are not strong enough to withstand extreme storm conditions. To increase the safety level of the dunes it is more effective to widen the dunes than to heighten the dunes. The widening of the dunes is possible both on the seaside as on the land-side. The largest difference is that the sea side has a morphological impact on the sediment system. The dynamic equilibrium of the cross-shore profile is disturbed and the nourished sediment is distributed across the length of the beach. Therefore a large volume of nourishing is needed. On the landward side it is unfortunately often not feasible due to existing infrastructure and property.

Due to different dynamic equilibrium systems the costs of raising the safety level will be different at the different locations. The estimation of the costs is based on the volume of sand that is needed to decrease the probability of failure with a factor. The price of sand is estimated to be €4,5 and the needed volumes per meter are respectively 500 m^3 and 900 m^3 for Kijkduin & Monster and Noordwijk. It is assumed that the additional volume of sand is an trapezium added in front and on top of the existing dunes. A larger volume of sand is needed to decrease the probability of failure at the dune section of Noordwijk, the length of the dune section is longer as well. This makes the investment costs for Noordwijk a factor 3 more expensive. The costs are shown in Table 6.3

Location	Length of dune section [km]	Costs to decrease PoF by 10 [Million €/km]	Total costs [€]
Monster	17,5	2,4	42
Kijkduin	17,5	2,4	42
Noordwijk	30,5	4,1	123

Table 6.3: Overview of the costs of decreasing the probability of failure ten times per kilometer based on VNK2.

6.3. Economic optimisation

The economical optimisation is needed to determine the optimal level of safety that represents the lowest estimated costs. The costs that represent the safety of the dijkring are composed of the investment costs that are used to rise the safety of the flood defence and the risk that is determined by the estimated damages and the probability of failure. To optimise this process both the probability of failure and the investment costs are dependent on the amount of sand that is added to decrease the probability of failure of the flood defence. In chapter 3.2 the methods of determining the costs as function of the amount of sand added can be found. To optimise economically both these functions, dependent on the amount of times that the safety level is increased, are used to calculate the costs by formula 6.3. If the costs are at an minimum the optimal safety level is reached, economically speaking.

$$R(x) = \frac{P_f(x) * D}{r - g} \tag{6.2}$$

where:

$R(x)$ = Risk dependent on the amount of times the safety level is increased.
P_f = Probability of failure dependent on the amount of times the safety level is increased.
D = Estimated damages per scenario for each location.
r = Discount rate to create unbound time horizon.
g = Growth rate to create unbound time horizon.

$$C(x) = I(x) + R(x) \tag{6.3}$$

where:

$C(x)$ = Costs dependent on the amount of times the safety level is increased.
$I(x)$ = Investments dependent on the amount of times the safety level is increased.
$R(x)$ = Risk dependent on the amount of times the safety level is increased.

When the economical optimum was determined the corresponding probability of failure was determined. If this probability of failure is below the minimal required level of safety it is determined that the investment is worth it. It was possible to evaluate for each of the scenarios if the current method of flood defences, with dunes is viable for the future with sea level rise.

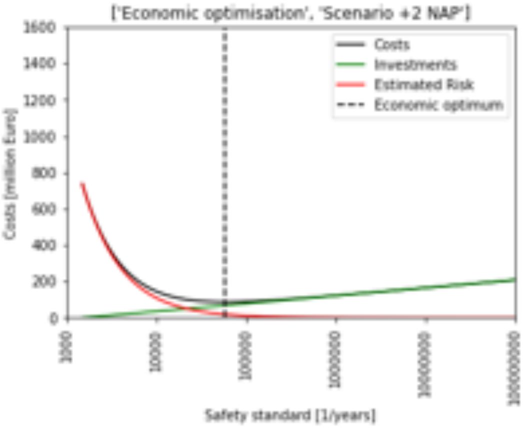


Figure 6.3: Economical optimisation of the future flood scenario of NAP +2m at Kijkduin.

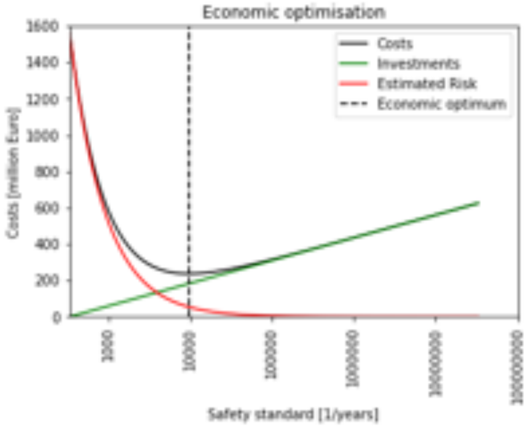


Figure 6.4: Economical optimisation of the future flood scenario of NAP +2m at Noordwijk.

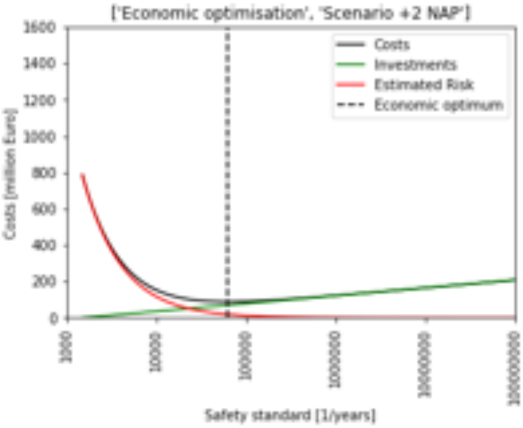


Figure 6.5: Economical optimisation of the future flood scenario of NAP +2m at Monster.

The economical optimum is calculated for each of the scenarios at every location. In the figures, 6.3, 6.5 and 6.4 the extreme future scenarios of NAP +2m are computed. The other scenarios are evaluated in appendix C

Kijkduin The breach location of Kijkduin is evaluated due to the fact that the consequences could be severe. A major city, The Hague, is located close to the breach location and part of that city is flood prone. Besides the consequences is the probability of failure in this dune area relatively large.

In Figure 6.6 the risk of each of the scenarios is plotted. As the sea level rises the risk increases significantly:

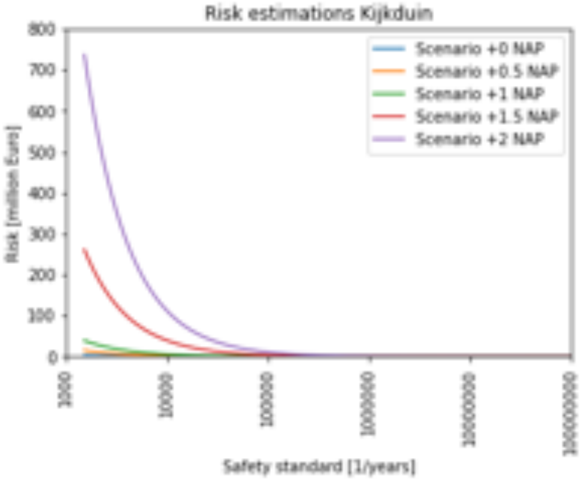


Figure 6.6: Risk functions of the different sea level rise scenarios dependent on the probability of failure in Kijkduin

Scenario	Optimal costs	Optimal probability of failure	Investment costs	# increased safety level
NAP	€$2,500 * 10^6$	1/15000	€0	0
NAP + 0,5m	€$15,000 * 10^6$	1/30000	€0	0
NAP + 1,0m	€$32,500 * 10^6$	1/31500	€$14,000 * 10^6$	0,32
NAP +1,5m	€$68,000 * 10^6$	1/32000	€$49,000 * 10^6$	1,15
NAP +2,0m	€$87,000 * 10^6$	1/59000	€$69,000 * 10^6$	1,59

Table 6.4: Characteristics of the optimal safety level of dunes for future flood scenarios in Kijkduin

With the results shown in Table 6.4 it becomes clear that the optimal safety level of the dunes is well above the required safety level of the 'Hoogwater Beschermings Programma'. This means that even with the extreme sea level rise scenario of two meters sea level rise, the Dutch coast is well protected by the dunes.

Noordwijk The breach location of Noordwijk is evaluated due to the fact that the probability of failure is relatively large. Behind the dunes a large polder is situated and therefore a large area is flood prone. Flooding of the national airport Schiphol could lead to large indirect damages.

In Figure 6.7 the risk of each of the scenarios is plotted. As the sea level rises the risk increases significantly:

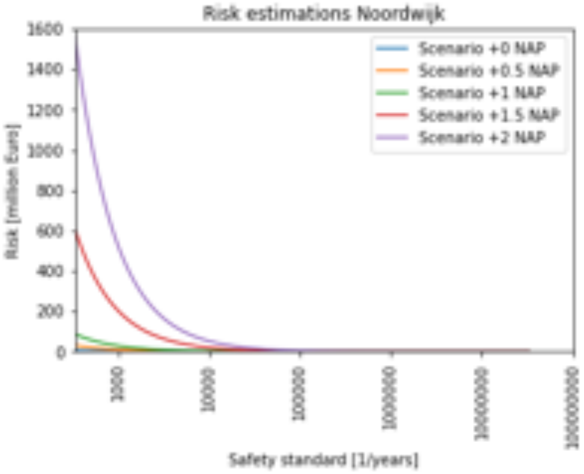


Figure 6.7: Risk functions of the different scenarios dependent on the probability of failure in Noordwijk

Scenario	Optimal costs	Optimal probability of failure	Investment costs	# increased safety level
NAP	€4,500 ∗ 10^6	1/33000	€0	0
NAP + 0,5m	€31,000 ∗ 10^6	1/6500	€0	0
NAP + 1,0m	€80,000 ∗ 10^6	1/5500	€26,000 ∗ 10^6	0,21
NAP +1,5m	€185,000 ∗ 10^6	1/7500	€131,00 ∗ 10^6	1,04
NAP +2,0m	€237,000 ∗ 10^6	1/9500	€182,000 ∗ 10^6	1,46

Table 6.5: Characteristics of the optimal safety level of dunes for future flood scenarios in Noordwijk

With the results shown in Table 6.5 it becomes clear that the optimal safety level of the dunes is below the required safety level of the 'Hoogwater Beschermings Programma'. This means that investment costs of the dune section at Noordwijk, the extreme sea level rise scenario of two meters sea level rise is too expensive to protect against. In that case the coastal area of Noordwijk is not feasible to protect by the dunes.

