Optimization of flood safety levels

Case study for unembanked areas in the Port of Rotterdam

T.F.J. Veenman

April, 2019

TU Delft

Royal HaskoningDHV
Enhancing Society Together

Optimization of flood safety levels

Case study for unembanked areas in the Port of Rotterdam

by

T.F.J. Veenman

Student number:	4270614	
Project duration:	December 12, 2018 – April 8, 2019	
Thesis committee:	Prof. dr. ir. S. N. Jonkman,	TU Delft
	Ir. E. C. van Berchum,	TU Delft
	Ir. A. J. Lansen,	TU Delft
	Ir. M. F. M. Bos,	Royal HaskoningDHV

Summary

Large parts of the Netherlands are low lying and prone to flooding. Therefore these areas are protected by dikes. Here, flood safety is the responsibility of the Dutch government. In the Port of Rotterdam, all areas are unembanked and built on planes higher than the average sea level. This should ensure flood safety with the absence of dikes. Here, landowners are responsible for their own flood safety. Due to climate change these areas may be threatened by flood risk in the future. Therefore, the Port of Rotterdam started the Flood Risk Management project with the goal to investigate the effect of climate change on the level of flood safety in the Port of Rotterdam. Royal HaskoningDHV was asked to perform the studies and make companies in the Port of Rotterdam aware of the risks.

A risk-framework had been set up to assess the risk. This risk-framework (existing risk-framework) consists of four steps. First, relation between the water level and the inducing damage is determined. Second, the probability of damage and the acceptable probability of damage are defined. Thirdly, the probability of damage and the acceptable probability of damage are compared with each other. After an expert session on the methods of the risk-framework with Prof.Ir.S.N Jonkman (TU Delft) and Dr.Ir.R. Jongejan (Jongejan RMC), it was advised to further investigate how the risk is calculated (incident risk vs cumulative risk) and how the acceptable level of risk is determined. This research concentrates on how these problems can be dealt within a new risk-framework.

The new risk-framework (proposed risk-framework) is based on a cost-benefit analysis (CBA). The CBA determines the economic optimum, based on a combination of the moment and height of investing in measures against flood risk. The input of the model are the measure, size of area, climate prediction, location, sector, shape of area, economic prospect, ground level, investment costs and time of recovery. The result of the CBA are the costs for each combination of measure height (Δz) and moment of investing (t*). In the latest step of the CBA the combination that leads to the lowest costs is chosen as the optimal solution. The output of the model is a 3D plot of all combinations of Δz and t* with their total costs. This 3D plot shows the influence to the total costs by the height of investing and moment of investing.

The model is intensively studied with a sensitivity analysis on the different inputs of the model. These input parameters are: measure, size, climate prediction, location, sector, shape, economic prospect, ground level, investment costs and recovery time. The parameters that seem to be most important to determine the optimal level of flood safety are the ground level and sector (consisting of water level - damage relation and the economic value per m^2). The size and shape seems to be most important parameters for determining the most suitable measure. The most uncertain factors are climate prediction, recovery time (indirect damage) and the cost of the different measures.

A case study was set up for the lowest part of the Waal- and Eemhaven: pier 7. The model was run for the whole pier. This run concluded a land fill is the cheapest solution for this pier. This case study showed how the model could be used to get a first, rough estimate of how to reduce flood risk in a cost efficient way. The case study explained the application of the model and could be used as an example how to implement the model in the future.

This research concludes with answering the research questions. The proposed risk-framework is an addition to the existing risk-framework. The existing risk-framework is made with the purpose to make flood risk understandable for companies and to make it easy to implement flood risk in a risk matrix of a company. The proposed risk-framework calculates the height and the moment of the measure that is most suitable for the case. This is determined by minimizing the total cost. Differences between the existing and proposed risk-framework are in calculating the risk and the acceptability of risk. The proposed risk-framework uses the cumulative risk instead and calculates the acceptability of risk based on the costs of measures against flood risk. The existing risk-framework uses the incident risk and a limiting value of damage for a flood as acceptability level.

In next workshops, it is advised to use both methods and to see how the proposed risk-framework could be implemented in an understandable way. It can be concluded the cost-benefit analysis is a good way to assess flood risk and to determine the appropriate measure to reduce the costs of flood risk due to climate change. Further improvements of the model could be done by implementing the indirect damage more realistically and make a difference in costs that are certain (investment costs) and probable (risk). Also land subsidence could improve the model.

Preface

In front of you lays the research on the optimization of flood safety by a cost-benefit analysis in the field of flood risk performed by T.F.J. (Tjerk) Veenman for Royal HaskoningDHV. This research gave me the opportunity to experience working for a big engineering firm. Also, this research gave me more knowledge and experience in the field of flood risk and flood safety. The research is an additional thesis as part of the curriculum of the MSc. Civil Engineering, track Hydraulic Engineering. An additional thesis (10 ECTS) is a smaller version of the Master thesis (40 ECTS).

First of all, I would like to thank my daily supervisor Mathijs Bos. Mathijs always had time to shine his light on the process and give some advise on how to continue. His experience with the Flood Risk Management project, existing risk-framework and flood risk in general, brought this research to a higher level. Next, Maarten Schoemaker helped me a lot with defining the method of the new risk-framework and writing the model for the cost-benefit analysis. He also thoroughly checked the script and made sure the script did not contain any errors. I also would like to thank the rest of the Rivers and Coast advisory group for the hospitality they showed me while working at their office in Rotterdam.

Lastly, I would like to thank Prof. Bas Jonkman and Erik van Berchum for their time and counsel on my research. Their assistance and critical view on my research and report helped me studying this subject and answering the research questions.

I hope you all enjoy reading this work as much as I enjoyed writing it.

T.F.J. Veenman
Rotterdam, April 2019

Contents

1

Introduction

Through history, the Netherlands have been flooded many times. The ongoing struggle to reduce flood impacts has resulted in endiked areas in low lying parts. The most recent devastating flood in the history of the Netherlands was in 1953 with more than 1800 casualties and a lot of damage as a result. This flood prompted the Dutch to take action. The first Delta committee was installed and were asked to design a method to approach the flood risk realistically and to make a cost-benefit analysis to protect the Netherlands from the water.

Following the findings of the Delta committee, a risk-based approach was developed to assess the flood safety in the Netherlands (van Dantzig [1956]). The risk is determined by the potential damage and vulnerability. This is expressed in terms of economic value. Next, the required investment is calculated and expressed in monetary value. The optimal level of flood safety is achieved by the lowest total cost (residual risk + investment). For the province of Zuid-Holland, dikes should therefore be high enough to withstand water levels corresponding to storms occurring once every 10.000 years (according to the old method of before 2017, the new method uses probability of failure but will not further be discussed in this research). More information on flood safety in the Netherlands can be found in 'De veiligheid van Nederland in kaart' by Vergouwe and Sarink [2014]. Today, most flood-prone areas in the Netherlands are within dike-rings. The height of the dikes is based on the flood risk (old method of before 2017). Due to the shared risk and benefits of all inhabitants in a dike ring, the Dutch government is responsible for flood safety by the Dutch Water Act (RWS-WVL [2016]).

There are still some areas that are not endiked. These so-called unembanked areas are above sea level which ensures flood safety. In contradiction to endiked land, the Dutch government is not responsible for flood safety outside the dikes. Here, inhabitants themselves are responsible. Not all owners of land outside the dikes are conscious of this responsibility or are aware of the possible flood risk (de Boer et al. [2012]).

A place with many unembanked areas, is the Port of Rotterdam. In the Port of Rotterdam all areas are located outside the dikes (Figure 1.1). These areas all have industrial activities. Usually, companies map the different risks to their operations. These risks could be fire, the loss of power or a broken machine. Although these companies are located in a flood prone area, flood risk is usually not mapped (van de Visch and Bos [2018]).

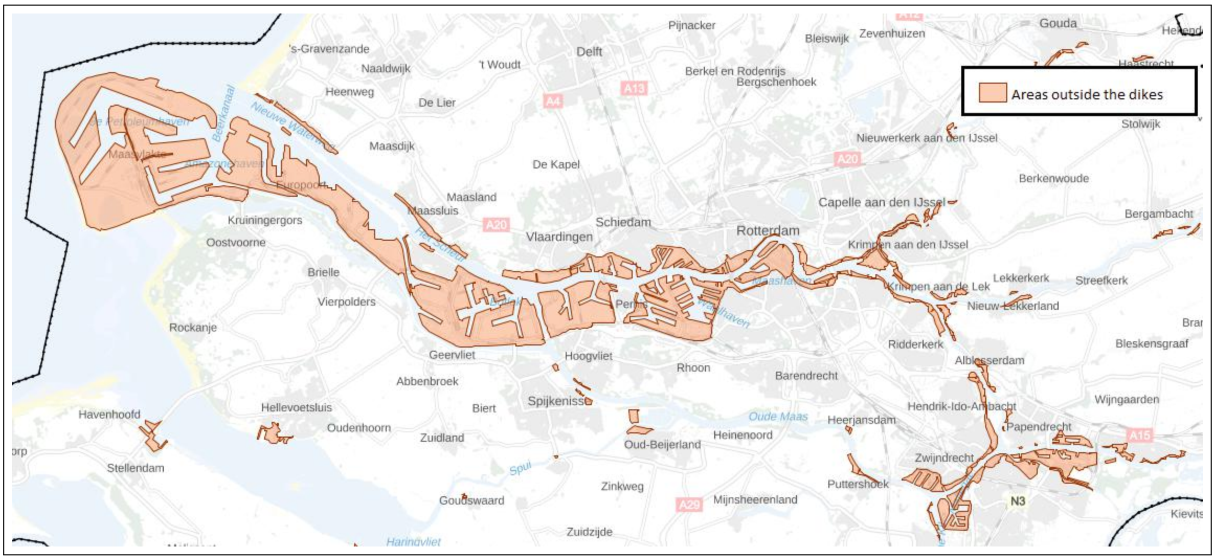


Figure 1.1: Areas around Rotterdam that are outside the dikes. Most parts are reserved for industrial activities, although some other areas are inhabited. Source: province of Zuid Holland [2019].

1.1. Flood Risk Management project

The Port of Rotterdam (PoR) aims to keep the harbour of Rotterdam safe. Due to climate change and more extreme water levels in the future, the flood risk of these unembanked areas will increase. PoR wants to know if the flood risk will still be acceptable and wants to create awareness for flood risk. Therefore, PoR started the Botlek Flood Risk Management pilot project in 2015 (port of Rotterdam [2019]). Royal HaskoningDHV (RHDHV) was asked to develop a strategy, determine the risk and make the stakeholders aware of the flood risk.

For this project, RHDHV made a program that informs these companies via different workshops. In four phases it is tried to make companies aware of the flood risk and their share of responsibility in flood risk. The goal of these phases is to come up with an adaptation strategy. These phases are:

1. **Calculation of flood risk.**
   The flood risk tool simulates a particular water level and determines which areas will flood. Next, the damage is determined. The expected amount of damage per water level and the probability the water will reach this particular water level, determines the flood risk.

2. **Necessity of measures**
   The acceptability of the current flood risk is determined. The acceptability of the current flood risk also determines the necessity of measures against flood risk. This is determined on different criteria, like economical risk, personal risk and environmental risk (Figure 1.2). Because economic risk seems to be most strict in other studies, this research will mainly focus on the economic risk.

3. **Possible measures**
   When measures are considered necessary, the possible measures are inventoried. One should look what measures are possible to implement at the location. Some possible measures are building a dike-ring or a land fill (raising the area). However, more options are possible here.

4. **Possible adaptation strategy**
   Per proposed measure, the effect is determined. Afterwards, the different effects per measure should be compared with each other and a possible adaptation strategy should be chosen.

The final adaptation strategy will be based on the different existing conditions and activities in these areas. After the Botlek Flood Risk Management pilot project in 2015 and 2016, RHDHV performed similar studies for the Waalhaven and Eemhaven (2017-2018), Merwe-Vierhaven (2018-2019), and is currently performing a study for the Europoort (2018-2019).

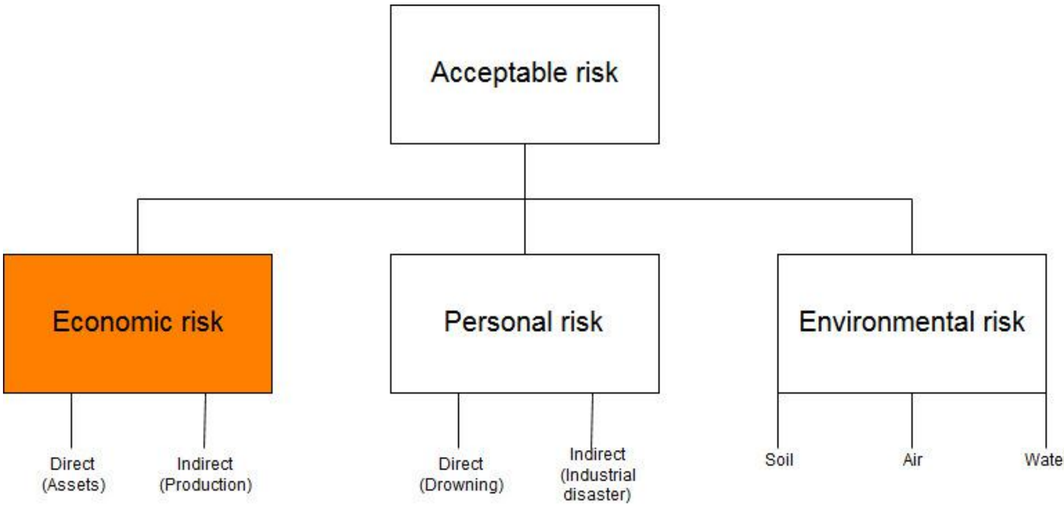


Figure 1.2: Diagram of the criteria for acceptable risk. This research will mainly focus on the economic risk because other studies showed this is the most strict criteria for these areas.

1.2. Problem description

At the 12^{th} of December 2018, an expert-session was organized to evaluate the existing methods of the risk-framework. This expert-session took place in the World Port Center in Rotterdam. Present were RHDHV, Port of Rotterdam, the city of Rotterdam and the experts Prof. Dr. Ir. S. N. Jonkman (TU Delft) and Dr. Ir. R. Jongejan (Jongejan RMC).

In the expert session some problems were found with calculating the acceptability for economic risk. In the current method, the risk is acceptable up to the point a single storm induces more damage than a certain limit. This could be written as:

$$E(D) = P_i \cdot D_i \tag{1.1}$$

In an earlier project in the Botlek area, the value for E(D) was set to be € $1 \cdot 10^6$ at max. This means, a storm that happens once every 1000 years (so $P_i = 0.001$) is acceptable if the damage is lower than € $1 \cdot 10^9$.The experts questioned to what extend this approach is correct, because:

- Smaller floods with a lower return period bring large risks. This is due to their relative high probability of occurrence. Because the damage is low, the current method assesses the risk too low. It would be better to integrate, and therefore use the **cumulative risk** instead of the **incident risk**. This means one should base the criteria of the acceptable limit on $E(D) = \sum P_i \cdot D_i$ instead of $E(D) = P_i \cdot D_i$. When looking only at the risk of a single event with possibly a lot of damage, the risk induced by several smaller events inducing not so much damage (but cumulative this could be a lot more) is neglected. Integrating the risk would therefore be more appropriate in this case.

- The acceptable risk of € 1.000.000,-/year is based on acceptable risk for endiked areas. However, it is not sure it is valid to assume the acceptable risk will be the same for unembanked areas. The acceptable risk could be based on a cost-benefit analysis.

Besides these questions by the experts, RHDHV would like to investigate when the best moment would be to invest measures. The reason for the Flood Risk Management project is to learn companies about the risk and responsibilities they have on flood safety when the sea level rises. Future climate change should therefore be accounted for in determining the acceptable risk. RHDHV would like to show what the costs and benefits are of postponing an investment in flood safety. The model should therefore be able to take the effect of devaluing of money into account. Also, RHDHV would like to be able to show the effectiveness of an investment. This could be shown by the cost/benefit-ratio.

These problems are researched with this additional thesis. Chapter 2 will first explain how the risk is calculated in the current method. Next, a cost-benefit analysis (CBA) will be proposed. This CBA calculates the optimal combination of the height of investment and the moment of investment. The rest of this chapter will explain how different, important parameters are approached and calculated. Chapter 3 will test the influence of the different parameters by different, small and simple test cases. The purpose of this chapter is to discover the influence of the different parameters and the assumptions done behind these parameters. Next, Chapter 4 uses the cost-benefit analyses to find the optimum level and height of investing for a more realistic case. The goal of this chapter is to show how the methods could be used and to see what the result will be for more realistic cases. The practicality of this method will also be shown and discussed. Chapter 5 will conclude this research and give some recommendations for future work.

1.3. Research questions

The main question to be answered by this research is:

- *How could the current risk-framework of RHDHV for food safety and flood risk in unembanked sectors be improved?*

The following sub questions will help in answering the main question:

- *How does the existing risk-framework assess the level of flood safety?*
- *How could the optimal level of flood safety be determined in a cost-benefit analysis?*
- *What influences the optimal level of flood safety determined by a cost-benefit analysis?*
- *How could a cost-benefit analysis be applied and what are the limitations of this new method?*

2

Methods

This chapter will explain the methodology behind the existing risk-framework that is used for the Flood Risk Management project. Section 2.1 explains the original method to access risk and acceptable risk.

Next, Section 2.2 introduces a cost-benefit analysis to determine the optimal level of flood safety. First, a short introduction of cost-benefit analyses in flood safety is given. Second, an application of a cost-benefit analysis in the risk-framework is given. This cost-benefit analyses compares different heights and moments of investment, and chooses the combination that leads to the lowest total cost. Here, the total cost is a combination of risk and investment. By combining different heights of investment which each other, the area will not be over or under protected. The optimal moment of investing is investigated because postponing an investment (and therefore the investment costs) could sometimes be worth the additional risk. The rest of Section 2.2 will discuss the possible measures (Section 2.2.2) with its cost (Section 2.2.4) and effectiveness on flood risk (Section 2.2.3). Further, Section 2.2 explains the probability of a flood (Section 2.2.5), the damage due to a flood (Section 2.2.6) and how the flood risk is calculated (Section 2.2.7).