Monster The breach location of Monster is evaluated because the consequences could be severe. A very large area is prone to flooding with polders from the Hague up till Rotterdam. In these polders there is a lot of greenhouse agriculture which has a significantly higher value than regular agriculture this could lead to disastrous damages.

In Figure 6.8 the risk of each of the scenarios is plotted. As the sea level rises the risk increases significantly:

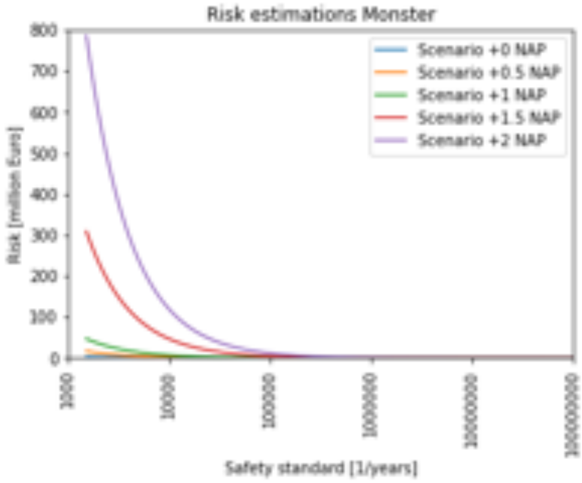


Figure 6.8: Risk functions of the different scenarios dependent on the probability of failure in Monster

Scenario	Optimal costs	Optimal probability of failure	Investment costs	# increased safety level
NAP	€2,000 ∗ 10^6	1/150000	€0	0
NAP + 0,5m	€16,000 ∗ 10^6	1/30000	€0	0
NAP + 1,0m	€36,000 ∗ 10^6	1/39000	€17,000 ∗ 10^6	0,40
NAP +1,5m	€71,000 ∗ 10^6	1/49500	€52,000 ∗ 10^6	1,22
NAP +2,0m	€88,000 ∗ 10^6	1/63000	€70,000 ∗ 10^6	1,62

Table 6.6: Characteristics of the optimal safety level of dunes for future flood scenarios in Monster

With the results shown in Table 6.6 it becomes clear that the optimal safety level of the dunes is well above the required safety level of the 'Hoogwater Beschermings Programma'. This means that even with the extreme sea level rise scenario of two meters sea level rise, the coastal location of Monster is well protected by the dunes.

Total coastal defence of Dijkring 14 Each of the locations is evaluated individually and it became clear that for the locations of Kijkduin and Monster the economically optimal probability of failure is larger than the minimal required safety level. Noordwijk however has a economically optimal probability of failure that does

Scenario	Costs[M €]	Optimal probability of failure[1/year]		Investment costs [M €]
		Northern section	Southern Section	
NAP	8,5	33.000	150.000	0
NAP+0.5m	58,0	6.500	30.000	0
NAP+1.0m	130,5	7.500	33.000	57,5
NAP+1.5m	270,5	10.000	45.000	197,0
NAP+2.0m	340,0	13.000	58.500	267,0

Table 6.7: Characteristics of the optimal safety level of dunes for future flood scenarios in Dijkring 14

not meet the required safety level. That is if each of the scenarios is evaluated individually. As mentioned in section 3.2 the locations are not entirely independent and they all protect the same dijkring. The locations of Monster and Kijkduin are located at the same dune section and therefore if this section is strengthened the risk is reduced for both the locations. In this final section the entire coastal flood defences existing out of dunes is evaluated as one system. That means that the risks and the investment costs are combined. The optimal probability of failure of each dune section is determined and is compared to the minimal required safety level. The results are shown in table

6.4. Reflection on the results of the economic optimisation

The economic optimisation resulted in an economically optimal probability of failure for each scenario. It became clear that for the individual scenarios with a sea level rise up to 2 meters, the economically optimal probability of failure was above the minimal required safety level for the breach locations of Kijkduin and Monster. At Noordwijk the economically optimal probability of failure for the individual scenario with a sea level rise up to 2 meters was below the minimal required safety level. That would mean that when these scenarios are evaluated individually protection by dunes would be to expensive for a breach scenario at Noordwijk. When taking into account the fact that all the breach locations are part of the same dijkring it became clear that the optimal probability of failure of all the locations was above the minimal required safety level. That is for the assumptions and values taken in this research. In this section the influence of the assumptions are reflected.

Price of Sand In this research the price of sand was taken as €$4,5/m^3$. Estimated volumes of $500m^3/m$ for Kijkduin & Monster and $900m^3/m$ for Noordwijk. Lengths of the dune section of 17,5km for Kijkduin & Monster and 30,5 km for Noordwijk. This results to the costs of investments that will significantly vary with a change of the price of sand. With a price range varying up to 30% the economically optimal probability will change significantly. To gain insight on the variation on economically optimal probability of failure, the extreme scenarios of all locations are evaluated.

Price Sand	Kijkduin MSL+2m		Noordwijk MSL+2m		Monster MSL+2m	
	Costs [M €]	PoF [1/year]	Costs [M €]	PoF [1/year]	Costs [M €]	PoF [1/year]
€$3,15/m^3$ (-30%)	66	84.500	179	13.500	66,5	90.000
€$4,50/m^3$ (-)	87,5	59.000	236,6	9.500	88,5	63.000
€$5,85/m^3$ (+30%)	107	45.500	289	7.500	108,5	48.500

Table 6.8: Impact of the variation of the price of m^3 sand

As can be seen in Table 6.8 the influence of the price of sand is larger at the breach location of Noordwijk. This can be explained by the larger length of the dune section and the larger volume of sand per meter needed to increase the safety level. Further more it can be seen that a percentage increase in the investments costs leads to approximately the same percentage increase for the total costs.

Discount ratio and growth ratio The discount and growth ratio used in this research are respectively 3% and 1,9% which results in a total discount ratio of 1.1%. This is based on the fact that the discount ratio is based on a risk premium of 3%. In reality contractors and engineering companies are using a risk free interest rate additional to the risk premium which results in a discount ratio up to 5.5%. With the same growth ratio this would lead to a total factor of 3.6%. When taking into account the combined discount ratio of 5.5 % the estimated damages of a flood event would decrease factor three. Therefore the optimal probability of failure would significantly increase. To gain insight on the effect of using a risk free interest rate on the economically optimal probability of failure, the extreme scenarios of all three locations are evaluated.

	Kijkduin	**Noordwijk**	**Monster**
Costs without risk free interest rate [million €]	87,5	236,5	88,5
Costs with risk free interest rate [million €]	46	172,5	66,5
P_f without risk free interest rate [1/year]	59.000	9.500	63.000
P_f with risk free interest rate [1/year]	18.000	2.900	19.000

Table 6.9: Overview of the impact of including the risk free interest rate

The influence of the discount ratio and the growth ratio is significant. As can be seen in Table 6.9 a difference of 3% results in a 20-30% difference in costs and a factor 3 in the economically optimal probability of failure. That is due to the large influence on the estimated risk.

Inclusion of indirect damages and the calibration factor The research determines the direct estimated damages. Because of the shorter duration of the hydrodynamic simulation compared to the VNK2 simulation, a part of the flood event was not simulated. To account for the area that is not flooded in the simulation but will be flooded over a longer time, the calibration factor $\beta = 1,2$ was introduced. Beside the calibration factor, the indirect damages are estimated in chapter 5, based on the research of Kind (2011).These factors result in direct influence of the estimated risk. This influence is significantly smaller as the influence of the discount and growth ratio.

7

Conclusion and recommendations

Chapter 7 contains the conclusions and recommendations for further research. The first paragraph shortly addresses the individual research questions and formulates an answer to the main research question. Recommendations for further research on future safety of flood defence systems are given in section7.2.

7.1. Conclusion

The research questions below, introduced in section 1.1, are answered based on the results of this research. Firstly the main research question is addressed by using the answers of the sub-questions. The answers to the sub-questions will be further elaborated afterwards.

To what extent is it possible to keep protecting dijkring 14 by upgrading the dunes that are part of the current flood defence system, when taking into account extreme sea level rise scenarios of up to 2m? A hydrodynamic flood model was used to simulate reliable future flood risk scenarios. The outcome of the flood risk scenario was used to determine the estimated damages and probabilities of failure. These parameters were applied to determine the influence of the sea level rise on the flood risk. The combination of the estimated flood risk and the investment costs of strengthening the flood defence system was used to compute the economically optimal safety levels.

These economically optimal safety levels of the individual extreme scenarios of NAP +2,0 meter for Kijkduin, 1/59.000 and Monster, 1/63.000 were above the required safety level, 1/10.000.
The economically optimal probability of failure of the individual extreme scenarios of NAP +2,0 meter for Noordwijk, 1/9.500 was below the minimal required safety level. For less extreme sea level rise scenarios the economically optimal probability of failure were even lower.

That means that the coastal flood defence at Noordwijk can not be protected by strengthening the dunes, while Kijkduin and Monster can be protected by strengthening the dunes.

However,the locations are not entirely independent and they all protect the same dijkring. The locations of Monster and Kijkduin are located at the same dune section and therefore if this section is strengthened the risk is reduced for both the locations. The entire coastal flood defences existing out of dunes is evaluated as one system. That means that the risks and the investment costs are combined. Then both the Northern, 1/13.000 and the Southern, 1/58.000 dune section of dijkring 14 have an economically optimal probability of failure above the minimal required safety level. In conclusion, this means that with the different assumption taken during this research it is possible to protect dijkring 14 by strengthening the dunes when taking into account an extreme sea level rise of up to two meters.

How can a hydrodynamic flood simulation be used to simulate reliable flood risk scenarios? Verification of the simulation is important when performing a reliable future flood risk scenario. The hydrodynamic flood simulation in itself should represent a very accurate display of the flood event. The hydrodynamic simulation of D-Flow FM used the unsteady shallow water equations that were solved based on the Navier Stokes equations. It was solved in 2 dimensions with an average value of the depth. This way the flow from cell to cell was accurately determined. To achieve a reliable simulation, the grid size of the hydrodynamic model as well as the grid size of the input parameters had to be small enough. Flood characteristics, the hydraulic boundary conditions and the location of the breach were of importance. The simulation was validated with a comparison using the widely accepted VNK2 model. This validation method was based on a visual comparison, inundation depth comparison and finally an damage assessment. Each of the breach locations was validated and proven similar. Future flood scenarios were determined after the successful validation of the simulation. The future flood scenarios, created by the model are assumed reliable, due to the validation results of the hydrodynamic flood simulation of the present flood scenario.

What is the influence of the sea level rise on the flood risk within dijkring 14? The expected damages and the probability of failure are needed, to determine the flood risk within dijkring 14. The expected damages are determined with the a land use map, a damage curve and an inundation map. The land use map shows the specifics of thirteen different categories of in the area. These categories determine the maximum value of the damage that is estimated. The estimated damages were determined by the Global Flood Risk Tool which combined the maximum estimated damage, the damage curve and the inundation map from the hydrodynamic simulation. Future flood scenarios resulted in larger estimated damages.Estimated damages were up to four times larger for the extreme sea level rise scenario. The second element of risk is based on the probability of failure of the dunes. The probability of failure increased exponential with sea level rise as the failure mechanism was dependent on the sea level, the probability of failure was estimated to increase by factor ten for one meter sea level rise. Therefore it can be concluded that the influence of sea level rise on the flood risk of dijkring 14 is positively correlated. The change of the probability of failure influences the flood risk most.

How can the flood defence system be upgraded to the optimal safety level and is that above required safety level? Economic optimisation was used, to determine the optimal safety level. The estimated cost were a combination of the risk and the investment costs. Methods to increase the safety level were to reinforce the dunes by sand supplementation and increasing the volume of the dunes. The costs to strengthen the dunes were the investment costs which increased as the probability of failure decreased. The risk decreased as the probability of failure decreased. To combine the risk, which was expressed in a monetary value over time, and the investment costs, which was in monetary value, the risk was discounted for an unbounded time horizon. The combination forms the total costs which showed the net present value of the combined costs. For each of the scenarios this combination of the risk and the investment costs, dependent on the decrease of the probability of failure, was used to find the economic optimum. This optimum represented the economically optimal probability of failure thus the optimal safety level. The optimal safety level was compared to the minimal required safety level of the 'Hoog Water Beschermings Programma'. For all the scenarios at Kijkduin,1/59.000 and Monster,1/63.000 the safety level was above the required safety level, 1/10.000. The scenarios for Noordwijk,1/9.500 resulted in a optimal safety level below the threshold of the HWBP. That means that the coastal flood defence at Noordwijk can not be protected by strengthening the dunes, while Kijkduin and Monster can be protected by strengthening the dunes.

However,the locations are not entirely independent and they all protect the same dijkring. The locations of Monster and Kijkduin are located at the same dune section and therefore if this section is strengthened the risk is reduced for both the locations. The entire coastal flood defences existing out of dunes is evaluated as one system. That means that the risks and the investment costs are combined. Then both the Northern, 1/13.000 and the Southern, 1/58.000 dune section of dijkring 14 have an economically optimal probability of failure above the minimal required safety level. The economically optimal probability of failures for the Northern dune section is only slightly above the minimal required safety level. The assumptions that are taken to conduct this research have significant influence on the results. It is possible that the only small differences would result in unsufficient safety level, but with these assumptions the dunes can be strengthened to resist sea level rise.

7.2. Recommendations

Recommendations for future research on future flood risk are given in this paragraph. First the recommendation that are about the simulation are made. Secondly recommendation on the method of the research are given and finally recommendations on the method of optimising are given.

Recommendation on damage value estimation The damage estimation in this research and most literature is based on the inundation depth, the damage curve and the land use category. In this research the damage curves are dependent on the inundation depth. With the use of the hydrodynamic simulation more accurate and diverse characteristics can be simulated. Flow velocity and duration of the inundation depth are expected to be of influence on the damage curve. With the use of this hydrodynamic simulation the expected damages could be based on more characteristics which increases the accuracy. Therefore further research to improve the damage value estimation is recommended.

Recommendation on modelling approach The hydrodynamical simulation uses the shallow water equations, flood characteristics such as flow velocity and arrival time are calculated per grid cell. As mentioned above these characteristics could contribute to more precise damage value functions. To retrieve these detailed simulations it is recommended to improve the computation efficiency. Computation times of a fine grid simulation are large. To decrease the computation time it is recommended to distinguish areas of interest and create a more detailed grid. By creating a fine grid in areas of interest and furthermore a coarse grid, computation time can be restrained.

Recommendation on economic optimisation The economic optimisation is based on the estimated risk and the estimated investments both dependent on the probability of failure. In this thesis the probability of failure of the dunes for future scenarios is based on the height that is needed to decrease the probability of failure with a factor ten. More precise definition of the probability of failure will increase the reliability of the risk estimation. Modelling the dune erosion for extreme sea level rise scenario is therefore recommended.

References

AHN Viewer | AHN. (n.d.). Retrieved from https://www.ahn.nl/ahn-viewer

Basisregistratie Overheid - Spoorbaan deel. (n.d.). Retrieved from https://brt.basisregistraties.overheid.nl/top10nl/doc/spoorbaandeel/127313758

Boersen, S., Berg, M. V. D., & Bos, M. (2017). Hydraulisch onderzoek verhoging Tuimelkade. (december).

De Bruijn, K., Slager, K., Piek, I. S. M. R., Riedstra, D., & Slomp, R. (n.d.). *Leidraad voor het maken van overstromingssimulaties* (Tech. Rep.).

Delft Cluster. (2003). Structural economic effects of large scale inundation : A simulation of the Krimpen dike breakage University of Twente University of Twente University of Twente University of Twente. *The Role of Flood Impact Assessment in Flood Defence Policies*, 1–50. Retrieved from https://ris.utwente.nl/ws/portalfiles/portal/5159901/Veen03structural.pdf

Delft3D flexible Mesh suite 1D/2D/3D Modelling suite for integral water solutions User Manual D-Flow Flexible Mesh (Tech. Rep.). (n.d.).

Delft3D-FLOW Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments User Manual Hydro-Morphodynamics permission from the publisher: Deltares (Tech. Rep.). (2011). Retrieved from http://www.deltares.nlhttp://www.delftsoftware.com

Documenten :: Nationaal Wegenbestand. (n.d.). Retrieved from https://nationaalwegenbestand.nl/documenten

Eijgenraam, C. J. (2006). Optimal safety standards for dikering areas. *CPB Discussion Paper*, *1*(62).

Huizinga, J., Meol, H. d., & Szewczyk, W. (2017). *Global flood depth-damage functions : Methodology and the Database with Guidelines.* Retrieved from http://publications.jrc.ec.europa.eu/repository/bitstream/JRC105688/global_flood_depth-damage_functions__10042017.pdf doi: 10.2760/16510

Jonkman, S. N., Bočkarjova, M., Kok, M., & Bernardini, P. (2008). Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. *Ecological Economics*, *66*(1), 77–90. doi: 10.1016/j.ecolecon.2007.12.022

Jonkman, S. N., Schweckendiek, T., Jorissen, R., & van den Bos, J. (2017). *Flood Defences.* -.

Jonkman, S. N., Vrouwenvelder, A. C. W. M., Steenbergen, R. D. J. M., Morales-nápoles, O., & Vrijling, J. K. (2016). *Probabilistic Design: Risk and Reliability Analysis in Civil Engineering.*

Kind, J. (2011). *Maatschappelijke kosten-batenanalyse Waterveiligheid 21e eeuw* (Tech. Rep.).

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, R., P, … Waterfields, T. (2019). Global Warming of 1.5C. An IPCC Special Report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strenghtening the global response to the threat of climate change, s. In *A companion to applied ethics* (p. 630). doi: 10.1002/9780470996621.ch50

Rijkswaterstaat. (2020). *Watersnoodramp 1953 | Rijkswaterstaat.* Retrieved from https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/watersnoodramp-1953/index.aspx

Sweet, W., Horton, R., Kopp, R., & Romanou, A. (n.d.). *Sea level rise* (Tech. Rep.). Retrieved from https://digitalcommons.unl.edu/usdeptcommercepub/581

Ter Horst, W. (2012). *Veiligheid Nederland in Kaart 2: Overstromingsrisico van dijkringgebieden 14, 15 en 44* (Tech. Rep. No. November). VNK.

Thiel, L. V., & Mol, P. (2020). Waterbewustzijn van de Nederlandse bevolking.

TOPNL Basis Registratie Topografie- PDOK. (n.d.). Retrieved from `https://www.pdok.nl/introductie/-/article/basisregistratie-topografie-brt-topnl`

van Dantzig, D. (1956). Economic Decision Problems for Flood Prevention. *Econometrica*, *24*(3), 276–287.

Van Schrojenstein Lantman, J. P. (2007). *Overstromingsschade in Dijkring 14: Een koppeling van het Hoogwater Informatie Systeem aan de Ruimtescanner* (Tech. Rep.). Milieu en Natuur Planbureau.

Vergrouwe, R. (2010). *Veiligheid Nederland in kaart* (Tech. Rep. No. November). Veiligheid Nederland in Kaart.