The chapter ends with a small discussion of the differences between the existing risk-framework and the proposed cost-benefit analysis. Some differences in approach and applicability are highlighted.

2.1. Existing risk-framework

A risk-framework is made by RHDHV for the Flood Risk Management project of PoR. This risk-framework accesses the acceptability of flood-risk for a structure, area or company and is used in the first two phases of the Flood Risk Management project. These first two phases are to calculate the flood risk and to determine if this amount of risk is acceptable (more on the Flood Risk Management project and all four phases can be found in Section 1.1).
The risk-framework uses three steps to find the actual flood risk and the acceptable level of flood risk:

- **Step 1: Define the relation between water level and damage of the subject.**
  In this step the relation between the water level and the amount of damage is defined. In the earlier versions of the risk framework this was done by using the criteria for service limit state (SLS) and ultimate limit state (ULS). Later, a more general *water level - damage* function is used. More on the *water level - damage* function can be found in Section 2.2.6.

- **Step 2a: Define the probability of failure.**
  The probability of failure is determined by the probability of exceedance of water levels

that are found for the SLS and ULS in step 1. With the damage-water level function and the probability of a particular water level the the inflicted flood-damage is calculated.

- **Step 2b: Define the acceptable probability of failure.**
  The acceptable probability of failure determines for each return period the acceptable event and its damage. The acceptability of failure is based on three criteria: economical risk, personal risk and environmental risk. For each of these criteria several levels of acceptability per probability of occurrence have been determined. Earlier sessions showed economical risk is most often the strictest criteria (van de Visch and Bos [2018]). Personal risk is very low because it is assumed there will not be any personal left when extreme conditions are predicted (the area is an industrial area). The criteria for environmental risk is determined in the spread of chemical, hazardous substances after a tank is broken or inflated. However, earlier assessments by RHDHV show this is very unlikely. In the earlier study in the Botlek area, the acceptable economic risk was set to € 1.000.000/year. This means that for an event occurring every 1.000 years, it is acceptable to have € 1 *billion* of damage. This criteria is the result of an interpolation of the acceptable risk for endiked areas in the Netherlands.

- **Step 3: Comparison probability of failure and acceptable probability of failure.**
  In this last step the result of step 2a and step 2b are compared with each other and the acceptability of the currently level of flood safety is determined.

The risk-framework and it steps are also visualized in Appendix B. Here, a schematized view of the different steps is shown with some explanation in Dutch. This schematized view is also shown during the workshops for the Flood Risk Management project.

2.1.1. Discussion

As described in the problem description in Section 1.2, there are some uncertainties about the validity of the existing risk-framework. It is questioned if the current risk approach is correct and the validity of the acceptable risk criteria of € 1.000.000/year is also not sure. Therefore, with this research a new approach to determine the risk and the acceptable risk is proposed.

The following improvements can be done with a cost-benefit analysis:

- More cost efficient method because investment and risks are weighed against each other;
- The acceptable or optimal level of protection is more objective approached because an objective criterion (the total costs) is used;
- The possible measures (and their costs) are direct visible. With a cost-benefit analysis it can be directly seen what the effect is of the investment;

2.2. Cost-benefit analyses

A cost-benefit analysis on flood risk has been performed by the first Delta committee after the flood of 1953. As shortly described in the introduction of this research, this was necessary due to the shortage of money and the necessity of measures.

The cost-benefit analysis for flood-risk consists of investment (I) and risk (R). The investment is the cost of measures against floods. Risk is the expected costs due to floods after the investment has been executed (therefore, this risk is also called residual risk). Together, these are the total cost (TC). Investment and rest risk are both dependent on the height of the measure, Δz. The formula for total cost is therefore:

$$TC(\Delta z) = I(\Delta z) + R(\Delta z) \tag{2.1}$$

Investment costs increase linear with Δz, while the risk decreases exponentially with Δz. Therefore, an optimum level exists where total costs are minimal. This is also visualized with the example in Figure 2.1.

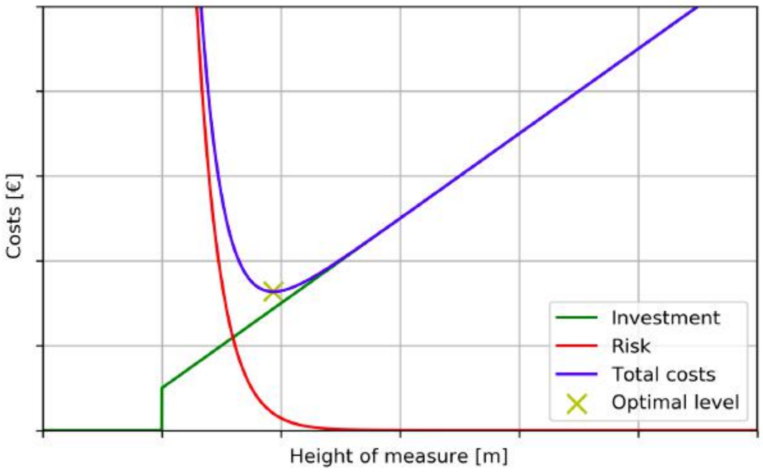


Figure 2.1: Example of the cost-benefit analysis for flood risk. The green line indicates the investment costs, starting with some initial cost and increasing linear with the height of the measure. The red line indicates the risk after the measure is implemented. When the height of the measure is small, the risk will be high. The risk decreases rapidly for increasing measures. The total costs is a summation of the risk and investment costs. This graph is based on the original cost-benefit analysis in flood risk by van Dantzig [1956].

The following statements on risk, investment and total costs can be made:

When Δz is small:

$$R >> I$$

$$TC \approx R$$

When Δz is large:

$$R << I$$

$$TC \approx I$$

When plotting risk, investment and total cost, the optimum level of flood protection can graphically be determined. However, this point can also be determined mathematically. This is the case when:

$$\frac{\delta TC}{\delta h} = 0$$

When the residual risk is already low, the investment costs will be higher than the reduction in residual risk will give. When this is the case, the assets are already protected enough (according to the CBA) and no action is required. The efficiency of a measure could also be expressed by a benefit-cost ratio. This means:

$$\frac{Benefits}{costs} = ratio \tag{2.2}$$

If ratio ≤ 1, the costs (investment) are not worth the benefits (reduction of risk). When ratio > 1, the benefits are worth the costs. One should strive to reach a ratio that is as high as possible. A ratio that is close to 1 (like 1.1) will need additional research or reasoning to justify the investment.

Recent studies on cost-benefit analysis

Lendering [2018] made a model for economic optimizations based on Van Dantzig's theory. With this model the existing methods are expanded. His model uses an analytical approach, for which he derived analytical formula's to calculate the risk for floods. With his model he looked into the parameters with influence, especially which parameters determine what measure (land fill or dike) to use. This research builds further on the work of Lendering. His formulas for risk are used and applied to realistic cases. The derived formulas can be found in Section 2.2.7.

Structure

The structure of this Section is as follows. First, the principles of the proposed risk-framework is given. This proposed risk-framework is based on a cost-benefit analysis with $\frac{benefit}{cost} - ratio$. Next, the different components are discussed step-by-step. This is visualized with the diagram in Figure 2.2.

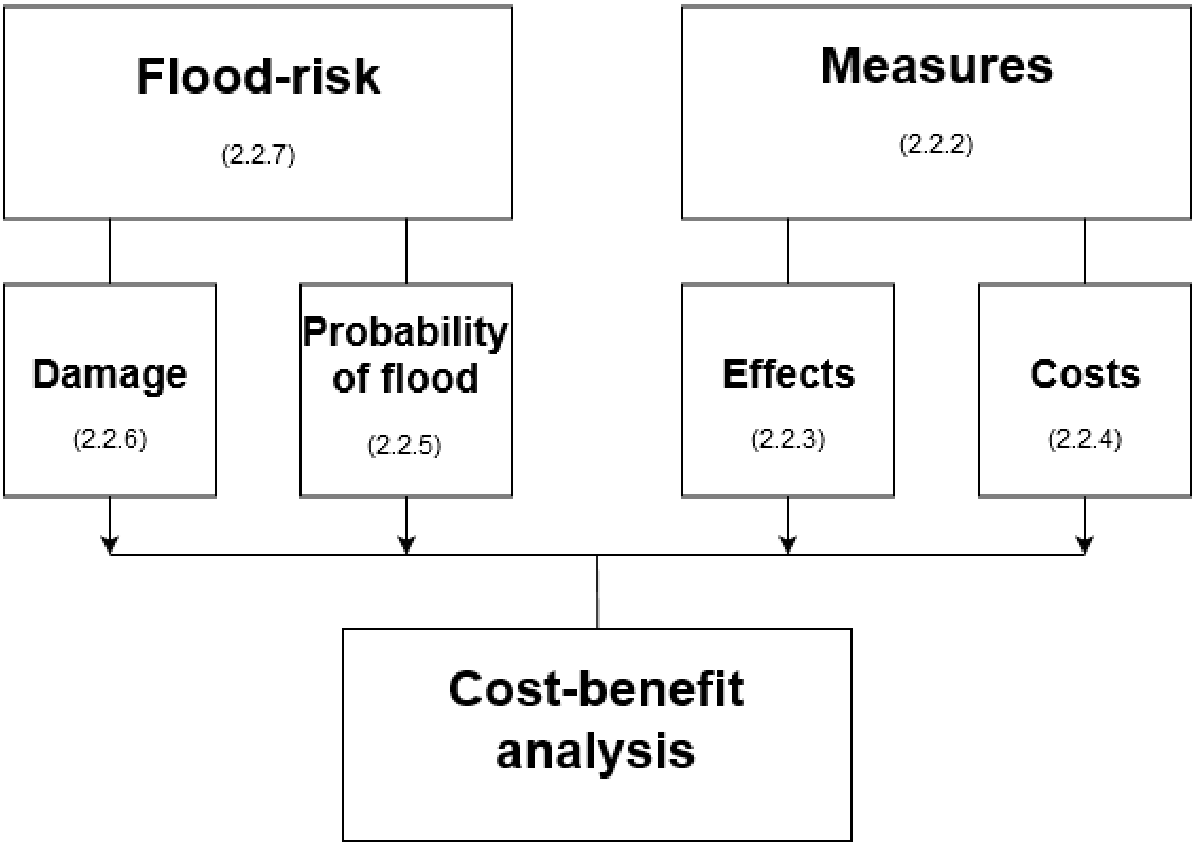


Figure 2.2: Structure of this section.

2.2.1. Proposed risk framework

A short introduction has been given into a cost-benefit analysis to determine the economic optimum for investing in flood defences. In this introduction it is assumed one needs to invest now. However, postponing an investment could be profitable. Due to the devaluation of money, € 1 in 2015 is more valuable than € 1 in 2030. This is simulated with a discount rate. Besides the decreasing value of money, uncertainties could make it profitable to postpone an investment. Different scenarios for climate change increase the uncertainties in sea level rise. Investments for a sea level rise of 1 m turn out to be a waste of money if the sea only rises 0,5 m. However, postponing the investment could also mean exposing the land to an undesired risk.

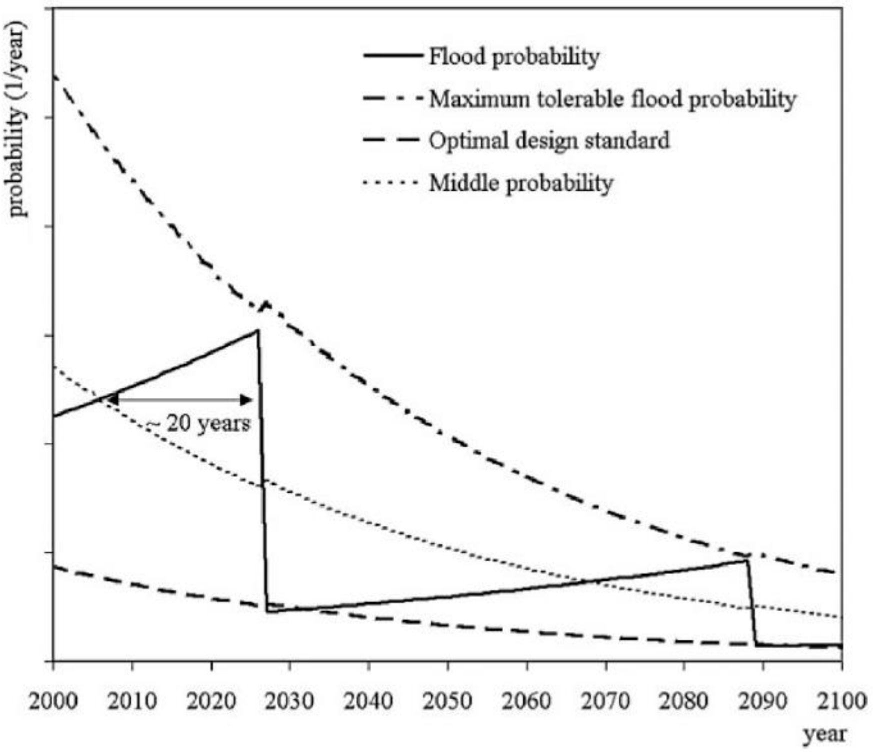


Figure 2.3: Plot of the method as described by Kind [2014]. The solid line shows the flood probability. As one can see, this increases over time. The sudden decrease in the flood probability is an investment in flood defences. The optimal design standard is the level of flood safety that is constructed. Source: Kind [2014]

Therefore, the proposed risk-framework describes a cost-benefit analysis that determines the height of investment and moment of investment. The basis for this method lies in the theory as described by Eigenraam [2006] and Kind [2014]. Figure 2.3 shows the model of Kind. In this model, the flood probability is shown with a solid black line. This probability increases. There are also lines for the maximum tolerable flood probability, the optimal design standard and the middle probability. When the flood probability crosses the line of the middle probability, this should be an indicator to start making plans for investing in flood safety. Kinds model is designed for dikes managed by the government. According to Kind, 20 years is necessary for all phases from planning to construction. Note that this method is mainly used for large dike projects that involve different planning stages by the government. It is assumed that smaller projects commissioned by companies could be executed faster.

After the middle probability is crossed, the flood probability still increases up to just beneath the maximum tolerable flood probability. On that moment, an investment is done an the flood probability decreases in one step to level of the optimal design standard. This is one investment cycle. The investment cycle is repeated when the flood probability is crossing the middle probability again.

The investment and its moment is determined by economic optimization. Although the approach is the same, a more simplified and schematized method is used than Kind and Eijgenraam did. This makes this method easier to use. With the method as described by Kind it is possible to use multiple, different dike sections and therefore more complex calculations (Kind [2014]). However, this is not necessary for the purpose of the risk-framework that only shows a rough, first estimate. Risk and investment can be described in terms of monetary value. The discounted value of risk and investment are integrated over time. The risk consists of two parts: before the investment and after the investment. The investment changes the level of risk. The investment is done once. The total cost is the sum of the integrated risk and investment. The combination of Δz and t^* that leads to the lowest total cost, is the optimum. The method is described by the following formula:

$$TC = \int_{t=t_0}^{t=t*} R_0 \times e^{-(r \times t)} dt + I(\Delta z) \times e^{-(r \times t*)} + \int_{t=t*}^{t=t_1} R_1(\Delta z) \times e^{-(r \times t)} dt \tag{2.3}$$

In this formula the total cost (TC) consists of the risk before the measure (R_0), the investment cost of the measure itself (I) and costs of the risk after the measure (R_1). The measure will be executed in year t*. By multiplying all factors by $e^{-(r \times t)}$, the net present value (NPV) is gain. The total NPV of the risk before and after the investment is gain by integrating the risk over the time. The risk before the measure needs to be integrated from now (t_0) to moment of the measure ($t*$), the risk after the measure needs to be integrated from the moment of the measure ($t*$) to the end of the period (t_1), or to $t = \infty$.

2.2.2. Measures

There are different ways to reduce the risk of floods. Preventative measures can reduce the probability of a flood. Adaptive and emergency measures reduce the damage in case of a flood. In this research, three different measures are used. These measures are a dike (preventive), land fill (adaptive) and flood proofing (adaptive). This should give an insight into the effects of common methods to reduce flood risk. Comparing more measures with each other is behind the scope of this work. Here, a short introduction is given into the different measures. Later, the effectiveness and costs will be discussed (Section 2.2.3 and Section 2.2.4) and how the calculated risk changes per measure (Section 2.2.7).

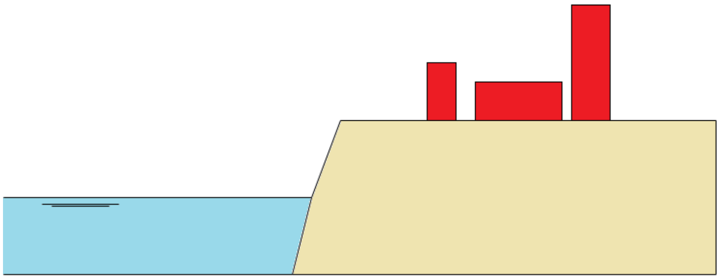


Figure 2.4: Base scenario. The assets (red) are located on the land (yellow) with the water (blue) in front of the coast.

Dike (preventive measure)
A dike is a surrounding preventive structure. The purpose of a dike is to keep the water out, even if the water level outside the dike is higher than the ground level inside the dike.
Dikes can increase the flood safety with surrounding an area, pier or company. The dike costs increase by the length of the circumference (m), the benefits increase by the area (m^2). Therefore, the dike gets more cost efficient for areas where the area is relative large compared with the circumference. With shapes like squares and circles this is the case. The other way around long, stretched rectangular are are less cost efficient. A dike only lowers the probability of a flood. Only failure due to overflow is taken into account. When a flood does occur ($h > h_{dike}$), it is assumed the damage will be the same as without a dike. A dike could be constructed around existing buildings. A dike is only effective when fully constructed. A schematized view of a dike can be seen in Figure 2.5.