Voortman, H. G., Van Gelder, P. H., & Vrijling, J. K. (2003). RISK-BASED DESIGN of LARGE-SCALE FLOOD DEFENCE SYSTEMS. *Proceedings of the Coastal Engineering Conference*, *2003-Janua*(March), 2373–2385. doi: 10.1142/9789812791306{_}0199

Vuik, V., & van Balen, W. (n.d.). *Overstromingskansen Nederlandse Kust* (Tech. Rep.). Retrieved from `http://www.hkv.nl`

Watersnoodmuseum. (2020). *Watersnoodramp van 1953 (1 februari 1953) - Watersnoodmuseum.* Retrieved from `https://watersnoodmuseum.nl/kennisbank/de-watersnoodramp/`

A

Sea level Rise

This thesis is focuses on the flood risk of the Netherlands in the future. Besides the ability to determine the risk of flooding, understanding the sea water level is of importance. In this chapter an introduction is given to the different influences on the sea water level in the North Sea. Besides the sea water level the expected sea level rise is evaluated.

A.1. Sea water levels

The flood defences are designed on hydraulic loads. These loads are composed of estimated values for storm duration, storm surge and the astronomical tides. In this section an introduction to the different components that influence the sea water level.

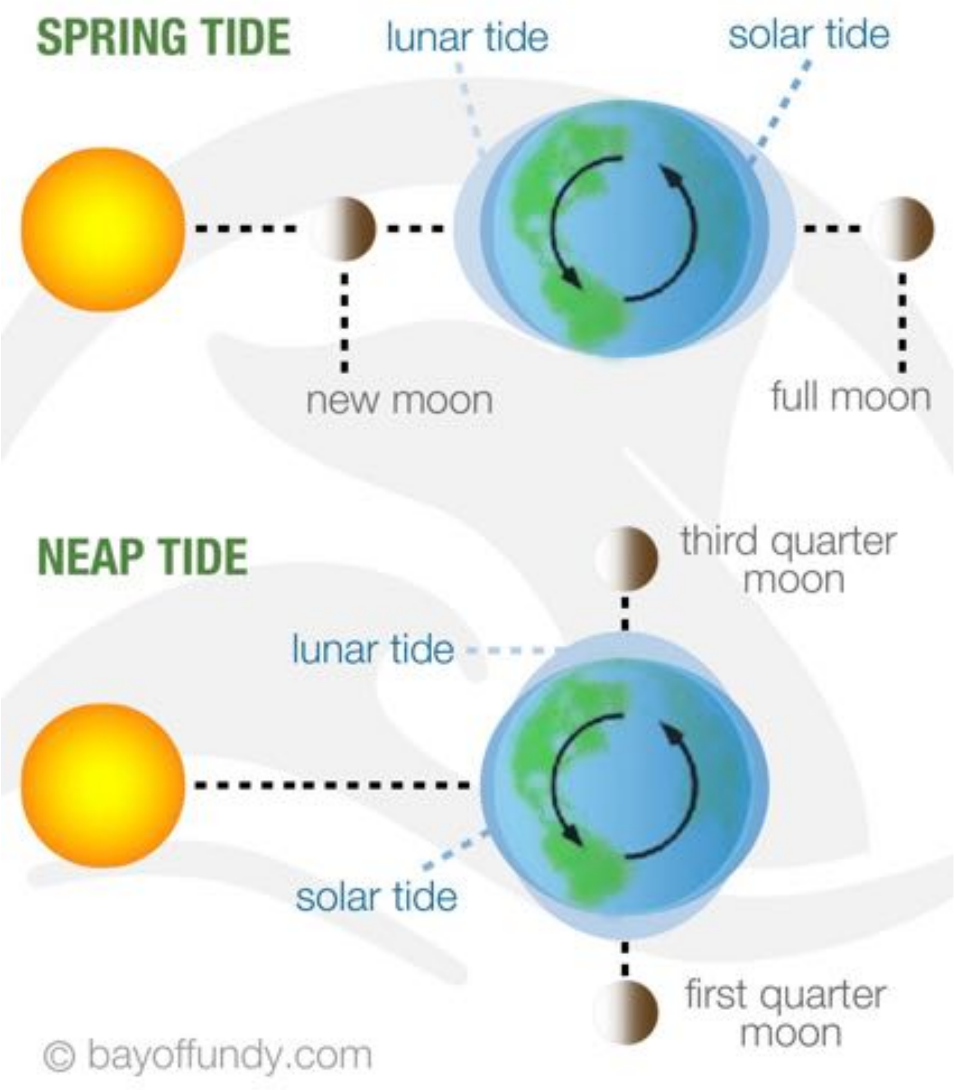


Figure A.1: Influence of position of the sun and moon on the tidal movement. [Source: bay of fundy]

A.1.1. Astronomical tide

Astronomical tide is generally the largest influence on the sea water level on a daily basis. The gravitational forces of the sun and the moon determine the movement of the tidal waves on earth. The rising and the falling of the tide vary over time due to the position of the moon and the sun. The position of the two influential elements can combine forces if aligned and divide force if opposed, see Figure A.1 . This is called spring tide and neap tide. In case of flood risk the most extreme condition is of importance. Therefore the focus in this thesis is on the spring tide.

The tidal influence in the Netherlands starts in the Atlantic Ocean. Due to the Coriolis effect the tidal movement spins counter clockwise around central points. These central points, amphidromes, have no tidal differences. Since the Netherlands is located in a protected area behind Great Britain in the North sea there are three amphidromes that influence the Dutch coasts, see Figure A.2. The most southern amphidrome is of largest influence on the Dutch coast. The distance from the amphidrome to the coast determines the height of the tidal movement. In the Northsea there is a diurnal tide. This means that there is high and low tide twice a day. More precise there is a period of 12 hours and 24 minutes. This means that the tidal movement is very predictable. For the Netherlands the tide is refers to the NAP (Nieuw Amsterdams Peil).

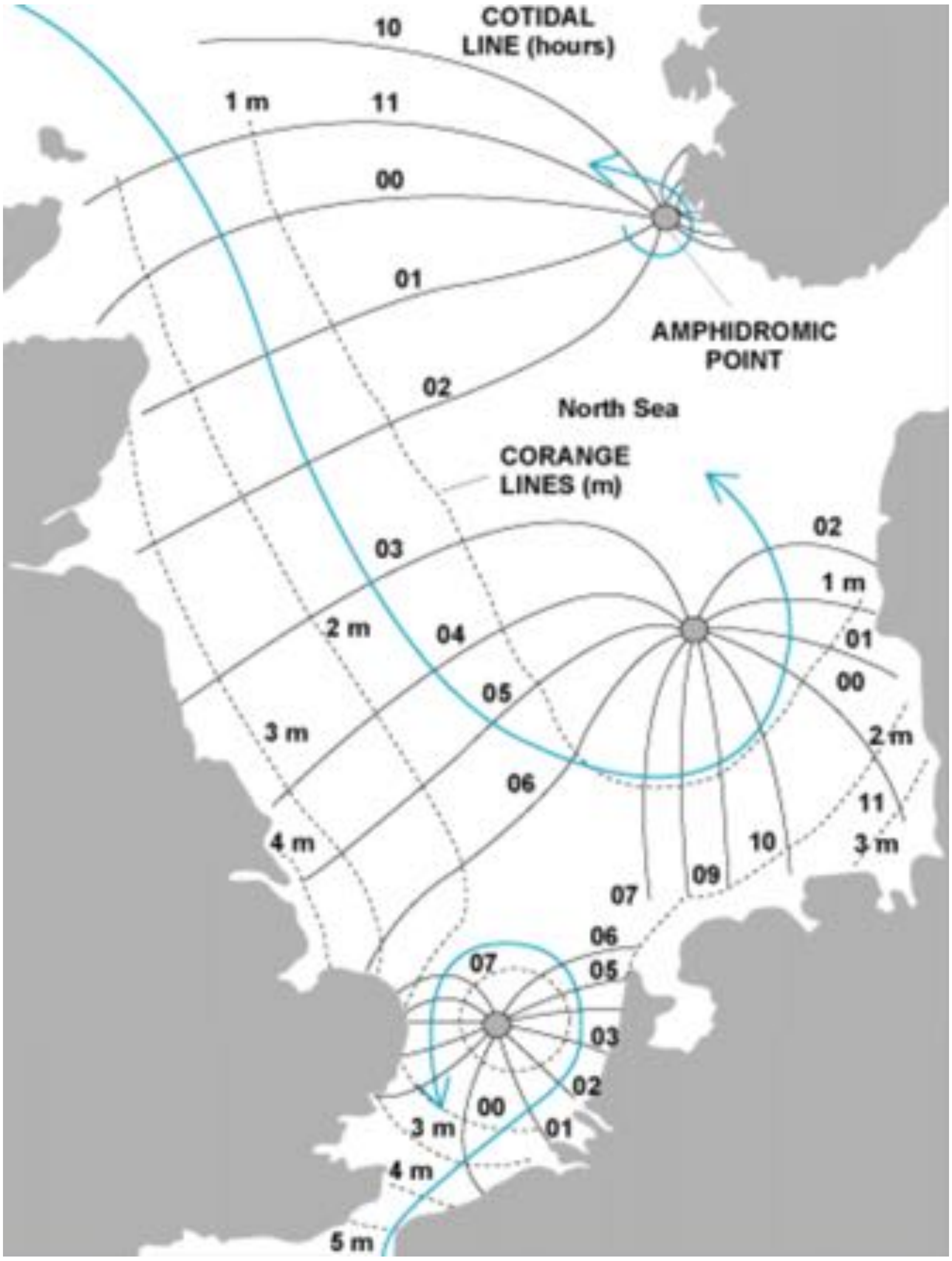


Figure A.2: Overview of the Amphidromes that determine the tidal wave in the North Sea

A.1.2. Storm Surge

Another important influence on the sea water level at the coasts is the weather. Wind can influence the water level. With wind coming from the west across the Atlantic Ocean, water is pushed towards the North Sea. This results in rise of the sea water level and is called storm surge. The storm surge is defined by the difference between the actual sea water level and the predicted astronomical tidal level. When there are storms, the storm surge is of large influence. This is due to the low atmospheric pressure, that allows the sea level to rise, the earths rotational forces that forces the water towards the coasts. A storm surge can be caused by the European weather systems and tropical storms. The surges last from hours up to days and can span areas of hundreds of square kilometres. The tropical storm surge can rise sea level up to 8 meters. The European seas are influenced up to 3 meters. This is an extra influence on the sea water level. Therefore the astronomical tide and the waves due to wind at location are to be added. In the Netherlands an automatic level writer is installed at Hoek van Holland since 1887. The water level in the Netherlands is therefore well documented, see table A.1 for extreme waterlevels of the past 123 years.

Date	[m + NAP]
1-Feb-1953	4.55
3-Jan-1976	3.94
12-Mar-1906	3.92
27-Feb-1990	3.84
1-Mar-1949	3.82
Every 2 years	3.40

Table A.1: Water levels measured at Vlissingen.

These storm water levels are composed of both the storm surge and the astronomical tide. Storm duration in the Netherlands are in the order of 24 hours. To dimension the flood defences, long storms are taken into account which resulted in storms of 35 hours. The duration of the storm determines the duration of the extreme water level. Extreme water levels with a longer duration result in a higher probability of failure. Typically the storm surge and the storm duration follow a certain shape, steep water level rise, slow water level rise, slow water level fall, steep water level fall.

A.2. Expected sea level rise

The flood defence systems are designed for a lifetime of preferable decades. Therefore it is important to evaluate the future hydraulic loads that could occur. The flood defence system in the Netherlands is planned ahead for 50 years. In the past 100 years the sea level has risen 20 cm. Therefore adding another 10 cm for the 50 years to come used to be practise. However new views on climate change predict increased values for future sea level rise. The current predictions of the IPCC find global mean sea level rise between 0,29m and 1,1m by 2100. These IPCC predictions are still somewhat conservative and do not include the full range of scenarios that are possible.

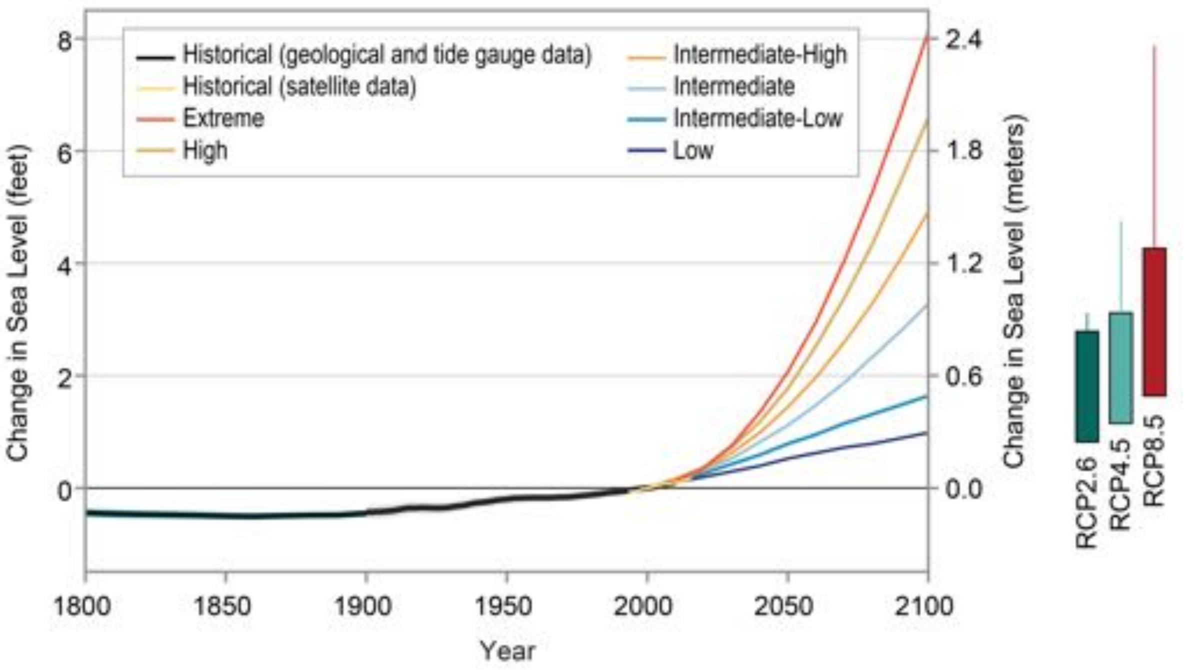


Figure A.3: How much global average sea level will rise over the rest of this century depends on the response of the climate system to warming, as well as on future scenarios of human-caused emissions of heat-trapping gases. The colored lines show the six different global average sea level rise scenarios, relative to the year 2000, that were developed by the U.S. Federal Interagency Sea Level Rise Taskforce 76 to describe the range of future possible rise this century. The boxes on the right-hand side show the very likely ranges in sea level rise by 2100, relative to 2000, corresponding to the different RCP scenarios. The lines above the boxes show possible increases based on the newest research of the potential Antarctic contribution to sea level rise (for example, DeConto and Pollard 201680 versus Kopp et al.). Regardless of the scenario followed, it is extremely likely that global average sea level rise will continue beyond 2100. Source: adapted from (Sweet et al., n.d.)

B

Damage curve

Damage functions Damage functions determine how much of damage is inflicted on the area of interest. The function is based on the hydraulic characteristics of the floods and the most influential characteristic is the inundation depth. Since the damage function is different for each land use category the most important ones are evaluated.

Commercial use To determine the damages to commercial enterprises, HIS-SSM is used.(**?**) To determine the damage curve an average is used. Because the categories that are used are combined to one category, commercial use, the average damage function of the damage functions shown in Figure B.1 is used.

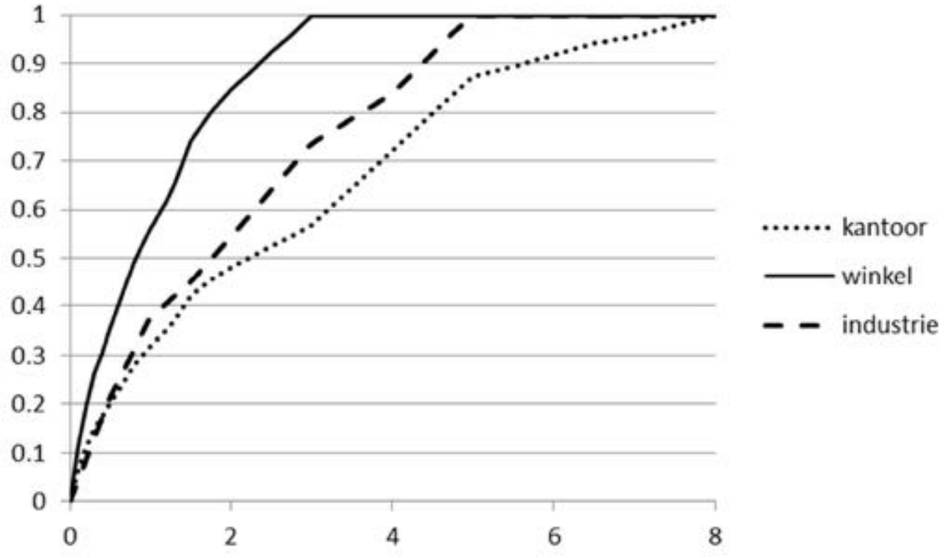


Figure B.1: Damage functions of direct damage commercial land use

Residential use To determine the damage to residential buildings HIS-SSM is used.(**?**) To determine the damage curve an average of the building value and the household effects is used, see Figure B.2.

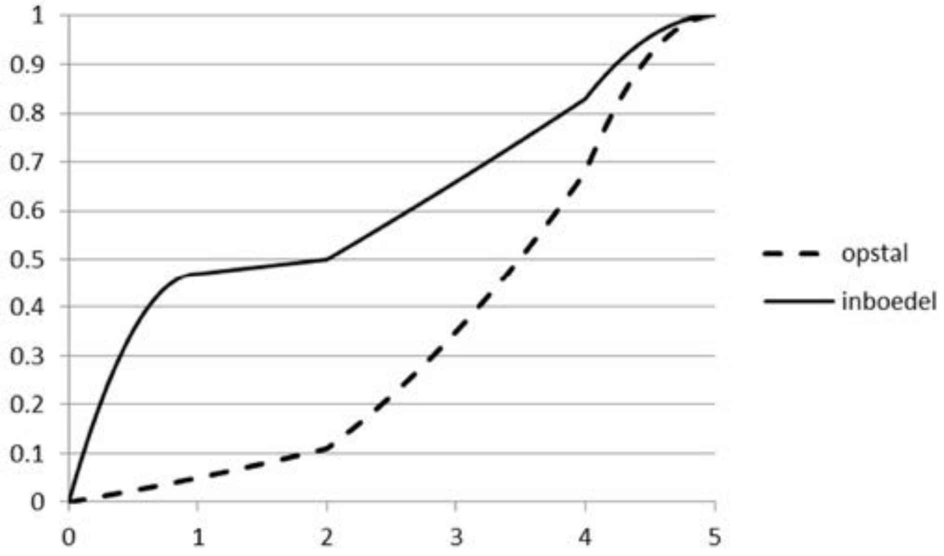


Figure B.2: Damage function of single-family housing, household effects and damage to building are separated.

The damage curves for apartments were divided as well. As water damage would not occur to higher floor apartments if the water depth in not high enough. The distinction is made up to second floor and higher since a water depth of 5 meter is unlikely to occur often. Since the different categories that applied on residential areas are combined, an average value of these damage functions is used. In Figure B.3 the damage curve of different appartment styles are shown.