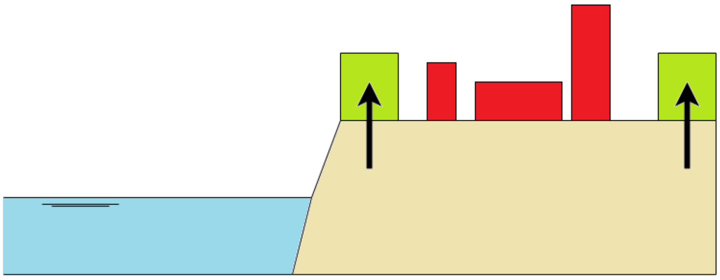


Figure 2.5: Dike. The assets (red) are located on the land (yellow) behind the dikes (green) with the water (blue) in front of the coast.

Land fill (adaptive measure)
The land fill raises the complete area. A land fill reduces the probability of flooding. This measure also reduces the damage because the water depth on the land will be lower than before a land fill (in case of a flood). Therefore, a land fill is an extremely effective measure against flooding. However, raising all land requires very much sand and is expensive. The price of a land fill increases with the area to protect (m^2). This means there is no scale advantage possible as with the dike. Implementing a fill on an existing company is difficult. This could be done by raising critical assets. In Figure 2.6 a schematized view of a land fill is shown.

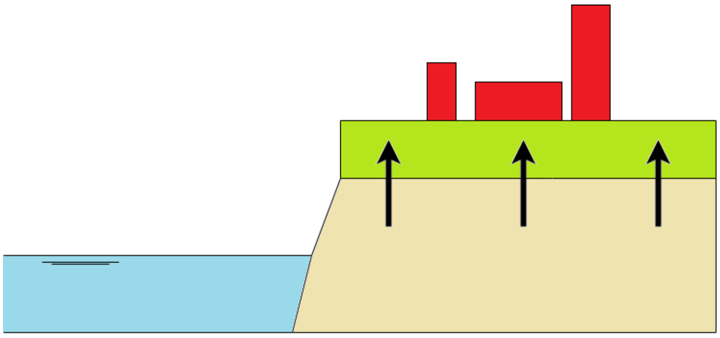


Figure 2.6: Land fill. The assets (red) are located on a land fill (green) on top of the original land (yellow) with the water (blue) in front of the coast.

Flood proofing (adaptive measure)
Flood proofing is a collection of different (smaller) measures against floods. These can be divided in dry proofing and wet proofing. With dry proofing valves or panels are installed around buildings to keep the water out. This way the area can be flooded, but the buildings remain dry. Wet proofing is making a building and its installation water proof. An example of wet proofing is raising power sockets and machines above the (accepted) inundation level. The costs of flood proofing are based on rough estimates by RHDHV (van de Visch and Bos [2018]). It is assumed flood proofing will be cheaper than a land fill and initial costs will be zero. Flood proofing is only effective up to 1 m. In Figure 2.7 a schematized view of flood proofing is shown.

Flood proofing is a relatively cheap way to reduce the effects of floods. However, the probability of floods is still the same. The direct damage decreases a lot, but indirect damage decreases only slightly.

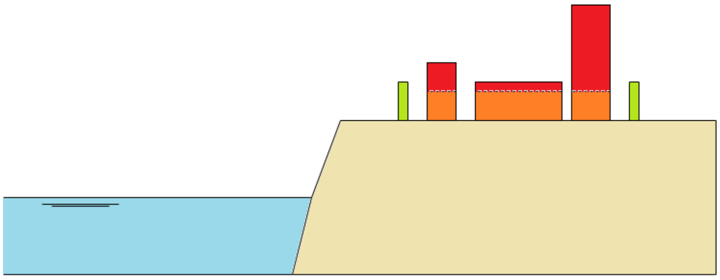


Figure 2.7: Flood proofing. The assets (red) are located on the original land (yellow). Around the assets flood panels are installed (green) and/or the assets are wet proof (orange). The water (blue) is in front of the coast.

2.2.3. Effectiveness of measures

This sections elaborates on the way the measures effect the risk. First, a small explanation on these effects will be given. Next, in Table 2.1 an overview will be given. Lastly, with Figure 2.8 the effect on the water level - damage curve will be shown.

The criteria that are used to show the effect of the measures are the probability of flood (P_f), direct damage (D_{Direct}) and indirect damage ($D_{Indirect}$). Effectiveness for the criterion probability of flood is reached by lowering the probability a certain area is flooded. Here, this means the surface gets higher. This is done by the measures dike and land fill. Although with flood proofing valves are installed to keep the water away from certain assets, the rest of the land is still allowed to be flooded. Therefore, flood proofing does not result in a decrease of probability of flood. Direct damage means the amount of damage a certain water depth causes. For example, this could be damage to structures or stored goods. Indirect damage is the amount of damage that results from discontinuities in the production line. This could also happen to companies that are not flooded: if the supplier is flooded and unable to produce the goods you ordered, your company will not be able to produce. The dike does not protect the assets from direct or indirect damage: once the water reaches a water level higher than the dike, the dike will be breached and the water level in and outside the dike will be the same. If this happens, the dike is unable to prevent any damage or reduction of damage compared to the original situation without a dike. When the water reaches a water level higher than the level of the land fill, only a small amount of water will be on the land. Because all assets are placed higher than the original situation, the water level damaging the assets is lower than it would have been in case of a land fill. This could be seen as a reduction of damage. Flood proofing only reduces the amount of damage. Direct damage will be reduced up to 90 %. It is expected there still will be some damage due to the water on the land. Indirect damage is reduced only slightly: the startup time of a facility after a flood will be lower, but will still take more time compared with a situation no water was allowed on the land. This is all based on previous estimations done by RHDHV.

Effectiveness of measures	Dike (D)	Land fill (LF)	Flood proofing (FP)
-Probability of flood (P_f)	100 %	100 %	0
-Direct damage (D_{Direct})	0	100 %	90 %
-Indirect damage ($D_{Indirect}$)	0	100 %	25%

Table 2.1: Effect of measures. The effectiveness of reducing the probability of flood by 100 %, can be interpreted as: there is no chance of flood up to $z_0 + \Delta z$, i.e. only the overflowing of the new dike or land fill height is the failure mechanism. Source: RHDHV.

To show the effect of the measures on the evolution of the water level vs the damage, Figure 2.8 is shown. First, some properties are summed:

- The ground level of the existing area is at +1 $[m]$
- The sector in this area is the transport industry. The value per $[m^2]$ and the damage function can be found in Table 2.4. This will further be elaborated in Section 2.2.6.

- Flood proofing is applied up to +1 $[m]$ above the ground level.
- The top of the dike is at +1 $[m]$ above the ground level.
- The land fill raises all land to +1 $[m]$ above the original ground level.

In the original situation (black line), damage starts when the water level is > +1 $[m]$. Flood proofing experiences reduced damage. When the water level rises even further, flood proofing is not working anymore. Immediately the same damage is reached as in the original situation. Once the dike is flooded, the damage curve follows the same track again as the original situation. The damage curve for the land fill has moved to the right. At a water level of +2 $[m]$, damage is experienced.

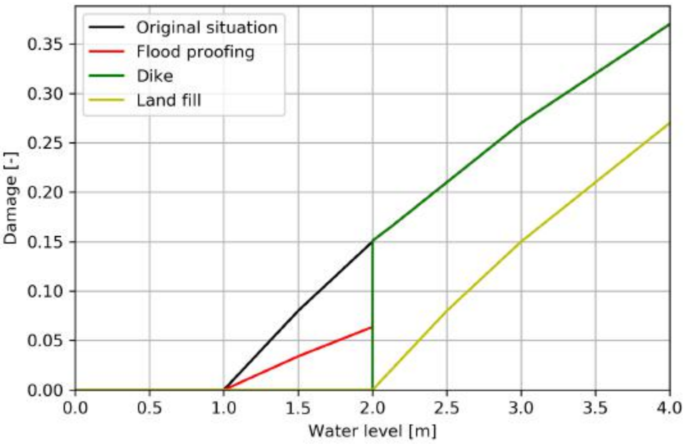


Figure 2.8: Damage - Water level curve. The black line indicates the original situation. The colored lines indicate the effect of the different measures. The damage is given in a factor of the total value. More information on damage can be found in Section 2.2.6.

2.2.4. Costs of measures

As said before, the cost of a land fill and flood proofing depend on the size of the area (A, $[m^2]$). The cost of a dike is dependent on the circumference (L, $[m]$). It is assumed the costs will increase when a measure is applied higher. Because for the construction of dikes and land fills heavy equipment is required, it is assumed these measure will also have some initial costs. For flood proofing these initial costs are expected to be zero ($C_{FP;int} = 0$). This for the fact that flood proofing will be applied on a more local scale.

The costs for the investment are calculated with the following formulas:

$$I_{Dike} = C_{D;\,int} \times L + C_{D;\,var} \times L \times \Delta z \tag{2.4}$$

$$I_{Land\,fill} = C_{LF;\,int} \times A + C_{LF;\,var} \times A \times \Delta z \tag{2.5}$$

$$I_{FP} = C_{FP;\,int} \times A + C_{FP;\,var} \times A \times \Delta z \tag{2.6}$$

From previous studies by RHDHV, it followed the typical price of a dike section is between € 1.000 and € 10.000 per m. The difference is due to the different strength that is required. The force that will applied on the dike is different for a small, extreme water level barrier than a polder dike with water above the hinterland. For a relative small dike (compared to polder dikes), the price is expected to be more in range of € 1.000 per m. Therefore, in this research € 1.000/m/m is used. The initial cost are set to € 400. These initial costs include the planning, permitting and development costs of a dike.

The costs for land fills differs per source. The typical range is between € $15/m^2$ (RHDHV in Mooyaart and Schoemaker [2017]) and € $25/m^2$ (Lendering [2018] and RHDHV in van de Visch and Bos [2018]). Because all are based on rough estimates, it is chosen to use € $20/m^2$ with initial costs of € $10/m^2$. These initial costs are estimated on the use of heavy equipment and the replacement of roads. These initial costs could be much higher when some buildings needs to be rebuild.

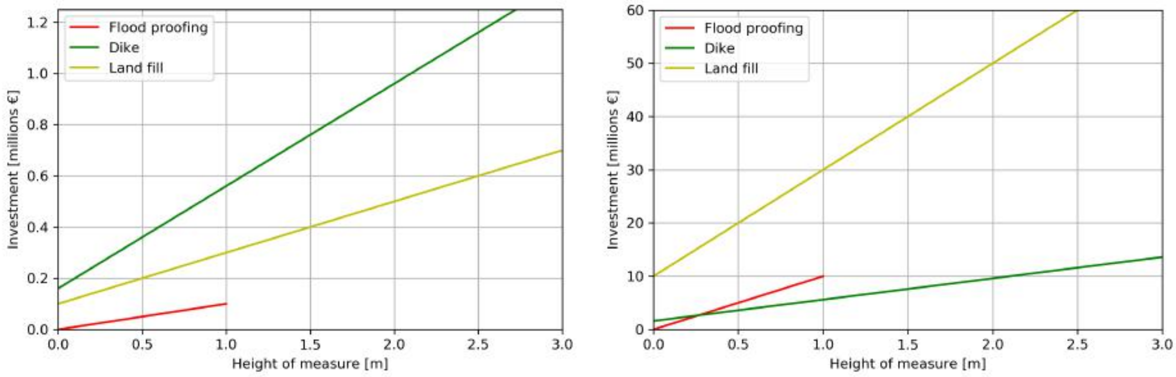
The costs for flood proofing are based on the cost for land fill and previous projects by RHDHV. The investment costs for flood proofing are assumed to be lower than a land fill. They are also assumed to increase linearly with the total area. This might be a rough approach because installing valves around a building will increase with the circumference instead of the area. However, because there are multiple options possible (like wet proofing) and it is not sure to what extend flood proofing could be more efficient for larger areas, the increase is assumed to be linear with the area to protect. The costs are estimated on 10 [€ $/m^2/m$], with a maximum effective height of 1 m (and therefor total cost of 10 [€ $/m^2$]).

In these formulas, the following values should be used:

	Dike (D)	Land fill (LF)	Flood proofing (FP)
Costs:			
-initial ($C_{\#;int}$)	400 [€ $/m$]	10 [€ $/m^2$]	0 [€ $/m^2$]
-variable ($C_{\#;var}$)	1000 [€ $/m/m$]	20 [€ $/m^2/m$]	10 [€ $/m^2/m$]

Table 2.2: Costs of investments against floods

Two simple examples have been used to show the costs for the three measures against flooding:
In the first example, a relatively small area of 10.000 [m^2] has been used. The area is shaped like a square (100 x 100 [m]). The costs of the measures are as shown in Table 2.2. The result of the first example can be seen in Figure 2.9a. Here, the dike is always most expensive, followed by the land fill and the cheapest solution is the flood proofing.
In the second example, a larger area has been taken. This area is also square-shaped (1.000 x 1.000 [m]). The total area is then 1.000.000 [m^2]. Now, the costs are very different. The land fill option is for the larger area much more expensive than the other options. The dike is the cheapest solution.
Concluding from these two examples can be said that the investment costs are dependent on the total area to be protected and the circumference of this area. This is in line with the findings by Lendering [2018] who showed the most efficient measure was largely dependent on the size of the area.



(a) A = 10.000 $[m^2]$, 100 × 100 $[m]$.

(b) A = 1.000.000 $[m^2]$, 1.000 × 1.000 $[m]$.

Figure 2.9: In these two figures the investment costs (in millions €) have been shown for the different measures. In two small examples it has been tried to show the difference in efficiency and to what extend the cheapest solution is dependent on the size of the area.

2.2.5. Probability of flooding

The probability of flooding is the probability of a particular water level will be exceeded. This could be expressed in a probability or in the average return period for this water level. Hydra-NL is a probabilistic model that calculates the probability of extreme water levels along the primary defences of the Netherlands. Hydra-NL is made by Rijkswaterstaat. More information on Hydra-NL can be found on the website of Rijkswaterstaat (Rijkswaterstaat [2019]).

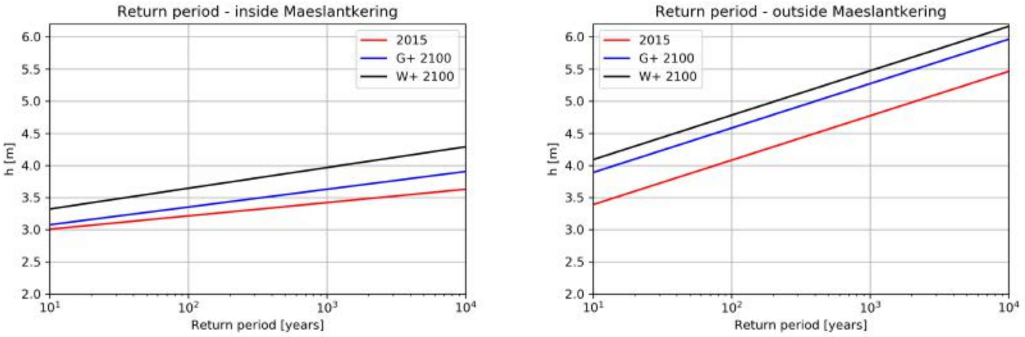
A commonly used type of distribution used for (simplified) characterization of water levels is the exponential distribution. The probability of the water level exceeding h_w is therefore given by:

$$P_f(h_w) = e^{-\frac{h_w - a}{b}} \tag{2.7}$$

In this formula a ($[m]$) is the location parameter, and b ($[m]$) the scale parameter.

As said before, climate change is included in this research. Hydra-NL makes projections for future return periods. For different climate scenarios, the water levels and their return periods are calculated. Parameters a and b are chosen to make the exponential distribution fit. In this research, three different climates are taken into account: climate 2015, G+ climate (moderate climate) and the W+ climate (warm climate). The G+ and W+ climates are predictions, with W+ the warmest climate. Therefore, the W+ climate predicts most sea level rise. The effect due to climate change is visualized in Figure 2.10. These predictions are made by the Dutch Meteorologic Institute (KNMI [2014]).

The Maeslant storm surge barrier is located in the Port of Rotterdam. This storm surge barrier closes when the sea level is expected to be higher than +3 m. Therefore, a distinction has been made for water levels inside and outside the reach of the Maeslant storm surge barrier. Inside the Maeslant-barrier the maximum water level is lower due to possibility of closure. However, due to the probability of failure of closing the Maeslantbarrier the water is able to be higher than +3 m (Figure 2.10). Outside the reach of the Maeslant storm surge barrier water levels are higher. The used values for a and b can be found in Table 2.3.



(a) Inside Maeslant-barrier

(b) Outside Maeslantbarrier

Figure 2.10: Return periods for water levels in the port of Rotterdam. In Figure (a) the water-levels behind the Maeslantbarrier are shown. In Figure (b) the water-levels in other parts of the port are shown. One is able to see the large influence of the storm surge barrier, which closes at h = 3.0 m. Due to the probability of failure of the Maeslantbarrier (1/100), it is still possible to have water levels higher than 3.0 m inside the Maeslantbarrier.

Climate & location	Inside Maeslantbarrier			Outside Maeslantbarrier		
	2015	G+ (2100)	W+ (2100)	2015	G+ (2100)	W+ (2100)
a (location)	2.8	2.8	3.0	2.7	3.2	3.4
b (scale)	0.09	0.12	0.14	0.30	0.30	0.30

Table 2.3: A and B values presenting different the climate prediction (W+, warm and G+, moderate) and location (inside or outside the Maeslantbarrier).

2.2.6. Damage

The damage induced by a flooding is based on Snuverink et al. [2000]. This report estimates damage in case of a flood for different industrial sectors. Damage is based on the economic value of the property in $[€/m^2]$ and a damage factor due to the water level. In Table 2.4, the total economic value per $[m^2]$ and the damage factors for different levels of water are shown. In Figure 2.11 the damage per sector is plotted.

It can be seen that the total economic value differs per sector. Also, the damage factors differ per sector. This can be explained by the different kinds of equipment and how these reacts to water. Although these numbers are based on scientific research, this should merely be used as guidelines since every company will differ from other companies in damage per meter of water on their property. For a more precise result, the damage should be estimated per individual company. This can be done with the relevant stakeholders or business owners.

For simplicity, a linear damage curve is often assumed. In this area a flood of more than 3 meter is very unlikely ($P_f < \frac{1}{10.000} yrs$). Therefore, it should be possible to take a linear damage function between 0 and 3 $[m]$. This should be checked per case to make sure no large differences occur.

Sector	Value	0m	0,5m	1m	1,5m	2m	3m	4m	5m	6m
Bulk terminals	€ 443	0,0	0,06	0,12	0,18	0,24	0,30	0,36	0,37	0,37
Container terminals	€ 696	0,0	0,09	0,18	0,2	0,21	0,33	0,33	0,45	0,45
Distriparks	€ 886	0,0	0,16	0,32	0,43	0,48	0,57	0,59	0,67	0,68
Public utilities	€ 1583	0,0	0,04	0,08	0,11	0,15	0,18	0,20	0,22	0,24
Goods transshipment	€ 886	0,0	0,15	0,30	0,35	0,38	0,55	0,57	0,72	0,74
Transport industry	€ 633	0,0	0,08	0,15	0,21	0,27	0,37	0,43	0,47	0,49
Other industry	€ 633	0,0	0,10	0,18	0,26	0,34	0,46	0,58	0,62	0,65

Table 2.4: In this table the different damage factors on the total economic value are shown. These values are from RHDHV (van Ledden; J van de Visch [2017]) and are modifications on the original report by Tebodin (Snuverink et al. [2000]).

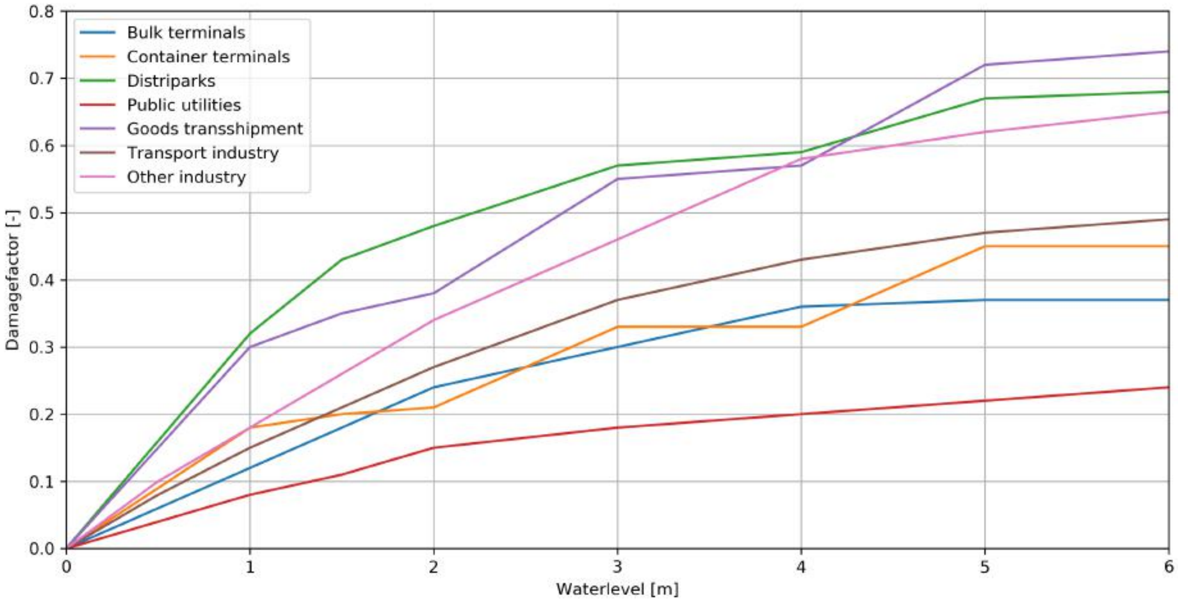


Figure 2.11: Damage curve for the different kinds of industry active in the port of Rotterdam. These values are from RHDHV (van Ledden; J van de Visch [2017]) and are modifications on the original report by Tebodin (Snuverink et al. [2000]).

Indirect damage

The indirect damage is the damage due to unavailability of economic services and other damages that are not directly on assets. This could be the loss of money due to a disruption of the production process. This means indirect damage is possible in areas that are not flood at all, but have an economic relation with flood companies. This makes the indirect damage difficult to assess (Robin Nicolai [2016]).

To assess the indirect damage, one should assume in what way the production process will recover from a flood. The rate of recovery determines the costs of the indirect damage. Convex means a slow recovery and therefore is most expensive. The concave variant is a fast recovery with low indirect damages. The linear form is between those forms. This has been visualized in Figure 2.12.

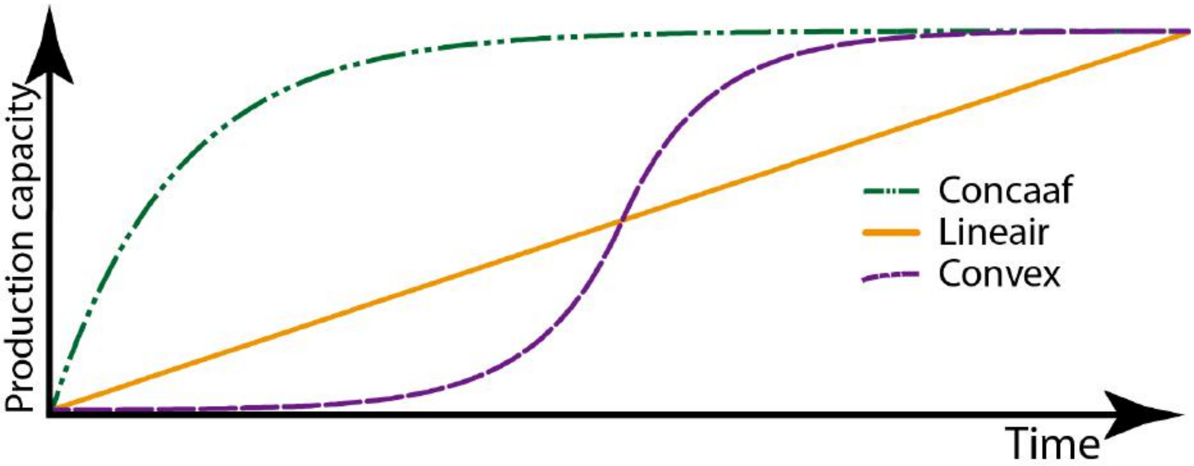


Figure 2.12: The different forms of recovery of the production process. Convex is the slowest and most damaging kind. Concave quickly restores and linear is between both forms. Source: Pilot Waterveiligheid Botlek: Kwantitatieve analyse overstromingsrisico's (Robin Nicolai [2016]).

Determining the rate of recovery of companies is difficult. Not much is known about this subject, and it is unclear recovery of an area will lead to the same companies and production. To determine the indirect damage is therefore extremely difficult and should be approached within certain ranges due to the uncertainties. Determining the indirect damage is beyond the scope of this research, and for simplicity the indirect damage is taken to be the equal to the direct damage. This is done in earlier projects by Mooyaart and Schoemaker [2017] for RHDHV. This means:

$$D_{total} = D_{direct} + D_{indirect}$$

With:

$$D_{direct} = D_{indirect}$$

Thus:

$$D_{total} = 2 \times D_{direct}$$

In the existing risk-framework the indirect damage is assessed as a factor of the direct damage. This is done with the an ARIO-model (Robin Nicolai [2016]) for the Flood safety Botlek case. With low (concave recovery) and high (convex recovery) factors the range of the indirect damage is approached (van de Visch and Bos [2018]).

2.2.7. Calculation of risk

Risk consists of the probability of a flood and the damage due to a flood. In the field of flood risk this is given by the probability the water reaches a particular water level and the induced damage when this water limit is reached. Therefore, the following formula can be applied:

$$R = P_f(h_f) \times D(h_f) \tag{2.8}$$

This formula gives the risk for a particular situation. When integrating this risk over all possible water levels, this gives the cumulative risk. This is also shown with the following formula:

$$R = \int_{h_f = z_t + \Delta z}^{h_f = \infty} D(h_f) \times P_f(h_f) dh_f \tag{2.9}$$

As one can see, the product of probability of exceedance (P_f) and damage (D) should be integrated from $h_f = z_t + \Delta z$ to $h_f = \infty$. Here, the flood level is h_f, the height of the original terrain is z_t and the height of the measure is Δz.

For the different measures as discussed earlier in Section 2.2.2, the cumulative risk after investing is calculated. This is done with Equation 2.10 (dike), 2.11 (land fill) or 2.12 (flood proofing).

R (Total risk after investment):

$$R_D = \frac{A \times I_v \times f_{max}}{d_{max}}\Big(\big(\frac{\Delta z + z_t}{b} - \frac{z_t}{b} + 1\big)e^{-\frac{z_t+\Delta z-a}{b}} - e^{-\frac{z_t+d_{max}-a}{b}}\Big) \tag{2.10}$$

$$R_{LF} = \frac{I_v \times f_{max} \times b}{d_{max}}\Big(e^{-\frac{z_t+\Delta z-a}{b}} - e^{-\frac{z_t+\Delta z+d_{max}-a}{b}}\Big) \tag{2.11}$$

$$R_{FP} = \frac{A \times I_v \times f_{max}}{d_{max}}\Big(e^{-\frac{z_t+\Delta z-a}{b}}\big((\Delta z + b) - FP_{red} + \Delta z + b\big) + b \cdot FP_{red} \cdot e^{-\frac{z_t-a}{b}} - b \cdot e^{-\frac{d_{max}+z_t-a}{b}}\Big) \tag{2.12}$$

In the Table 2.5 the used units and quantities are shown.

Sign	Quantity	Unit
A	Area	$[m^2]$
a	Location parameter	$[m]$
b	Scale parameter	$[m]$
d_{max}	Depth of maximum damage	$[m]$
Δz	Height of measure	$[m]$
f_{max}	Factor of total value that will be lost in case of a flooding	$[-]$
FP_{red}	Flood proofing reduction	$[-]$
I_v	Total value of land	$[€/m^2]$
L_{total}	Circumference	$[m]$
z_t	Height of original land	$[m]$

Table 2.5: Units and quantities used in the risk formulas

Formula 2.10 and 2.11 are from Lendering [2018]. The derivation of 2.12 is based on the derivation for the other formulas. In Appendix C the steps to get to the integrated risk are further elaborated. Here, the different steps are shown with each of their plots to increase visibility of the method. These formulas will be used to determine the optimal level of flood safety.

2.3. Discussion

The newly proposed risk-framework improves the existing risk-framework on several points. First of all, the risk is assessed in a different way. Instead of the incident risk, now the cumulative risk is used. Second, the cost-benefit analysis is a more cost efficient method. The acceptable risk is based on the costs of investments and the reduction of risk. Therefore, this likely more cost efficient than the existing risk-framework (by RHDHV). Next, the approach is objective: in the existing risk-framework the limits had to be chosen on judgement, while in the proposed risk-framework the costs and reduction of risk are compared. Lastly, this new method makes possible measures and their costs directly visible.

However, the existing risk-framework was easy to implement in a company its risk-matrix. With the proposed risk-framework this is more difficult to do. Further, a company could ask for certain limitations that are different from the economic optimum, like a minimum return period for exceeding water levels. Although the proposed risk-framework could be used to calculate the total costs of the requirement for a minimum return period, this is not the main outcome. Lastly, the proposed risk-framework does not make a difference between possible costs (risk) and costs that are sure (investment in flood defence). The investment costs could be spread over a large number of years and therefore payable. The costs of a flood could come all in once at an unexpected moment. This could be a problem for a company.

Note that the risk-framework only looks at the economical risk. Environmental risk and personal risk are both present as well, but earlier assessments by RHDHV has shown the economic risk is most dominant in all comparable cases (see also Chapter 1). However, when one is assessing the risks of floods, one should always check the environmental and personal risk as well.

3

Application of risk-framework

This Chapter discusses the sensitivity of the proposed risk-framework to different parameters. The goal of this chapter is to discover the relative importance of the parameters and their effect on the result. The proposed risk-framework will be analysed with the sensitivity analysis.
The sensitivity on the following aspects is analysed:

Aspect	**Parameters**	**Extra**
Measures	I & $R_{residual}$	Dike, land fill or flood proofing
Size	A, L_{total}	Size of the area to protect
Climate	a, b	G+ and W+ scenario
Location	a, b	In- or outside Measlantbarrier
Sector	d_{max}, f_{max}, I_v	Value and damage-curve
Shape	A, L_{total}	Shape of the land
Economic prospect	r	Discount rate could change
Ground level	z_t	Determines current flood risk
Investment costs	C_D, C_{LF}, C_{FP}	Determines the investment curve
Indirect damage	D_{total}	Factor for indirect damage

Table 3.1: Different properties in sensitivity analyses

First, a base case will be determined to show the order of magnitude. Next, each parameter or aspect will be analysed individually.

3.1. Base case

For the base case, the following is applied:

- The used measure is a dike.
- The location is outside the Maeslantbarrier and a W+ climate prediction is assumed (Section 2.2.5).
- The sector is transport industry (Table 2.4).
- The shape is rectangular, 500 x 300 m.
- The discount rate is, due to the economic prospect, 3.6 %
- The original terrain height is 4.2 m (+NAP).
- The costs of investment are the same as proposed in Section 2.2.4 and Table 2.2.
- Indirect damage are the same as direct damage:
  $D_{ind} = D_{dir}$ and $D_{tot} = D_{ind} + D_{dir} = 2xD_{dir}$.

For the base case, the following results are gain:

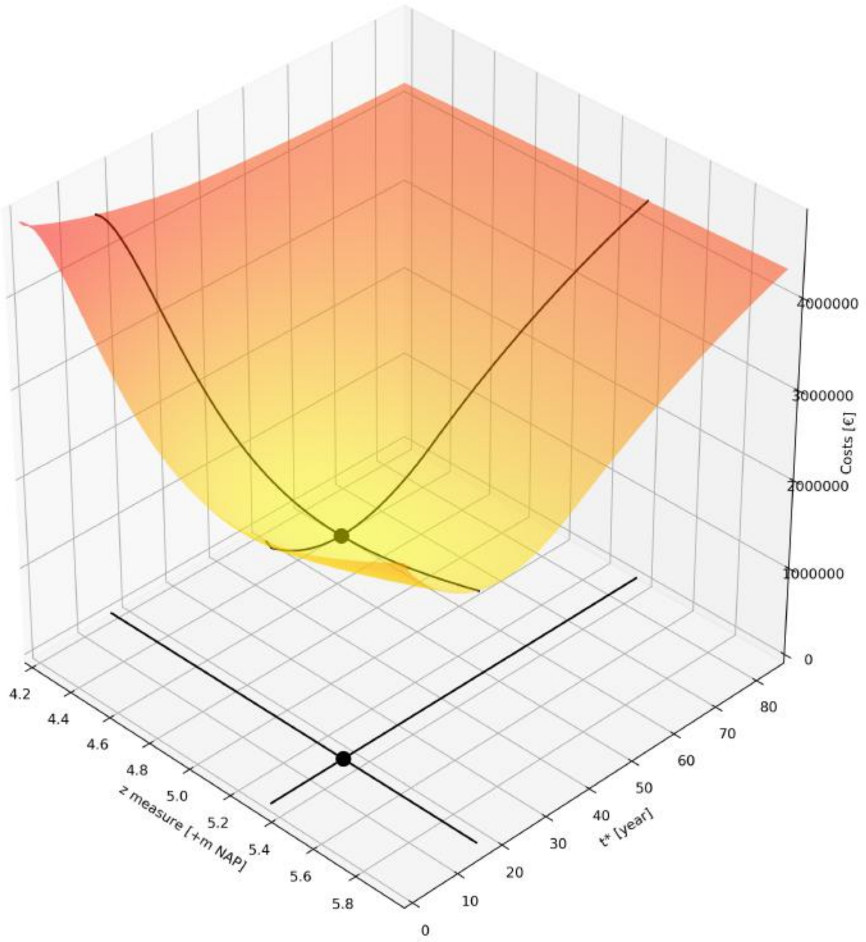
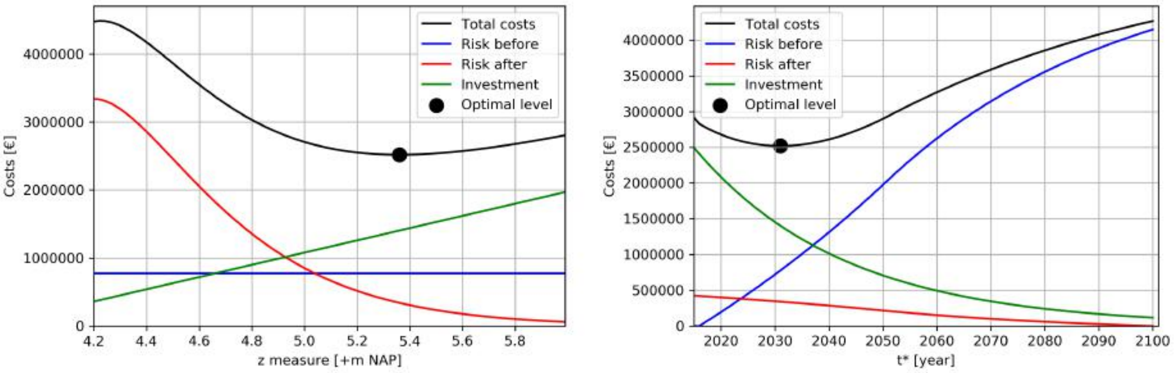


Figure 3.1: 3D plot of base case. On the three axes the height of investment, moment of investment and the total costs are shown. The optimal combination is indicated by a point. Through this point, two lines are drawn. These cross-sections are further elaborated in Figure 3.2



(a) Cross-section for t* = 16 year

(b) Cross-section for Δ_z = 5,36 m

Figure 3.2: Cross-sections through the optimal combination in the 3D plot of Figure 3.1. With both plots also the development of the different components can be seen. Note: t* is the moment of investing, so this plot does not show how the risk develops over the time.