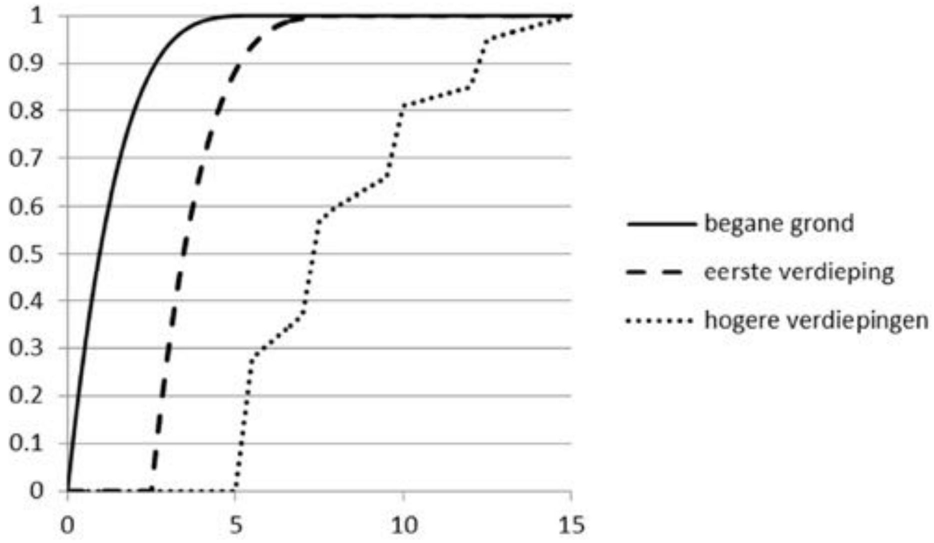


Figure B.3: Damage function of apartments.

Infrastructure The damage function of the different infrastructural categories is equal. The identical damage curve holds for railroads, roadways and airports. It is shown in Figure B.4

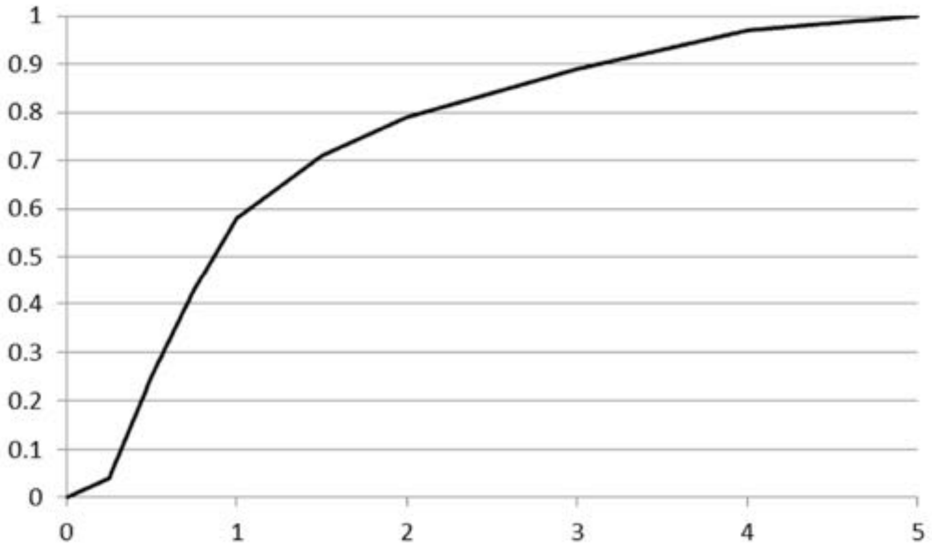


Figure B.4: Damage function infrastructure.

C

Economic Optimisation

In this appendix the economic optimisations of the different scenarios are further evaluated.

Kijkduin The economic optimisations of the different sea level rise scenarios at the Kijkuin location are plotted in the following figures:

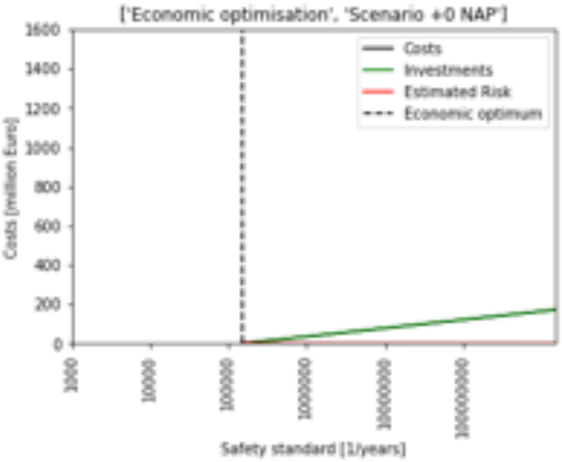


Figure C.1: Economic optimisation of the flood event at Kijkduin. Based on a hydrodynamic simulation with a scenario of 0m sea level rise

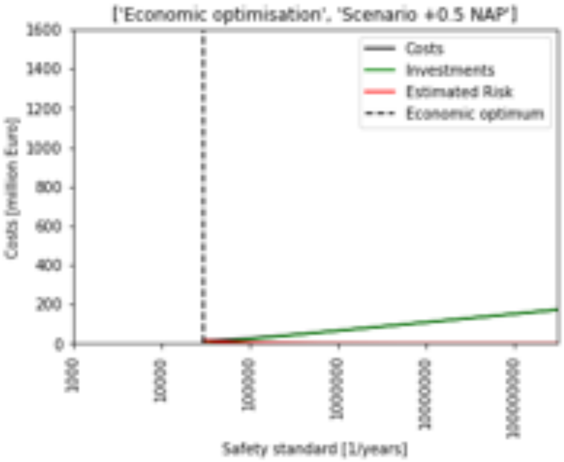


Figure C.2: Economic optimisation of the flood event at Kijkduin. Based on a hydrodynamic simulation with a scenario of 0,5m sea level rise

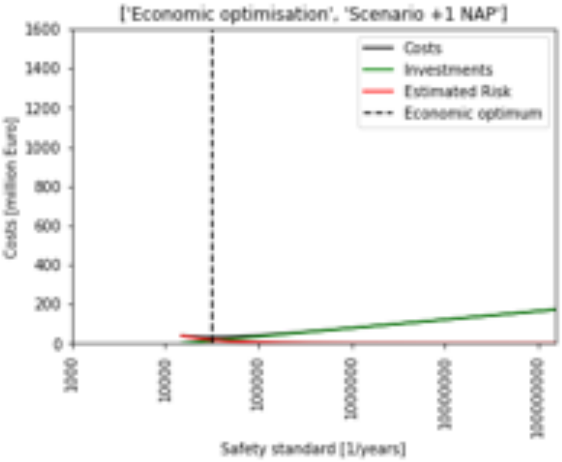


Figure C.3: Economic optimisation of the flood event at Kijkduin. Based on a hydrodynamic simulation with a scenario of 1,0m sea level rise

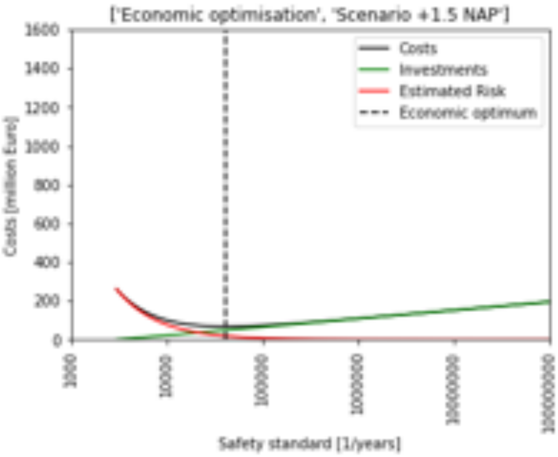


Figure C.4: Economic optimisation of the flood event at Kijkduin. Based on a hydrodynamic simulation with a scenario of 1,5m sea level rise

This results in the following characteristics:

Scenario	Optimal costs [M €]	Optimal PoF	Investment costs [M €]	# increased safety level
NAP	2,500	1/15000	0	0
NAP + 0,5m	15,000	1/30000	0	0
NAP + 1,0m	32,500	1/31500	14,000	0,32
NAP +1,5m	68,000	1/32000	49,000	1,15
NAP +2,0m	87,000	1/59000	69,000	1,59

Table C.1: Characteristics of the optimal safety level of dunes for future flood scenarios in Kijkduin

Noordwijk The economic optimisations of the different sea level rise scenarios at the Noordwijk location are plotted in the following figures:

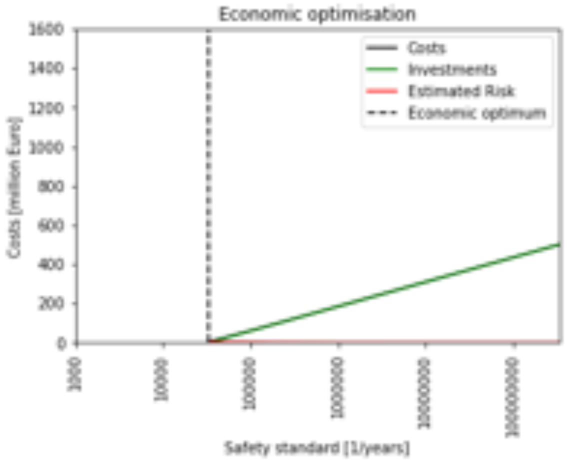


Figure C.5: Economic optimisation of the flood event at Noordwijk. Based on a hydrodynamic simulation with a scenario of 0m sea level rise

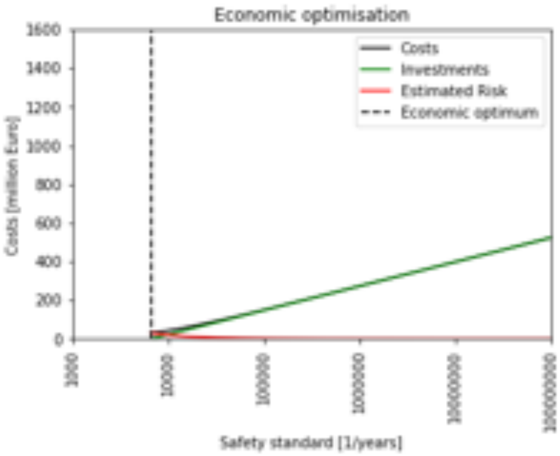


Figure C.6: Economic optimisation of the flood event at Noordwijk. Based on a hydrodynamic simulation with a scenario of 0,5m sea level rise