As one can see from the plots, the investment could best be postponed until 2031. At that moment, a dike reaching up to +5,36 m NAP should be constructed.

The 3D plot (Figure 3.1) shows all combinations of t* and Δz. One is able to see the development of the total cost for a postponed investment or higher dike.

In the left plot of Figure 3.2, the moment of investing is constant and only the height of the investment is changing from 4,2 m to 6 m. As one can see, constructing a dike that is too low results in a residual risk that is still high after installing the dike. Vise versa, a dike that is higher than +5,36 m NAP results in higher investment costs than the reduction of risk. The blue line, the risk before investing, stays constant because this is independent of the amount of investing.

In the right plot of Figure 3.2, the height of investing is constant (+5,36 m NAP) but the moment of investing is varying. The costs of investing (green line) decreases due to the devaluation of money (discount rate). The risk before the investment (blue line) increases. This is due to the fact that the rising sea level increases the risk and the assets are exposed over a longer period of time. The residual risk (red line) decreases for postponing the investment. This is due to the fact the net present value of the risk is decreasing for postponed exposure (devaluation of money) and the amount of years the risk is calculated over decreases.

All results are summarized in Table 3.2. The total cost and its components are given: R_1 (risk before measure), I (investment cost) and R_2 (residual risk). Also, the $\frac{Benefit}{Costs}$-ratio is given. Further, in the table the optimal Δz with respect to the original terrain level and with respect to the local reference level (here: NAP) is given. The return period for exceeding water levels is shown. This return period is given for the W+ climate prediction on three different moments: 2015, 2050 and 2100. One can see the return period decreases over the time; the return period for water levels of +5.36 m NAP is 7092 yrs in 2015, while only 688 yrs in 2100. This is due to climate change. Lastly, the table shows the optimal moment of investing by t*.

Sensitivity analysis	base case
TC (Total costs)	€ $2.52x10^6$
R_1 (Risk before)	€ $0.78x10^6$
I (Investment)	€ $1.40x10^6$
R_2 (Residual risk)	€ $0.34x10^6$
$\frac{Benefit}{Cost}$-ratio	2.2
Δz	1.16 m
	5.36 m
Return period (2015)	7092 yrs
Return period (2050)	1339 yrs
Return period (2100)	688 yrs
$t*$	16 yrs
	2031

Table 3.2: Results of the base case.

The base case shows how the model could be used for a case. Only a few parameters are needed to know. The model could be used for a variety of applications. First of all, companies that are already active in the area could use the model to see how exposed they are to flood risk and how this develops in the future due to climate change. Second, companies could use the tool when determining the lifetime of a factory and to what extend renovation works are necessary. Lastly, companies that are planning to settle in the Port of Rotterdam could also quickly see what the expected expenses are due to flood risk when settling here. There might be more possibilities to use the model, but these applications as mentioned above will be the most common.

3.2. Sensitivity analysis

For each criterion, the sensitivity of the model is investigated one by one. First is explained why this criterion is important and what the expected influence is. Next, scenarios are set up that should show the influence of the criterion. The input is summed in a table.

The output of the scenarios per criterion is discussed and shown by a table. The 3D plots of the total costs for different levels of Δz and t* are given for all scenarios in Appendix E.

3.2.1. Measures & size

For these criteria, the sensitivity analysis is made in two steps. First, for a large terrain (500 x 300 m) the different measures are compared. Next, the same comparison is made for a small terrain (50 x 30 m). The measures that are compared for the small and large terrain are the dike, land fill and flood proofing.

It can be seen that for the large terrain the dike is the cheapest solution (Table 3.4). Flood proofing is the most expensive measure. The benefit-cost ratio is also highest for the dike and the highest levels of safety (return periods) are realised. The return periods for the land fill are low, but the damage in case of a flood will also be lower than for the other measures (more on the effectiveness of measures in Section 2.2.6). The return periods for flood proofing are calculated for water levels exceeding the top of the flood proofing. However, because with flood proofing it is accepted to have some smaller floods with reduced damage, this is less comparable with the land fill and the dike. The return periods for accepted floods in case of a flood proofing are 148 yrs in 2015, 28 yrs in 2050 and 14 yrs in 2100. The return periods given in Table 3.4 are for water levels exceeding the top of the flood proofing (+5.08 m NAP). With an accepted flood there will still be damage, although less than without flood proofing. This explains the high residual risk after applying flood proofing. The investment costs are lowest for the flood proofing.

The results are different for the smaller terrain. The dike is not cost efficient, as one can see by the optimal dike height ($\Delta z = 0m$). The measures land fill and flood proofing are not subjective to size differences; the total cost is 100 times smaller, just like the size of the terrain. All other results, Δz, $\frac{Benefit}{Cost}$-ratio, return period and t* are the same for the small area as for the large area.

Sector	Dike	Land fill	Flood proofing
TC (Total costs)	€ 2.52$x10^6$	€ 3.02$x10^6$	€ 3.70$x10^6$
R_1 (Risk before)	€ 0.78$x10^6$	€ 1.44$x10^6$	€ 1.25$x10^6$
I (Investment)	€ 1.40$x10^6$	€ 1.19$x10^6$	€ 0.56$x10^6$
R_2 (Residual risk)	€ 0.34$x10^6$	€ 0.40$x10^6$	€ 1.90$x10^6$
$\frac{Benefit}{Cost}$-ratio	2.2	1.8	1.8
Δz	1.16 m	0.60 m	0.88 m
	+5.36 m NAP	+4.80 m NAP	+5.08 m NAP
Return period (2015)	7092 yrs	1097 yrs	2789 yrs
Return period (2050)	1339 yrs	207 yrs	527 yrs
Return period (2100)	688 yrs	106 yrs	270 yrs
$t*$	16 yrs	23 yrs	24 yrs
	2031	2038	2039

Table 3.3: Results of the sensitivity analysis on the different measures for large terrains.

Sector	Dike	Land fill	Flood proofing
TC (Total costs)	€ 0.041$x10^6$	€ 0.030$x10^6$	€ 0.037$x10^6$
R_1 (Risk before)	€ 0.041$x10^6$	€ 0.012$x10^6$	€ 0.012$x10^6$
I (Investment)	€ 0	€ 0.014$x10^6$	€ 0.006$x10^6$
R_2 (Residual risk)	€ 0	€ 0.040$x10^6$	€ 0.019$x10^6$
$\frac{Benefit}{Cost}$-ratio	-	1.8	1.8
Δz	-	0.60 m	0.88 m
	+4.2 m NAP	+4.80 m NAP	+5.08 m NAP
Return period (2015)	148 yrs	1097 yrs	2789 yrs
Return period (2050)	28 yrs	207 yrs	527 yrs
Return period (2100)	14 yrs	106 yrs	270 yrs
$t*$	-	23 yrs	24 yrs
	-	2038	2039

Table 3.4: Results of the sensitivity analysis on the different measures for small terrains.

3.2.2. Climate & location

As described earlier in Section 2.2.5, the probability of exceedance of different water levels is determined by the climate prediction (G+ climate or W+ climate) and the location (inside or outside the Maeslantbarrier). The return periods of different extreme water levels can be seen in Figure 2.10. Both determine the a (location) and b (scale) parameters in the formula for the probability of exceedance. Therefore, the sensitivity to those parameters is tested in the same simulation. This leads to four scenarios:

Climate & location	Inside Maeslantbarrier			Outside Maeslantbarrier		
	2015	G+ (2100)	W+ (2100)	2015	G+ (2100)	W+ (2100)
a (location)	2.8	2.8	3.0	2.7	3.2	3.4
b (scale)	0.09	0.12	0.14	0.30	0.30	0.30

Table 3.5: Input values for the sensitivity analysis on climate and location.

The height of the original terrain is very determining for the outcome of the risk-framework. In the Port of Rotterdam there is a large difference in the height of the original terrain between in- and outside the Maeslantbarrier. For outside the Maeslantbarrier, the original terrain height is chosen to be the same as in the base case: 4.2 m +NAP. For inside the Maeslantbarrier, most of the terrain is lower. There has been chosen for a terrain height of 3.2 m +NAP. The effect of the different terrain heights will be further investigated in Section 3.2.6. The results of the model can be found in Table 3.6.

Climate & location:	Inside Maeslantbarrier		Outside Maeslantbarrier	
	G+	W+	G+	W+
TC (Total costs)	€ 1.00$x10^6$	€ 1.41$x10^6$	€ 2.18$x10^6$	€ 2.52$x10^6$
R_1 (Risk before)	€ 1.00$x10^6$	€ 0.49$x10^6$	€ 0.91$x10^6$	€ 0.78$x10^6$
I (Investment)	€ 0	€ 0.79$x10^6$	€ 1.00$x10^6$	€ 1.40$x10^6$
R_2 (Residual risk)	€ 0	€ 0.13$x10^6$	€ 0.27$x10^6$	€ 0.34$x10^6$
$\frac{Benefit}{Cost}$-ratio	-	2.6	1.4	2.2
Δz	-	0.58 m	0.95 m	1.16 m
	-	+3.78 m NAP	+5.15 m NAP	+5.36 m NAP
Return period (2015)	471 yrs	4379 yrs	3512 yrs	7092 yrs
Return period (2050)	285 yrs	2029 yrs	1295 yrs	1339 yrs
Return period (2100)	218 yrs	940 yrs	665 yrs	688 yrs
$t*$	-	19 yrs	24 yrs	16 yrs
	-	2034	2039	2031

Table 3.6: Results of sensitivity analysis on climate and location.

The W+ scenarios both result in higher costs than the G+ scenario. This could be explained by the fact that a warmer climate means the probability of extreme water levels increase. For the G+ scenario inside the Measlantbarrier it is not cost efficient to build a dike. For all other scenarios it is best to postpone the investment. For the W+ scenarios this is 16-19 yrs, for the G+ scenario outside the Measlantbarrier the investment could best be postponed up to 28 yrs. The benefit-cost ratio is higher for the W+ scenarios: the reduction in risk is higher for the W+ climates than for the G+ climates. The W+ climates have a larger decrease of return periods than the G+ climates. Again, this could be explained by the fact that extreme water levels will occur more often in the warmer climate scenario.

3.2.3. Sector

The sector determines the value of the land (I_v) and the damage factor (d_{max} and f_{max}). For this criterion, two scenarios are made. Both scenarios are the base case but with a different sector. In the first scenario, a bulk terminal is used as sector. In the second scenario, a distripark is used. These two sectors are chosen due to the difference in land value and damage factor. In case of a flood of 2 m, the bulk terminal will suffer € 106 damage$/m^2$. The same flood will induce € 425 damage$/m^2$ to a distripark. This difference in flood damage will lead to a different optimal level of flood safety. The hypothesis is the optimal level of flood safety will be higher for a distripark than for a bulk terminal. The used input values can be found in Table 3.7.

Sector	Bulk terminals	Distriparks
d_{max}	2 m	2 m
f_{max}	0.24	0.48
I_v	€ 443/m^2	€ 886/m^2

Table 3.7: Sensitivity analysis on sector.

The result of the sensitivity analysis on sectors can be found in Table 3.8. Due to the difference in value (€ /m^2) of the two sectors, the optimal level of safety differs a lot. This could be seen from the optimal measure height, Δz, and the return period. One can see the return period is around 3.4 times higher for Distriparks than for Bulk terminals. The moment of investing for Distriparks is now, for Bulk terminals the investment can still be postponed by 23 years.

For the Distriparks, this means R_1 (risk before measure) is zero. The time before the investment is zero and therefore also the integrated risk over this time. However, because one should invest now, the investment costs can not be postponed and are also high. Component R_2 (residual risk) is also relatively high (compared with the bulk terminal). This is due to the fact that the time after investing is long; 85 years. The bulk terminal accepts more risk and it is therefore acceptable to postpone the investment to 2038. This reduces the costs of the investment. The benefit-cost ratio is higher for the Distripark. This is mainly due to the fact more risk is reduced.

Sector	Bulk terminals	Distriparks
TC (Total costs)	€ $2.09x10^6$	€ $3.38x10^6$
R_1 (Risk before)	€ $0.81x10^6$	€ 0
I (Investment)	€ $1.01x10^6$	€ $2.81x10^6$
R_2 (Residual risk)	€ $0.27x10^6$	€ $0.57x10^6$
$\frac{Benefit}{Cost}$-ratio	1.7	3.8
Δz	1.05 m	1.42m
	+5.25 m NAP	+5.62 m NAP
Return period (2015)	4915 yrs	16871 yrs
Return period (2050)	928 yrs	3186 yrs
Return period (2100)	477 yrs	1636 yrs
$t*$	23 yrs	0 yrs
	2038	2016

Table 3.8: Results of the sensitivity analysis on sector.

3.2.4. Shape

By comparing two shapes, possible scale advantages of the dike are further investigated. Two relatively large areas with different circumferences are compared for constructing a dike. The selected shapes are 400 x 500 m (more square-shaped) and 1000 x 200 m (more rectangular-shaped). It is expected that the square-shaped area will result in a higher optimal level of flood safety than the rectangular-shaped area because the investment costs are lower (due to a smaller circumference).

Shape	D: # 1	D: # 2
L_1	400 m	1000 m
L_2	500 m	200 m
L_{total}	1800 m	2400 m
A	200 000 m^2	200 000 m^2

Table 3.9: Sensitivity analysis on shape.

In Table 3.10 the results of the analysis on shapes can be found. Although the same amount of m^2 is protected, the total cost for shape # 2 is much higher. As explained before, this is due to the larger circumference that increase investment cost. When the investment costs to increase the level of safety are higher, more exposure to risk is justified.

The return periods of storms with water levels that exceed the height of the dike are for both measure in the same order of magnitude, although slightly larger for shape # 1. The construction of the dike for # 2 is later than the dike of # 1.

Shape	D: # 1	D: # 2
TC (Total costs)	€ $3.04x10^6$	€ $3.58x10^6$
R_1 (Risk before)	€ $0.81x10^6$	€ $1.19x10^6$
I (Investment)	€ $1.81x10^6$	€ $1.92x10^6$
R_2 (Residual risk)	€ $0.42x10^6$	€ $0.47x10^6$
$\frac{Benefit}{Cost}$-ratio	2.4	2.0
Δz	1.21 m	1.13 m
	+5.41 m NAP	+5.33 m NAP
Return period (2015)	8378 yrs	6417 yrs
Return period (2050)	1582 yrs	1212 yrs
Return period (2100)	812 yrs	622 yrs
$t*$	13 yrs	18 yrs
	2028	2033

Table 3.10: Results of the sensitivity analysis on shape.

3.2.5. Economic prospect

With implementing the time in the model, a prediction needs to be made about the present value of money in 2100. How much will € 1 today, be worth in the year 2100? This is calculated with the discount rate (r).

The difference in value will be determined by the economic growth between now and 2100 and the interest rate of risk. For a cost-benefit analysis, the interest rate should be 2.5 % with a risk raise of 3 %. The economic growth, according to the Trans-Atlantic market scenario, is 1.9 % and should be subtracted from the interest rate for risk. This means: $2.5\% + 3\% - 1.9\% = 3.6\%$ (from: RHDHV, Mooyaart and Schoemaker [2017]).

The sensitivity to the discount rate is tested with three different values. A low discount rate of 2.5 %, the base case of 3.6 % and a high discount rate of 5 % (Table 3.11). Note: high economic growth results in a low discount rate and vise versa.

Economic prospect	High	Base	Low
Economic growth	3.0 %	1.9 %	0.5 %
r	2.5 %	3.6 %	5 %

Table 3.11: Sensitivity analysis on economic prospect

The results of the model runs can be found in Table 3.12. What can be seen, is that the net present value of the total cost is high for a low discount rate and decreases for an increasing discount rate. Looking at the components of the total cost, the costs due to risk before the investment increase for a higher discount rate, while the investment and residual risk decrease. This can be explained by the fact that a high discount rate makes it more profitable to postpone an investment. With postponing the investment, the time before the investment increases and therefore the costs of the risk before the investment. Similarly, the residual risk decreases. Also, a higher discount rate leads to a lower optimal level of safety and lower return periods of exceeding water levels.

Economic prospect	High	Base	Low
TC (Total costs)	€ 3.00$x10^6$	€ 2.52$x10^6$	€ 1.96$x10^6$
R_1 (Risk before)	€ 0.42$x10^6$	€ 0.78$x10^6$	€ 0.97$x10^6$
I (Investment)	€ 2.12$x10^6$	€ 1.40$x10^6$	€ 0.78$x10^6$
R_2 (Residual risk)	€ 0.47$x10^6$	€ 0.34$x10^6$	€ 0.20$x10^6$
$\frac{Benefit}{Cost}$-ratio	2.6	2.2	1.8
Δz	1.26 m	1.16 m	1.07 m
	+5.46 m NAP	+5.36 m NAP	+5.27 m NAP
Return period (2015)	9897 yrs	7092 yrs	5254 yrs
Return period (2050)	1869 yrs	1339 yrs	992 yrs
Return period (2100)	960 yrs	688 yrs	509 yrs
$t*$	9 yrs	16 yrs	22 yrs
	2024	2031	2037

Table 3.12: Results of the sensitivity analysis on economic prospect.

3.2.6. Ground level

The ground level differs for different areas in the Port of Rotterdam. As in the base case, only areas outside the Maeslantbarrier are investigated here. To show the effect of the ground level on the model, three different heights are chosen. This are the base case (+4.2 m NAP), a low scenario (+3.7 m NAP) and a high scenario (+4.7 m NAP). Table 3.13 lists the input vales.

Ground level	low	average	high
z_t	+3.7 m NAP	+4.2 m NAP	+4.7 m NAP

Table 3.13: Sensitivity analysis on ground level

Table 3.14 shows the output values of the sensitivity analysis on ground level. One can see the total cost is reducing rapidly for higher terrains. From a particular ground level and higher, it will be cheaper to postpone the investment after 2100. An original terrain height of 4.7 m is behind this point, while 3.7 m and 4.2 m are before this point. Further research on this turning point shows a ground level of +4.55 m NAP is the turning point in this case.

Further things to notice, is the fact that the optimal dike height for the low and the base case are almost the same; +5.37 m NAP and +5.36 m NAP. In case of the low ground level, one needs to invest earlier. Therefore this is much more expensive.

Ground level	low	base	high
TC (Total costs)	€ $3.74x10^6$	€ $2.52x10^6$	€ $0.78x10^6$
R_1 (Risk before)	€ 0	€ $0.78x10^6$	€ $0.78x10^6$
I (Investment)	€ $3.19x10^6$	€ $1.40x10^6$	€ 0
R_2 (Residual risk)	€ $0.55x10^6$	€ $0.34x10^6$	€ 0
$\frac{Benefit}{Cost}$-ratio	6.7	2.2	-
Δz	1.67 m	1.16 m	-
	+5.37 m NAP	+5.36 m NAP	+4.7 m NAP
Return period (2015)	7332 yrs	7092 yrs	786 yrs
Return period (2050)	1385 yrs	1339 yrs	148 yrs
Return period (2100)	711 yrs	688 yrs	76 yrs
$t*$	1 yrs	16 yrs	-
	2016	2031	-

Table 3.14: Results of the sensitivity analysis on ground level. **Note:** For the low ground level, the risk before the measure is € 0. This is due to the fact one needs to invest now. Therefore, the cumulative risk of the years before investing is 0.

3.2.7. Investment costs

The investment costs are based on rough estimates and ranges of prices from earlier assessments. It is therefore important to investigate the effect of a different price for the measures. More on the costs of investment can be found in Section 2.2.2. In Table 3.15 the used input values can be found.

Cost of measure		Low	High
C_D	int	400	1000
	var	1000	2500
C_{LF}	int	10	10
	var	15	25
C_{FP}	int	0	10
	var	5	15

Table 3.15: Sensitivity analysis on investment costs

The different output values per kind of measure can be found in Table 3.16 (dike), Table 3.17 (land fill) and Table 3.18 (flood proofing). As one can see, a higher price results in higher total cost. The optimal height of the measure decreased for all cases and it seems to be more profitable to postpone the investment. Interesting to see is the fact that for the land fill the component of investment cost decreased. This is due to the fact the optimal height is lower and the investment is postponed. The high price for flood proofing is not worth the investment anymore, and therefore one should not invest at all.

Investment costs: dike	low	high
TC (Total costs)	€$2.52x10^6$	€$3.87x10^6$
R_1 (Risk before)	€$0.78x10^6$	€$1.49x10^6$
I (Investment)	€$1.40x10^6$	€$1.90x10^6$
R_2 (Residual risk)	€$0.34x10^6$	€$0.47x10^6$
$\frac{Benefit}{Cost}$-ratio	2.2	1.2
Δz	1.16 m	0.87 m
	+5.36 m NAP	+5.07 m NAP
Return period (2015)	7092 yrs	2697 yrs
Return period (2050)	1339 yrs	509 yrs
Return period (2100)	688 yrs	262 yrs
$t*$	16 yrs	34 yrs
	2031	2049

Table 3.16: Results of the sensitivity analysis on investment costs: dike.

Investment costs: land fill	low	high
TC (Total costs)	€$2.80x10^6$	€$3.20x10^6$
R_1 (Risk before)	€$1.01x10^6$	€$1.43x10^6$
I (Investment)	€$1.46x10^6$	€$1.31x10^6$
R_2 (Residual risk)	€$0.33x10^6$	€$0.46x10^6$
$\frac{Benefit}{Cost}$-ratio	1.9	1.7
Δz	0.67 m	0.54 m
	+4.87 m NAP	+4.74 m NAP
Return period (2015)	1385 yrs	898 yrs
Return period (2050)	262 yrs	170 yrs
Return period (2100)	134 yrs	87 yrs
$t*$	20 yrs	25 yrs
	2035	2040

Table 3.17: Results of the sensitivity analysis on investment costs: land fill.

Investment costs: flood proofing	low	high
TC (Total costs)	€$3.32x10^6$	€$4.15x10^6$
R_1 (Risk before)	€$0.45x10^6$	€$4.15x10^6$
I (Investment)	€$0.52x10^6$	€0
R_2 (Residual risk)	€$2.35x10^6$	€0
$\frac{Benefit}{Cost}$-ratio	2.6	-
Δz	1.0 m	0.0 m
	+5.2 m NAP	+4.2 m NAP
Return period (2015)	4160 yrs	148 yrs
Return period (2050)	786 yrs	28 yrs
Return period (2100)	403 yrs	14 yrs
$t*$	10 yrs	-
	2025	-

Table 3.18: Results of the sensitivity analysis on investment costs: flood proofing.

3.2.8. Indirect damage

Section 2.2.6 introduced the effect of indirect damage and its dependency on the recovery time. Because the indirect damage and the recovery time are difficult to assess, it is important to know the sensitivity of the model to the indirect damage.

Here, this is done by simulating a concave recovery, linear recovery and convex recovery (more on the different kinds of recovery in Section 2.2.6). The different values for the indirect damage can be seen in Table 3.19. The factor between the different kinds of recovery, linear is 5 times the indirect damage of concave and convex even 10 times the indirect damage of concave recovery, is in line with the factors for indirect damage as calculated in the pilot report by HKV and VU by Robin Nicolai [2016].

Indirect damage	concave	linear	convex
Factor D_{direct}	0,3	1	2
Total damage (x D_{direct})	1,3	2	3

Table 3.19: Sensitivity analysis on indirect damage and speed of recovery.

As one can see, the difference in total costs between the concave and convex recovery is roughly € 1.000.000 or 1,5 times more. For convex recovery the time to invest is shorter and the optimal height of investment is higher, which says the optimal level of flood safety is much higher than for the concave recovery. This is logically, since the costs in case of a flood are much higher and therefore higher investment costs are justified to decrease the risk.

Indirect damage	concave	linear	convex
TC (Total costs)	€ $2.04x10^6$	€ $2.52x10^6$	€ $2.95x10^6$
R_1 (Risk before)	€ $0.81x10^6$	€ $0.78x10^6$	€ $0.52x10^6$
I (Investment)	€ $0.97x10^6$	€ $1.40x10^6$	€ $1.99x10^6$
R_2 (Residual risk)	€ $0.26x10^6$	€ $0.34x10^6$	€ $0.44x10^6$
$\frac{Benefit}{Cost}$-ratio	1.7	2.2	2.7
Δz	1.04 m +5.24 m NAP	1.16 m +5.36 m NAP	1.26 m +5.46 m NAP
Return period (2015)	4754 yrs	7092 yrs	9897 yrs
Return period (2050)	898 yrs	1339 yrs	1869 yrs
Return period (2100)	461 yrs	688 yrs	960 yrs
$t*$	24 yrs 2039	16 yrs 2031	8 yrs 2023

Table 3.20: Results of the sensitivity analysis on indirect damage and speed of recovery.

3.3. Discussion

Different conclusions can be drawn from this sensitivity analyses. The model uses a lot of different inputs, which all could highly influence the outcome of the model. Some parameters also have some kind of uncertainty. Parameters with a lot of uncertainty are the climate, the indirect damage and the cost of the different measures. These parameters are all difficult to determine and submissive for change. The sensitivity analyses give insight in the response of the model to the parameters and the effect of the uncertainty.

The parameters that seem to be most important to determine the optimal level of flood safety are the ground level and sector. These factors are both related to the damage. The size and shape seems to be most important parameters for determining the most suitable measure. The size and shape are related to the ratio between the area (in m^2) and the circumference (in m). A said before, when area/circumference is large, a dike will be more suitable. When area/circumference is small, a land fill or flood proofing might be more suitable. For more research into this relation, there is referred to Lendering [2018].

Earlier, it was questioned to what extend the risk criterion used in the current risk-framework (€ 1.000.000/year) is valid. With the different sensitivity analyses, it is difficult to determine the validity of this criterion. This is due to the fact both risk-frameworks work differently. The proposed risk-framework does take the variable price of measures into account and the possibility to postpone a measure, while the existing risk-framework only calculates the risk and compares this with the acceptable level. Furthermore, the used definition of risk differs from each other; here, the cumulative risk is used, while the existing risk-framework only looks for the incident risk. To check the risk criterion, it is advised to run both risk-frameworks parallel on several cases and compare the outcome.

Further insight into the response of the model could be gain by observing the plots of the different scenarios. These can be found in Appendix E.

4

Case study

Besides the sensitivity analyses of Section 3, the model is tested on a realistic case. For this case study, Pier 7 of the Waal- Eemhaven is chosen.

The aim of this chapter and the case study is to show how the model works for a realistic case. Besides how this model works, also the applicability for cases in the Port of Rotterdam is shown. The model should show the optimal height of flood defences for a limited amount of input values that are easy to find.

First, Section 4.1 introduces the case study and lists the input values for the model. It is also shown how these input values are determined. Next, the model is run and Section 4.2 shows the results. Section 4.4 concludes the case study with a short discussion of the results and some final remarks. The applicability of the model for this problem will be reviewed as well.

4.1. Input

The Waal- and Eemhaven is situated in the Port of Rotterdam, behind the Maeslantbarrier. The location can be seen in Figure 4.1.

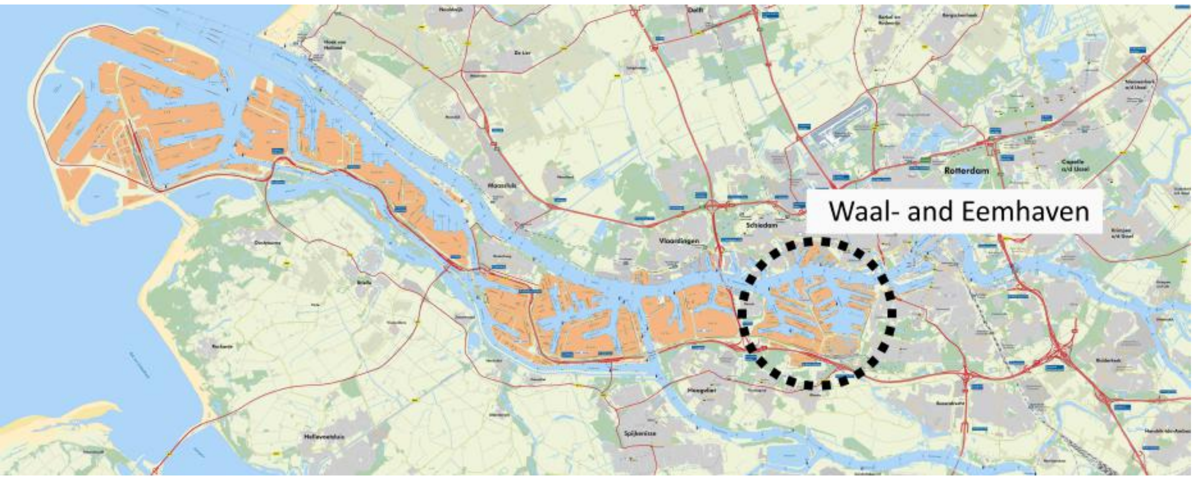


Figure 4.1: Map of the Port of Rotterdam with the location of the Waalhaven and Eemhaven encircled. From: Port of Rotterdam

The Waal- and Eemhaven is divided into different piers. The division into the different piers is shown in Figure 4.2. This is case study is focusing on Pier 7.

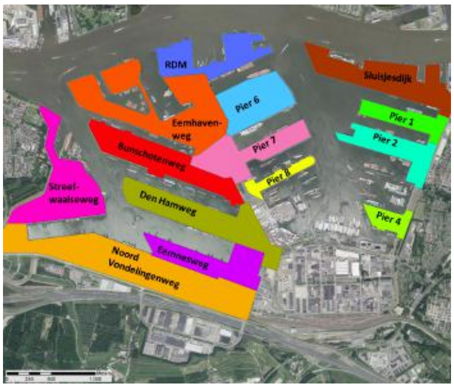


Figure 4.2: Different areas in the Waal- and Eemhaven. From: RHDHV.

The terrain height of the Waal- and Eemhaven can be seen in Figure 4.3. The average terrain height of pier 7 is +3.06 m NAP (calculated by RHDHV in previous assessment).

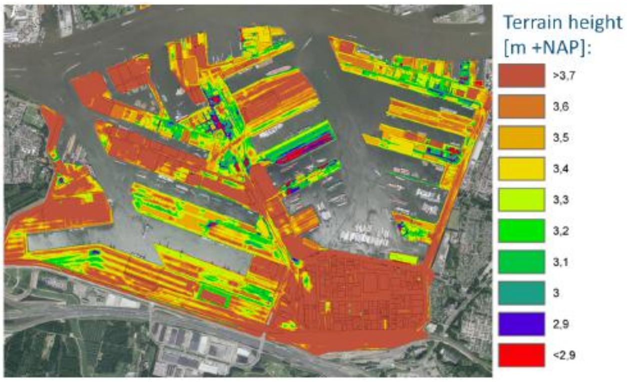


Figure 4.3: Land height of the Waal- and Eemhaven. From: RHDHV.

The different sectors that are active in the Waal- and Eemhaven are mapped out in Figure 4.5. As one can see, pier 7 is a container terminal. The damage factor for the container terminal does not increase linear with the water depth. However, a flood of more than 1.5 m is very unlikely. Therefore, it is possible to assume a linear relation for a short range of water depths. Linearity is assumed, with d_{max} = 2.0 m and f_{max} = 0.27.

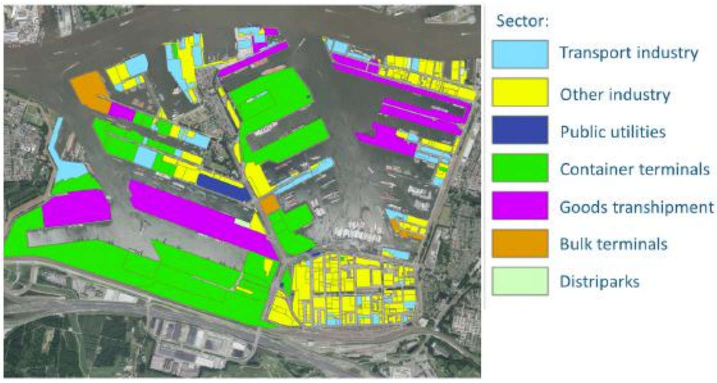


Figure 4.4: Sectors active in the Waal- and Eemhaven. From: RHDHV.

Figure 4.5: Size and shape of Pier 7

The input values are summed in Table 4.1. These values are all as prescribed in Section 2, except for the costs of a dike. When looking at the circumference (the place where the dike will be constructed), it is visible that a large part will be used as quay wall. Because a quay wall is an more expensive structure than a small dike, $C_{D;Var}$ is expected to be higher than € 1000. Based on expert judgement by RHDHV, the average costs for 1 m of dike are therefore raised to € 5000 instead of € 1000.

Pier 7		
Climate		
$a(2015)$	2.8	$[m]$
$a(2100)$	3.0	$[m]$
$b(2015)$	0.09	$[m]$
$b(2100)$	0.14	$[m]$
Sector		
d_{max}	2.0	$[m]$
f_{max}	0.27	$[-]$
I_v	696	$[€/m^2]$
Terrain		
A	0.2	$[km^2]$
L_{total}	2.7	$[km]$
z_t	3.0	$[m+NAP]$
Measure costs		
$C_{D;int}$	€ 400	$[€/m]$
$C_{D;var}$	€ 5000	$[€/m/m]$
$C_{LF;int}$	€ 10	$[€/m^2]$
$C_{LF;var}$	€ 20	$[€/m^2/m]$
$C_{FP;int}$	€ 0	$[€/m^2]$
$C_{FP;var}$	€ 10	$[€/m^2/m]$

Table 4.1: Input values of the model for the case study on pier 7.

4.2. Output

The cheapest solution in terms of total costs is the land fill. Due to the high construction costs of quay walls and the shape and size of the land, a dike is expensive to construct around pier 7. The total costs of flood proofing is one order of magnitude more expensive than the other solutions.

All solution propose action now: the risk on this moment is unacceptably high. For the dike and the land fill, the majority of the costs are investment costs. The investment costs of flood proofing are relatively low with only € 1.10_{10^6}. However, the residual risk of the dike and land fill are low, where with the flood proofing the residual risk is still very high.

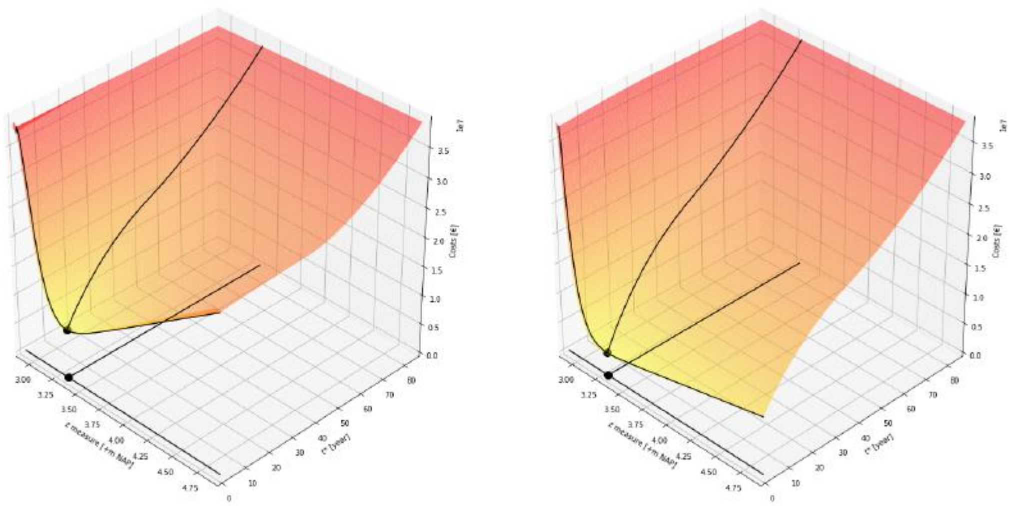
The height of the measures is around the same level for the dike and land fill. Flood proofing is a bit higher. The level of safety, given by the return periods, is therefore around the same level for a dike and a land fill. Flood proofing shows return periods that are slightly larger. However, more floods will occur but are accepted. The return period for the accepted floods is 3 yrs (2015), 2 yrs (2050) and 0.5 yrs (2100). Although these are accepted, still some minor damage will be inflicted with each flood.