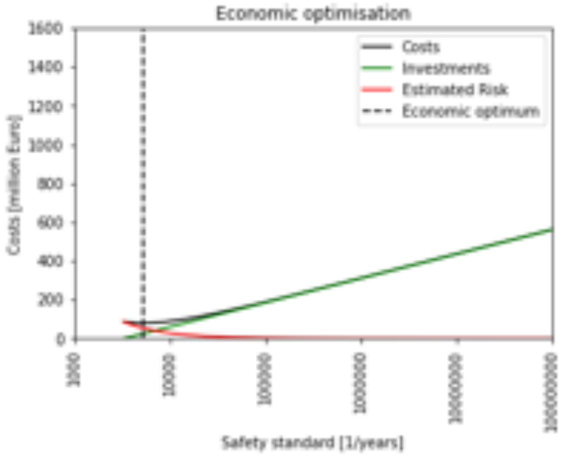


Figure C.7: Economic optimisation of the flood event at Noordwijk. Based on a hydrodynamic simulation with a scenario of 1,0m sea level rise

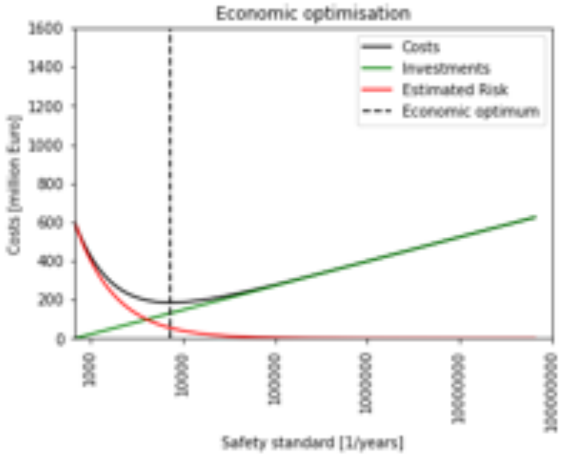


Figure C.8: Economic optimisation of the flood event at Noordwijk. Based on a hydrodynamic simulation with a scenario of 1,5m sea level rise

This results in the following characteristics:

Scenario	**Optimal costs [M €]**	**Optimal PoF**	**Investment costs [M €]**	**# increased safety level**
NAP	4,500	1/33000	0	0
NAP + 0,5m	31,000	1/6500	0	0
NAP + 1,0m	80,000	1/5500	26,000	0,21
NAP +1,5m	185,000	1/7500	131,00	1,04
NAP +2,0m	237,000	1/9500	182,000	1,46

Table C.2: Characteristics of the optimal safety level of dunes for future flood scenarios in Noordwijk

Monster The economic optimisations of the different sea level rise scenarios at the Monster location are plotted in the following figures:

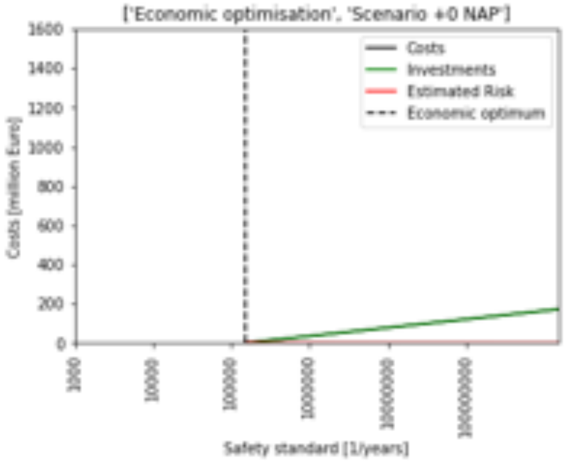


Figure C.9: Economic optimisation of the flood event at Monster. Based on a hydrodynamic simulation with a scenario of 0m sea level rise

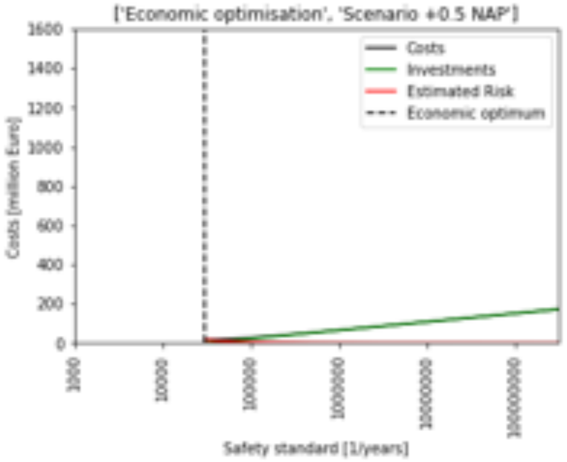


Figure C.10: Economic optimisation of the flood event at Monster. Based on a hydrodynamic simulation with a scenario of 0,5m sea level rise

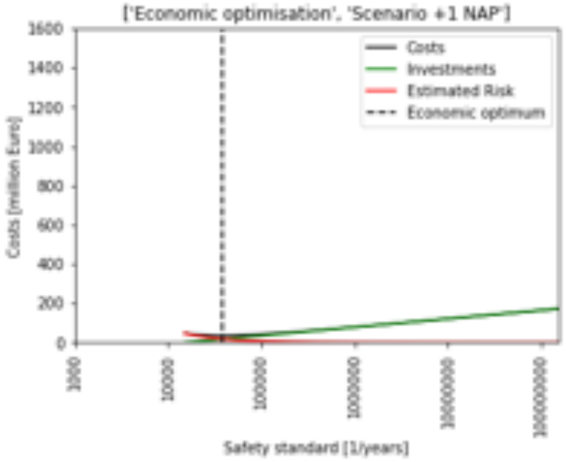


Figure C.11: Economic optimisation of the flood event at Monster. Based on a hydrodynamic simulation with a scenario of 1,0m sea level rise

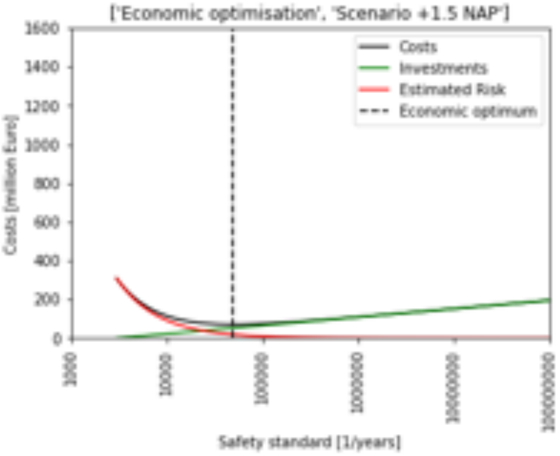


Figure C.12: Economic optimisation of the flood event at Monster. Based on a hydrodynamic simulation with a scenario of 1,5m sea level rise

This results in the following characteristics:

Scenario	Optimal costs [M €]	Optimal PoF	Investment costs [M €]	# increased safety level
NAP	2,000	1/150000	0	0
NAP + 0,5m	16,000	1/30000	0	0
NAP + 1,0m	36,000	1/39000	17,000	0,40
NAP +1,5m	71,000	1/49500	52,000	1,22
NAP +2,0m	88,000	1/63000	70,000	1,62

Table C.3: Characteristics of the optimal safety level of dunes for future flood scenarios in Monster

D

Python code optimisation

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib
#%% Economical Optimalisation Kijkduin
DKD = [2.578*10**9,3.340*10**9,4.316*10**9,5.743*10**9,8.102*10**9] # Damage in scenario sea lev
S = ['Scenario +0 NAP','Scenario +0.5 NAP','Scenario +1 NAP','Scenario +1.5 NAP','Scenario +2 NA
P = [1/150000,1/30000,1/15000,1/3000,1/1500]
#Invest  = [26*10**6,43*10**6,86*10**6]
#r = [0.02,0.03,0.04]
#for j in range(3):
r = 0.03# Discount rate
g = 0.019 # Grow rate
for i in range(5):
    Invest = 43 *10**6*0.7 #Investment cost for raising safety level by factor 10
    x = np.linspace(0,5,100000)#Times safety level is raised
    Pf = (P[i])/(10)**x #Probability of failure of the Dune
    IKD = Invest*x # Total Investment
    RKD = Pf*1.5*DKD[i]/(r-g)
    CostKD = IKD+RKD
# ==============================================================================
#     plt.figure()
#     plt.plot (x,CostKD/10**6, color = 'black')
#     plt.plot(x,IKD/10**6,color = 'green')
# ==============================================================================
    plt.plot(x,RKD/10**6)
   # plt.axvline(x[np.argmin(CostKD)],color = 'black', linestyle = 'dashed')
    plt.xlim(0,4)
    plt.ylim(0,800)
    logIn = 1000*P[i]
    plt.xticks([np.log10(logIn)/np.log10(10),np.log10(logIn*10)/np.log10(10),np.log10(logIn*100)
    plt.xlabel('Safety standard [1/years]')
    plt.ylabel('Risk [million Euro]')
    plt.legend(['Scenario +0 NAP','Scenario +0.5 NAP','Scenario +1 NAP','Scenario +1.5 NAP','Sce
    plt.title('Risk estimations Kijkduin')

    print ('the optimal cost seen from economic point of view in',S[i],'is',np.round(np.min(Cost
    print ('the probability of failure at economic optimization in',S[i],'is', np.round(1/Pf[np.
    print ('the optimal investment seen from economic point of view in',S[i],'is',np.round(IKD[n
    print ('the optimal amount of times that the probability of failure is decimaled in',S[i],'i
    print(' the range of the Economical damages due to investment costs:',np.round(np.min(CostKD
#%%
print(np.min(CostKD[0]))
#%% Economical Optimalisation Noordwijk
DNW = [1.640*10**9,2.273*10**9,3.160*10**9,4.395*10**9,5.674*10**9] # Damage in scenario sea lev
S = ['Scenario +0 NAP','Scenario +0.5 NAP','Scenario +1 NAP','Scenario +1.5 NAP','Scenario +2 NA
P = [1/33000,1/6600,1/3300,1/660,1/330]
for i in range(5):
    Invest = 125 *10**6*0.7 #Investment cost for raising safety level by factor 10
    x = np.linspace(0,5,100000)#Times safety level is raised
    Pf = (P[i])/(10)**x #Probability of failure of the Dune
    INW = Invest*x # Total Investment
    RNW = Pf*DNW[i]/(r-g)
    CostNW = INW+RNW
# ==============================================================================
#     plt.figure()
#     plt.plot (x,CostNW/10**6, color= 'black')
#     plt.plot(x,INW/10**6, color = 'green')
# ==============================================================================
    plt.plot(x,RNW/10**6)
    #plt.axvline(x[np.argmin(CostNW)],color = 'black', linestyle = 'dashed')
    plt.xlim(0,4)
    plt.ylim(0,1600)
    logIn = 1000*P[i]
    plt.xticks([np.log10(logIn)/np.log10(10),np.log10(logIn*10)/np.log10(10),np.log10(logIn*100)
    plt.xlabel('Safety standard [1/years]')
    plt.ylabel('Risk [million Euro]')
```