Although the residual risk is still high, the $\frac{Benefit}{Cost}$-ratio is the highest for the flood proofing. This is due to the fact the investment costs are low. The ratio for the land fill is 10.7 which is still very high. The ratio for the dike is with 5.2 the lowest, but still shows to be effective and efficient.

All results could be found in Table 4.2. The 3D-plots can be found in Figure 4.6. Cross sections per scenario for the optimal level of protection and the optimal moment of investing can be found in Appendix F.

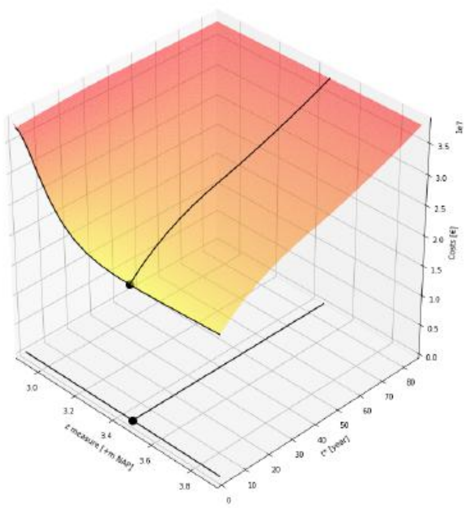
Case study	Dike	Land fill	Flood proofing
TC (Total costs)	€ 8.40_{10^6}	€ 3.90_{10^6}	€ 22.69_{10^6}
R_1 (Risk before)	€ 0	€ 0	€ 0
I (Investment)	€ 7.03_{10^6}	€ 3.55_{10^6}	€ 1.10_{10^6}
R_2 (Residual risk)	€ 1.37_{10^6}	€ 0.35_{10^6}	€ 21.59_{10^6}
$\frac{Benefit}{Cost}$-ratio	5.2	10.7	15.1
Δz	0.46 m	0.42 m	0.57 m
	3.36 m	3.32 m	3.47 m
Return period (2015)	871 yrs	746 yrs	1329 yrs
Return period (2050)	403 yrs	346 yrs	616 yrs
Return period (2100)	187 yrs	160 yrs	285 yrs
$t*$	0 yrs	0 yrs	0 yrs
	2016	2016	2016

Table 4.2: Results of the sensitivity analysis on indirect damage and speed of recovery. **Note:** The risk before the measure is in all cases € 0. This is due to the fact one needs to invest now. Therefore, the cumulative risk of the years before investing is 0.



(a) Dike

(b) Land fill



(c) Flood proofing

Figure 4.6: 3D plots for the model results on the case study.

4.3. Comparison with existing risk-framework

This case has been solved before by the existing risk-framework. With the existing risk-framework, the acceptable risk has been scaled from € 1.000.000/year for the complete Botlek area to € 8.000/year for Pier 7 of the Waal- and Eemhaven. It is found the value for acceptable risk will be exceeded in the current situation. Therefore, direct action is required. RHDHV advised to raise the level of flood safety to once every 3000 years.

The proposed risk-framework also advises to invest in flood risk at this moment. However, the level of flood safety is different. The proposed risk-framework advises the optimal level of flood safety is lower, namely around 800 years.

One can see both risk-frameworks gave comparable advises, although the existing risk-frameworks seems to have given a more conservative advise on the level of flood safety that is required by the proposed risk-framework. However, this is only one case. To get more insight into the working of both risk-frameworks with respect to each other, it is advised to use both risk-frameworks on multiple (different) cases and compare the advise of both.

4.4. Discussion

The model showed immediate action should be taken. The land fill seems to be cheapest, next to a dike and a flood proofing.

The following side notes are made on the use of the model:

- The model only looks for an economic optimum. However, it could be a requirement by a company to limit the return period of flood to a particular limit. With some small modifications to the model, the difference in costs between the optimal level and a required minimum return period could be determined.
- The model does not make a difference between costs that are for sure (investment) and average/possible (risk). The costs for an investment could be spread over a longer period of time, while it is not sure if the damage due to a flood could be spread.
- The model assumes each square meter is worth the same value. This is a good first assumption, but while discussing the case with the owner, certain areas could be appointed as more valuable and less valuable. Only protecting these high-value areas, this could reduce the investment costs.

When these side notes are taken into account, the model shows to be highly usable to make a quick, first assessment to determine the economic optimum in height of investment and moment of investing. As shown by this case study, the model is applicable for realistic cases. Further, the model makes the components of costs visible and shows what the costs will be of postponing a measure or prescribing a higher level of safety.

5

Conclusion & recommendations

This chapter draws a conclusion by answering the research questions formulated in the Introduction (Chapter 1) and ends with some recommendations how to use the proposed risk-framework and how this risk-framework could further be improved in the future.

5.1. Research questions

First, the sub questions will be answered:

How does the existing risk-framework assess the level of flood safety?

The main objective of the existing risk-framework was to present the flood risk for the next 100 years in an understandable way to companies in the Port of Rotterdam. From the workshops, RHDHV experienced companies have their own risk matrices which determine what risk is acceptable for a particular consequence (amount of damage). Therefore, RHDHV decided to treat flood risk in this case as an event with a particular water level and value of damage. For this single event (high water level), one could easily determine what the return period is and therefore the risk of floods ($risk/year = \frac{damage}{return\ period}$). This is called the incident risk. This incident risk for floods could be compared with other risks, and could be determined if the risk is acceptable or not. However, normally in the field of flood safety, cumulative risk is used. With cumulative risk, the damage and return periods of lower water levels is also used. Smaller floods that induce only a limited amount of damage are neglected in the approach of incident risk, and could therefore underestimate the flood risk.

In three steps is determined if the probability of occurrence for a particular consequence (probability of flood inducing damage) is acceptable:

- Step 1: Define the relation between water level and damage of the subject.
- Step 2a: Define the probability of failure.
- Step 2b: Define the acceptable probability of failure.
- Step 3: Comparison probability of failure and acceptable probability of failure.

Problems with this method are the use of the incident risk (which might underestimate the risk compared to cumulative risk) and the acceptable probability of failure (which is based on a general relation for embanked areas that might not be suitable for all cases). More on the existing could be found in Appendix B.

How could the optimal level of flood safety be determined in a cost-benefit analysis?
With a cost-benefit analysis the economic optimum of flood safety is determined. The cost is the investment in dikes, land fills or flood proofing (measures). The benefit is the reduction of risk between the original situation and the situation with a measure applied.

The cost-benefit analysis (the model) seeks the economic optimum. The model determines the combination of Δz (height of measure) and t* (moment of investing) that leads to the lowest total cost (investment + (residual) risk).

What influences the optimal level of flood safety determined by a cost-benefit analysis?

The model uses the following input:

- Probability of flood (determined by the location and climate prediction);
- Sector (determines the value and damage-water level relation);
- Shape and size of area;
- Economic prospect (determines the discount rate and therefore the net present value (NPV) of future expenses);
- Ground level;
- Cost of investment;
- Type of recovery (determines the factor for indirect damage).

Based on the sensitivity analysis of Chapter 3, the most influencing sectors for the height and moment of investing are the ground level and the sector (mostly the value of assets). The kind of measure is determined by the size and shape of the terrain, where for larger terrains a dike is a suitable solution and for smaller terrains a land fill seems more appropriate. Uncertainties arise with the input values for climate change, recovery time and cost of measure. Those are difficult to determine or submissive for change.

How could a cost-benefit analysis be applied and what are the limitations of this new method?
The proposed model should be used as a first estimator. The damage is calculated quite rough. This is due to the fact the value of the land is averaged per m^2 and a water level - damage function is used. When more is known about critical assets, one could look into more detailed solutions.

Besides estimating the damage quite rough, the model has further limitations. Some companies will have other requirements than only economic optimization. A company could want to limit the return period for floods. Another limitation is the fact that the model does not take the difference in type of costs into account; an investment in flood protection is a cost which is sure to be made and could be spread and planned over multiple years. Flood risk is not a cost which is sure to be made; this has some kind of uncertainty. But, costs due to a flood could not be planned or spread over some years. The model does not make a difference in unexpected costs and certain costs. Especially smaller companies might have more problems paying a lot of unexpected costs at once due to a flood.

The main research question:
How could the existing risk-framework of RHDHV for food safety and flood risk in unembanked sectors be improved?

The current risk-framework is a good tool to use in collaboration with companies. It makes flood risk more understandable and easy to implement into existing risk matrices. The proposed risk-framework could improve this existing risk-framework to show total costs of a proposed measure or to calculate the optimal level of flood safety.

Another way the existing risk-framework could be improved by the proposed risk framework, is by determining the acceptable risk. Acceptable risk should be dependent on the measures to reduce this risk. In the proposed risk-framework this is implemented. With a cost-benefit analysis the proposed level of protection will be suitable for the value of the assets. In the existing risk-framework, the acceptable level of risk is based on a relation derived from cases inside dike-rings. However, a general relation does not take slight differences into account. These slight differences could determine the efficiency of a measure.

5.2. Recommendations

The recommendations consists of two parts. First, recommendations will be given on the use of the model in practice. Second, recommendations will be given on how the model could be improved.

Because the model is more difficult to use with existing risk matrices, the model might need some more explanation during the workshops. When looking at the phases of the Flood Risk Management project (Section 1.1), the model seems to be doing all phases at once. Therefore, the model could be used for all phases: calculation of flood risk (phase 1), necessity of measures (phase 2), possible measures (phase 3) and possible adaptation strategy (phase 4). The model could also show some intermediate answers; like the cost of flood risk without taking any measures. Intermediate answers will make the model and the topic of flood risk more understandable for the companies of the Port of Rotterdam.

The model could be improved on several aspects. The indirect damage is calculated quiet rough and as a factor of the direct damage. This is a good first assumption, but this assumes indirect damage could only occurs when direct damage is inflicted. In reality, indirect damage might occur due to floods at e.g. neighbouring companies, supplying companies or access roads. Further improvements of the model could be done by making a difference in costs that are certain (investment costs) and possible (e.g. risk; possibly much higher and more difficult to spread over a couple of years).

Bibliography

Joop de Boer, Wouter Botzen, and Teun Terpstra. Percepties van burgers over binnen- en buitendijks wonen. *Gemeente Rotterdam (Rotterdam Climate Initiative)*, 2012.

Karing de Bruijn and Marcel van der Doef. Gevolgen van overstromingen - informatie ten behoeve van het project waterveiligheid in de 21e eeuw. *Deltares*, 2011.

C.J.J. Eigenraam. Optimal safety standards for dike-ring areas. *CPB*, (62), 2006.

Jarl Melchior Kind. Economically efficient flood protection standards for the netherlands. *J. Flood Risk Manage.*, 7:103–117, 2014.

KNMI. Knmi'14-scenario's. *http://www.klimaatscenarios.nl/*, 2014.

Kasper Lendering. Advancing methods for evaluating flood risk reduction measures. *TU Delft*, pages 61–84, 2018.

Leslie Mooyaart and Maarten Schoemaker. Kba terreinhoogte buitendijks. *Royal HaskoningDHV on behalf of the City of Rotterdam*, 2017.

port of Rotterdam. Water safety, 2019. URL `https://www.portofrotterdam.com/en/our-port/our-themes/a-safe-port/water-safety`.

province of Zuid Holland. Programma ruimte - buitendijks bebouwd gebied, 2019. URL `https://www.ruimtelijkeplannenzuidholland.nl/VRM`.

Rijkswaterstaat. Hydra-nl, 2019. URL `https://www.helpdeskwater.nl/onderwerpen/applicaties-modellen/applicaties-per/omgevings/omgevings/hydra-nl-0/`.

Gerbert Pleijter Jan Huizinga Elco Koks Hans de Moel Robin Nicolai, Saskia van Vuren. Pilot waterveiligheid botlek: Kwantitatieve analyse overstromingsrisico's. *HKV and VU*, 2016.

RWS-WVL. *Waterveiligheid: Begrippen begrijpen 2.0.* 2016.

M Snuverink, K van den Berg, L Sluijs, and A Wiertz. Schadecurves industrie ten gevolge van overstroming. *Tebodin B.V.*, 2000.

D van Dantzig. Economic decision problems for flood prevention. *Econometrica*, pages 276–287, 1956.

Jarit van de Visch and Matthijs Bos. Waterveiligheid buitendijkse havengebieden. *Royal HaskoningDHV on behalf of Port of Rotterdam*, 2018.

M van Ledden; J van de Visch. Botlek waterveiligheid. *Royal HaskoningDHV on behalf of Port of Rotterdam*, 2017.

Ronny Vergouwe and H Sarink. De veiligheid van nederland in kaart. *Rijkswaterstaat Projectbureau VNK*, 2014.

A

Flood risk in the Netherlands

This appendix is written for people who not have a background in Dutch flood-risk. The Netherlands is a flood prone land with many parts that are lower than the sea level. The land is protected by dikes and barriers. All figures in this appendix are from de Bruijn and van der Doef [2011].

In Figure A.1, the inundation-depth is shown for different flood scenarios. A large area is prone to floods (potentieel overstroombaar gebied in legend of Figure A.1). In areas that are prone to floods, the water could reach 6 m and higher. Not only the sea brings large risks, more inland the rivers could lead to large floods.

Figure A.2 shows the possible damage due to floods. The colors indicate the damage in [€ 1.000/ha]. In the cities the colors are turning purple, where in the more rural areas the colors are more yellow. This picture should give an idea how large the amount of damage is in case of a flood in the Netherlands.

Figure A.3 shows the different dike-rings. These dike-rings should protect the land from floods. The level of protection for each dike-ring is based on a cost-benefit analysis.

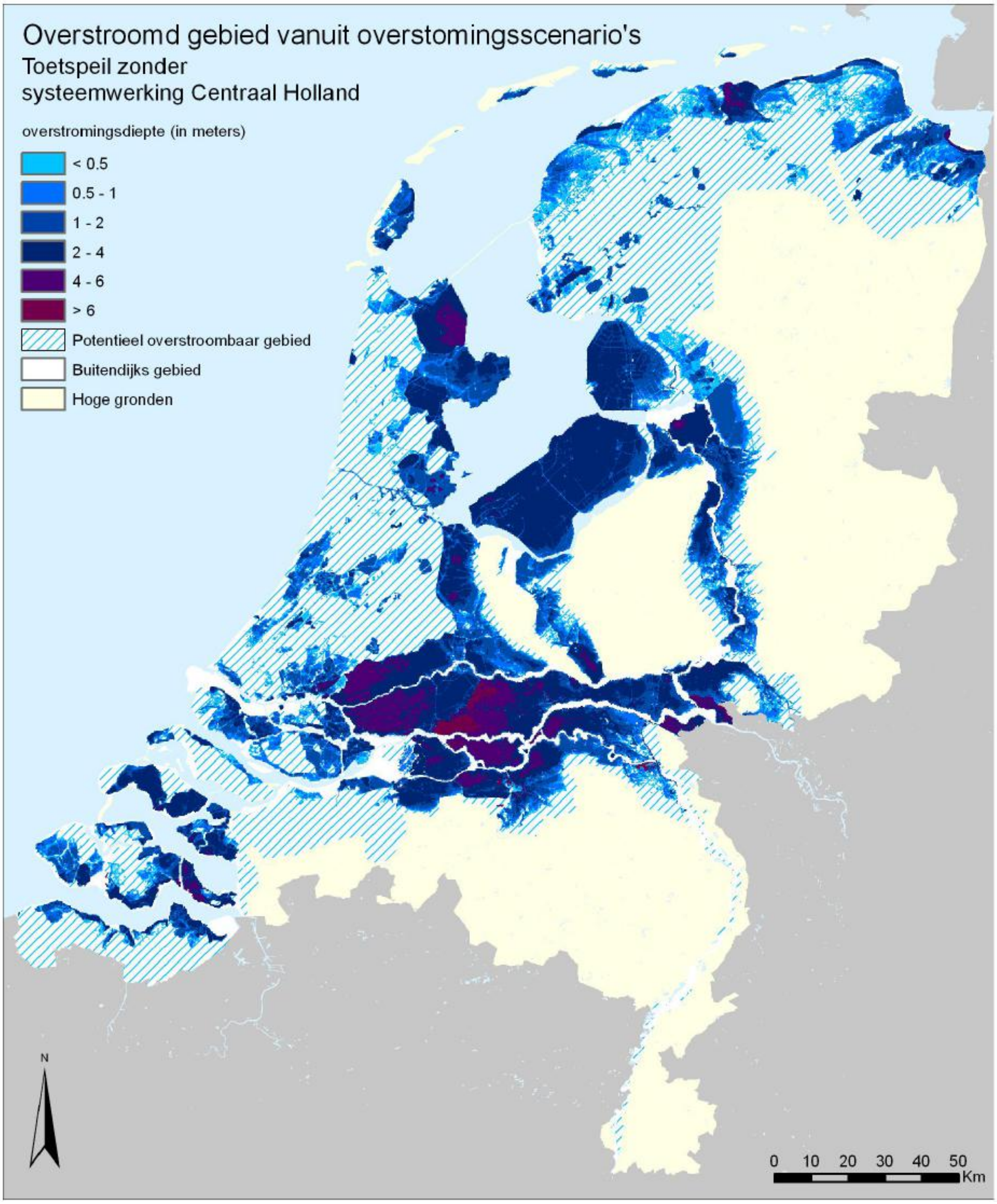


Figure A.1: Flooded area from flood-scenarios. Possible water depths (*Dutch: overstromingsdiepte*) in case of a flood are calculated with different flood-scenarios. From this picture the treat of the water for the Netherlands gets visible. From: de Bruijn and van der Doef [2011].