```
    plt.legend(['Scenario +0 NAP','Scenario +0.5 NAP','Scenario +1 NAP','Scenario +1.5 NAP','Sce
    plt.title('Risk estimations Noordwijk')
    print ('the optimal cost seen from economic point of view in',S[i],'is',np.round(np.min(Cost
    print ('the probability of failure at economic optimization in',S[i],'is', np.round(1/Pf[np.
    print ('the optimal investment seen from economic point of view in',S[i],'is',np.round(INW[n
    print ('the optimal amount of times that the probability of failure is decimaled in',S[i],'i
#%% Economical Optimalisation Monster
DM = [4.038*10**9,5.416*10**9,7.768*10**9,10.190*10**9,12.974*10**9] # Damage in scenario sea le
S = ['Scenario +0 NAP','Scenario +0.5 NAP','Scenario +1 NAP','Scenario +1.5 NAP','Scenario +2 NA
P = [1/150000,1/30000,1/15000,1/3000,1/1500]
for i in range(5):
    Invest = 43 *10**6*0.7 #Investment cost for raising safety level by factor 10
    x = np.linspace(0,5,100000)#Times safety level is raised
    Pf = (P[i])/(10)**x #Probability of failure of the Dune

    IM = Invest*x  # Total Investment
    RM = Pf*DM[i]/(r-g)
    CostM = IM+RM
# =============================================================================
#     plt.figure()
#     plt.plot (x,CostM/10**6, color = 'black' )
#     plt.plot(x,IM/10**6, color = 'green')
# =============================================================================
    plt.plot(x,RM/10**6)
    #plt.axvline(x[np.argmin(CostM)],color = 'black', linestyle = 'dashed')
    plt.xlim(0,4)
    plt.ylim(0,800)
    #plt.title(['Economic optimisation',S[i]])
    logIn = 1000*P[i]
    plt.xticks([np.log10(logIn)/np.log10(10),np.log10(logIn*10)/np.log10(10),np.log10(logIn*100)
    plt.xlabel('Safety standard [1/years]')
    plt.ylabel('Risk [million Euro]')
    plt.legend(['Scenario +0 NAP','Scenario +0.5 NAP','Scenario +1 NAP','Scenario +1.5 NAP','Sce
    plt.title('Risk estimations Monster')
    print ('the optimal cost seen from economic point of view in',S[i],'is',np.round(np.min(Cost
    print ('the probability of failure at economic optimization in',S[i],'is', 1/Pf[np.argmin(Co
    print ('the optimal investment seen from economic point of view in',S[i],'is',np.round(IM[np
    print ('the optimal amount of times that the probability of failure is decimaled in',S[i],'i
#%%
# =============================================================================
#     Invest = 150*10**6 #Investment cost for raising safety level by factor 10
#     x = np.linspace(0,5,100000)#Times safety level is raised
#     Pf = (1/2000)/(10)**x #Probability of failure of the Dune
#     D = 90*10**9
#     r = 0.055 # Discount rate
#     g = 0.029 # Grow rate
#     I = Invest*x+500000000 # Total Investment
#     R = Pf*D/(r-g)
#     Cost = I+R
#     plt.figure()
#     plt.plot (x,Cost)
#     plt.plot(x,I)
#     plt.plot(x,R)
#     plt.xlim(0,5)
#     plt.ylim(0,1.75*10**9)
#     plt.xlabel('Amount of times safety is increased by factor 10 [-]')
#     plt.ylabel('[Euro]')
#     plt.legend(['Costs','Investments','Estimated Risk'])
#     print(R[0])
#
#     print ('the optimal cost seen from economic point of view in',S[i],'is',np.round(np.min(Co
#     print ('the probability of failure at economic optimization in',S[i],'is', 1/Pf[np.argmin(
#     print ('the optimal investment seen from economic point of view in',S[i],'is',np.round(I[n
#     print ('the optimal amount of times that the probability of failure is decimaled in',S[i],
# =============================================================================
#%% With indirect costs
# =============================================================================
```

```
# DKD = [2.578*10**9,3.340*10**9,4.316*10**9,5.743*10**9,8.102*10**9] # Damage in scenario sea l
# S = ['Scenario +0 NAP','Scenario +0.5 NAP','Scenario +1 NAP','Scenario +1.5 NAP','Scenario +2
# P = [1/150000,1/30000,1/15000,1/3000,1/1500]
# for i in range(5):
#     Invest = 43 *10**6 #Investment cost for raising safety level by factor 10
#     x = np.linspace(0,5,100000)#Times safety level is raised
#     Pf = (P[i])/(10)**x #Probability of failure of the Dune
#     r = 0.03 # Discount rate
#     g = 0.019 # Grow rate
#     IKD = Invest*x # Total Investment
#     RKD = Pf*1.5*DKD[i]/(r-g)
#     CostKD = IKD+RKD
#     #plt.figure()
#     #plt.plot (x,CostKD)
#     #plt.plot(x,IKD)
#     plt.plot(x,RKD)
#     plt.xlim(0,4)
#     plt.xticks([0,1,2,3,4,5],[np.round(1/((P[i])/(10)**0)),np.round(1/((P[i])/(10)**1)),np.rou
#     #plt.axvline(x[np.argmin(CostKD)])
#     plt.xlabel('Return period of probability of failure [years]')
#     plt.ylabel('[Euro]')
#     plt.legend(['Scenario +0 NAP','Scenario +0.5 NAP','Scenario +1 NAP','Scenario +1.5 NAP','S
#     plt.title('Risk of different scenarios Kijkduin')
#
# =============================================================================
#%% Total Coastline of Dijkring 14.
DKD = [2.578*10**9,3.340*10**9,4.316*10**9,5.743*10**9,8.102*10**9] # Damage in scenario sea lev
DM = [4.038*10**9,5.416*10**9,7.768*10**9,10.190*10**9,12.974*10**9] # Damage in scenario sea le
DNW = [1.640*10**9,2.273*10**9,3.160*10**9,4.395*10**9,5.674*10**9] # Damage in scenario sea lev
S = ['Scenario +0 NAP','Scenario +0.5 NAP','Scenario +1 NAP','Scenario +1.5 NAP','Scenario +2 NA
PKDM = [1/150000,1/30000,1/15000,1/3000,1/1500]
PNW = [1/33000,1/6600,1/3300,1/660,1/330]
Damage= np.zeros(5)
Damage1= np.zeros(5)
for i in range(5):
    Damage[i] = DKD[i]+DM[i]
    Damage1[i] =DNW[i]
    InvestKDM = 43 *10**6 #Investment cost for raising safety level by factor 10
    InvestNW = 125 *10**6
    x = np.linspace(0,5,100000)#Times safety level is raised
    Pf1 = (PKDM[i])/(10)**x #Probability of failure of the Dune
    Pf2 = (PNW[i])/(10)**x #Probability of failure of the Dune
    r = 0.03 # Discount rate
    g = 0.019 # Grow rate
    Itot = InvestKDM*x +InvestNW*x # Total Investment
    RKD = Pf1*DKD[i]/(r-g)
    RM =  Pf1*DM[i]/(r-g)
    RKDM = Pf1*Damage[i]/(r-g)
    RNW = Pf2 *Damage1[i]/(r-g)

    Rtot = RKDM+RNW
    CostTot = Itot+Rtot
    plt.figure()
    plt.plot (x,CostTot/10**6, color = 'black')
    plt.plot(x,Itot/10**6, color ='green')
    plt.plot(x,Rtot/10**6, color = 'red')
    plt.xlim(0,4)
    plt.xticks([0,1,2,3,4,5],[np.round(1/((Pf1[i])/(10)**0)),np.round(1/((Pf1[i])/(10)**1)),np.r
    plt.axvline(x[np.argmin(CostTot)], color = 'black', linestyle = 'dashed')
    plt.xlabel('Probability of failure [1/years]')
    plt.ylabel('Costs [million Euro]')
    plt.legend(['Costs','Investments','Estimated Risk','Economic optimum'])
    plt.title('Risk of coastal area in total ')
    print ('the optimal cost seen from economic point of view in',S[i],'is',np.round(np.min(Cost
    print ('the probability of failure at economic optimization for Southern coastal area in',S[
    print ('the probability of failure at economic optimization for Northern coastal area in',S[
    print ('the optimal investment seen from economic point of view in',S[i],'is',np.round(Itot[
```

```
print('The ratio of the Total risk that is part due to the Kijkduin is',np.round(RKD[np.argm
print('The ratio of the Total risk that is part due to the Monster  is',np.round(RM[np.argmi
print('The ratio of the Total risk that is part due to the Noordwijk is',np.round(RNW[np.arg
#print('The ratio of the Total risk that is part due to the Hydraulic structures combination
#print ('the optimal amount of times that the probability of failure is decimaled in',S[i],'
print('Total Risk:', Rtot[np.argmin(CostTot)])
```