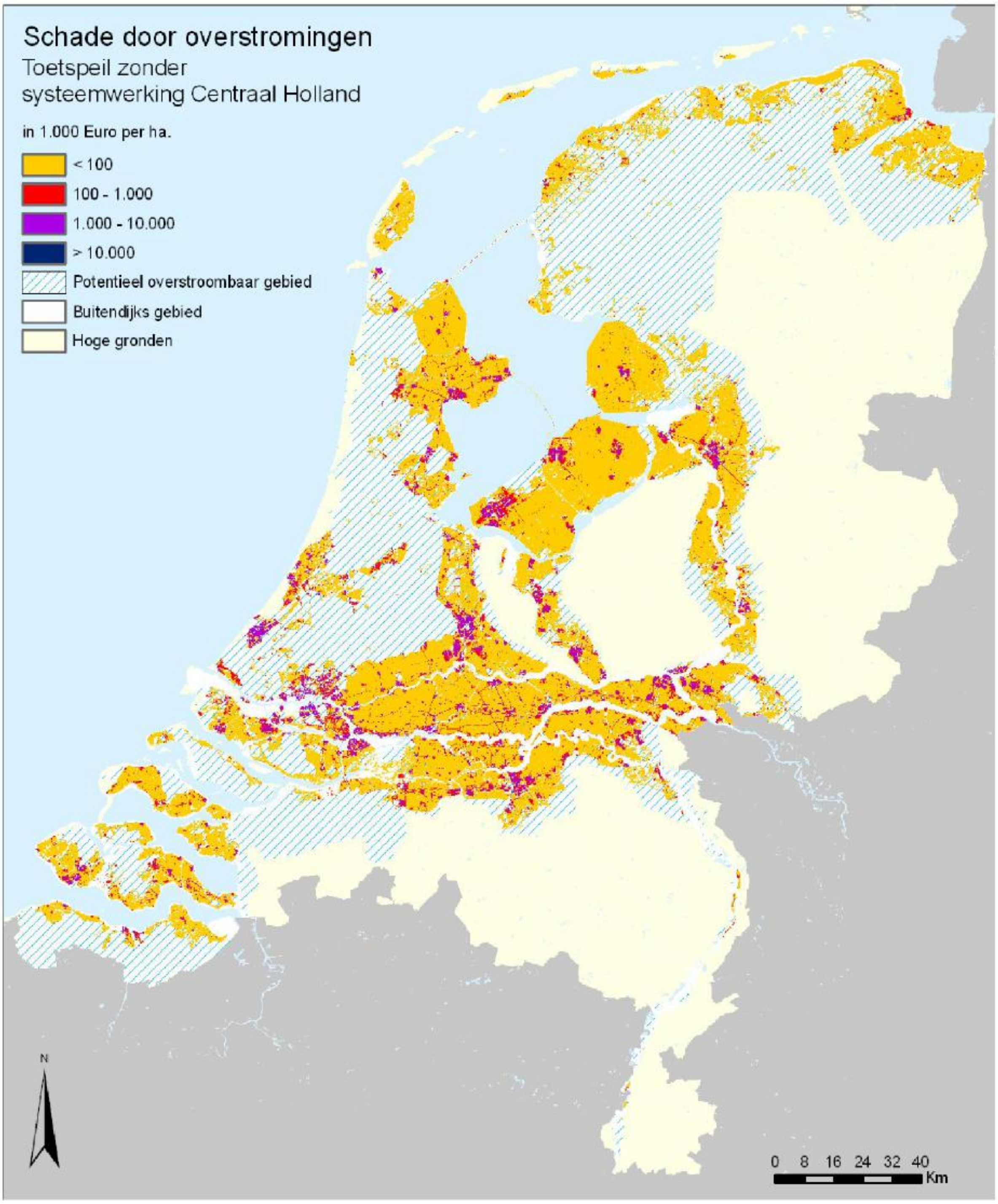


Figure A.2: Damage due to floods. Based on the water-depths from Figure A.1, the damage in case of a flood is calculated. The damage is shown in [€ 1.000/ha]. From: de Bruijn and van der Doef [2011].

Figure A.3: In this figure, all dike-rings and dike-ring sections are shown. 14-1 stands for dike ring 14, section 1. From this figure one can see the large amount of flood defences through the Netherlands. From: de Bruijn and van der Doef [2011].

B

Risk-framework

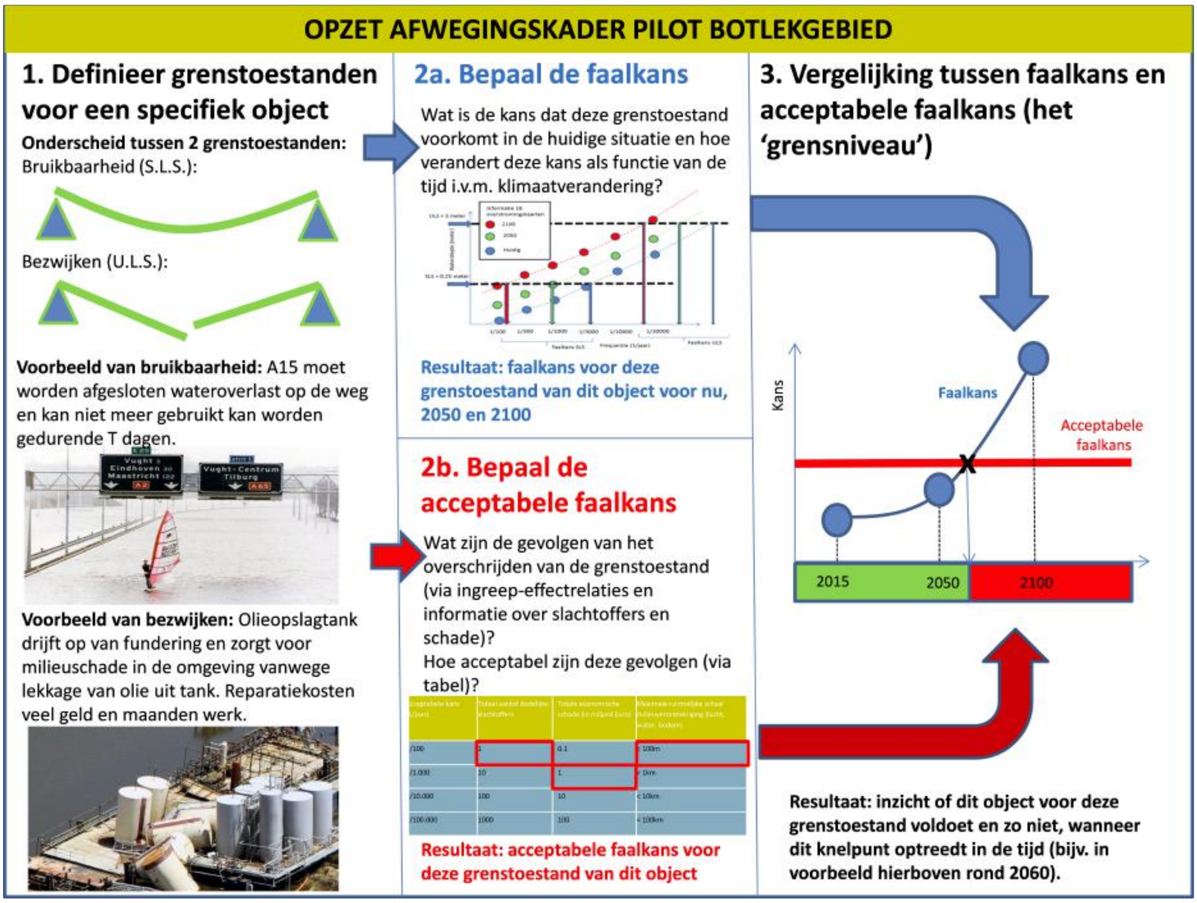
Schematized view of the risk-framework as is shown on the workshops of the Flood Risk Management project. The workshops are in Dutch and so is the image. A translation of the steps is given:

- **Step 1: Define the service limit state (SLS) and ultimate limit state (ULS) of the subject.**
  In this step the relation between the water level and the amount of damage is defined. First SLS and ULS have been used to determine this, later a more complex damage-water level function is used. More on the damage-water level function can be found in Section 2.2.6.

- **Step 2a: Define the probability of failure.**
  The probability of failure is determined by the probability of exceedance of water levels that are found for the SLS and ULS in step 1. With the damage-water level function the probability, the probability of a particular water level and the inflicting damage is calculated.

- **Step 2b: Define the acceptable probability of failure.**
  The acceptable probability of failure determines for each return period the acceptable event and its damage. The acceptability of failure is based on three criteria: economical risk, personal risk and environmental risk. For each of these criteria several levels of acceptability per probability of occurrence have been determined. Earlier session showed economical risk is most often the strictest criteria; personal risk is very low because it is assumed there will not be any personal left when extreme conditions are predicted (the area is an industrial area). The criteria for environmental risk is determined in the spread of chemical, hazardous substances after a tank is broken or inflated. However, earlier assessments by RHDHV show this is very unlikely. In the earlier study in the Botlek area, the acceptable economic risk was set to € 1.000.000/year. This means that for an event occurring every 1.000 years, it is acceptable to have € 1.000.000.000 of damage. This criteria is based on the acceptable risk for endiked areas in the Netherlands.

- **Step 3: Comparison probability of failure and acceptable probability of failure.**
  In this last step the result of step 2a and step 2b are compared with each other and the acceptability of the currently level of flood safety is determined.



OPZET AFWEGINGSKADER PILOT BOTLEKGEBIED

1. Definieer grenstoestanden voor een specifiek object

Onderscheid tussen 2 grenstoestanden:
Bruikbaarheid (S.L.S.):

Bezwijken (U.L.S.):

Voorbeeld van bruikbaarheid: A15 moet worden afgesloten wateroverlast op de weg en kan niet meer gebruikt kan worden gedurende T dagen.

Voorbeeld van bezwijken: Olieopslagtank drijft op van fundering en zorgt voor milieuschade in de omgeving vanwege lekkage van olie uit tank. Reparatiekosten veel geld en maanden werk.

2a. Bepaal de faalkans

Wat is de kans dat deze grenstoestand voorkomt in de huidige situatie en hoe verandert deze kans als functie van de tijd i.v.m. klimaatverandering?

Resultaat: faalkans voor deze grenstoestand van dit object voor nu, 2050 en 2100

2b. Bepaal de acceptabele faalkans

Wat zijn de gevolgen van het overschrijden van de grenstoestand (via ingreep-effectrelaties en informatie over slachtoffers en schade)?
Hoe acceptabel zijn deze gevolgen (via tabel)?

cceptabele kans (1/jaar)	Totaal aantal dodelijke slachtoffers	Totale economische schade (in miljard Euro)	Maximale ruimtelijke schaal milieuverontreiniging (lucht, water, bodem)
/100	1	0.1	< 100m
/1.000	10	1	< 1km
/10.000	100	10	< 10km
/100.000	1000	100	< 100km

Resultaat: acceptabele faalkans voor deze grenstoestand van dit object

3. Vergelijking tussen faalkans en acceptabele faalkans (het 'grensniveau')

Resultaat: inzicht of dit object voor deze grenstoestand voldoet en zo niet, wanneer dit knelpunt optreedt in de tijd (bijv. in voorbeeld hierboven rond 2060).

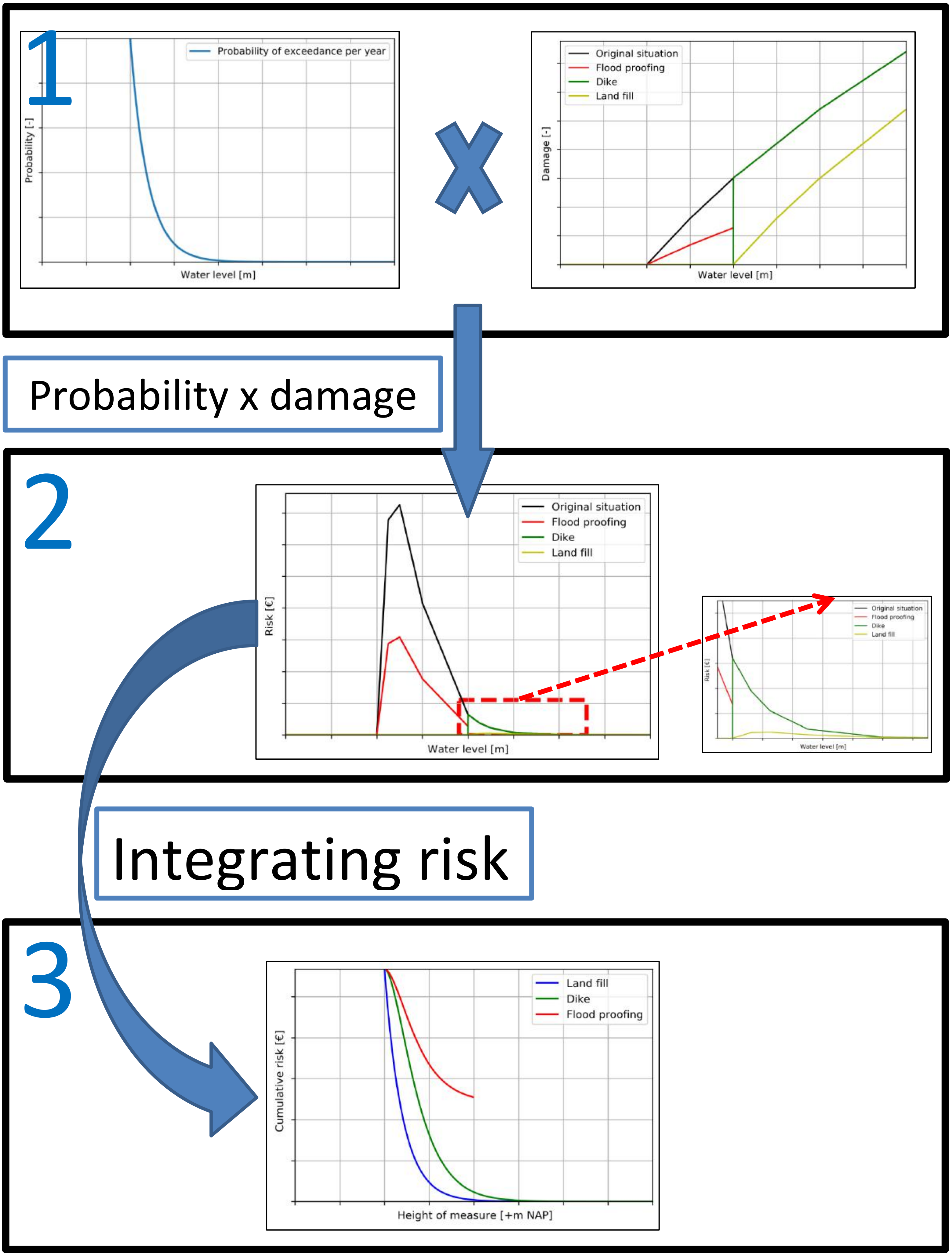
Figure B.1: The steps of the risk-framework in a schematized view. Although all text is in Dutch, one can see the plots that are made by each step. Because this framework is used in workshops with lay people, there has been chosen to make the different steps as visible as possible.

C

Calculation of cumulative risk

This Chapter shows step-by-step how the cumulative risk is calculated. On the next page, the steps are visualized with exemplary plots.

- **Step 1**
  Risk is defined as probability x damage. This is the first step. On the left, the probability of exceedance of the water level is plotted. On the right, the damage function for different measures is plotted. The damage function presents one scenario of all measures, i.e. all measures are applied up to 1 m above the ground level.
- **Step 2**
  Now the risk per water level is plotted. Again, this plot presents only one scenario. One can see with the detailed view the risk with a dike or land fill is much lower than with flood proofing or the original situation. This is due to the fact that in the original situation and flood proofing it is still possible to have a flood with a relative low water level (and a high probability of exceedance).
- **Step 3**
  Next, the risk of step 2 is integrated and the cumulative risk is calculated. Step 1 and step 2 now needs to be repeated for each possible/realistic height of a measure. When for each scenario (height of measure and measure) the cumulative risk is calculated, a plot as in step 3 is made.



Probability x damage

Integrating risk

D

Computer model investment height and moment

The model is written in Python. First, a grid is constructed with each possible combination of Δz and t*. This grid can be seen in Figure D.1.

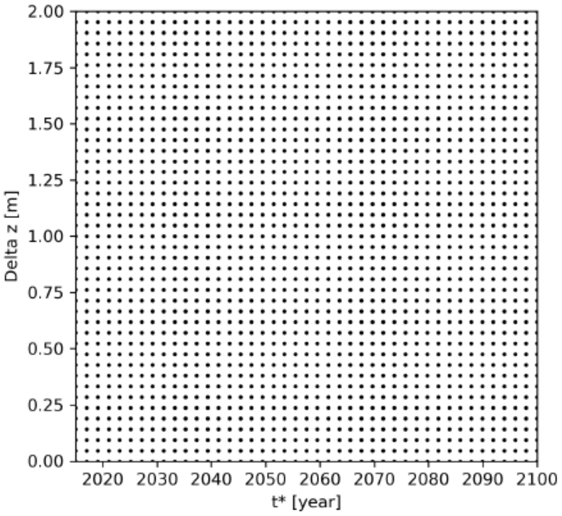


Figure D.1: Grid with possible options for moment of investment (t*) and height of investment (Δz). The values on the axes are used as an example and could be different in other cases.

In the Python script, each possible combination is calculated with formula 2.3. Here, different combinations are possible by changing t* and Δz. This results in a 3D-plot on top of the grid. The height of each point indicates the total cost per combination. An example of such a 3D plot with the axes of the minimal total costs is shown in Figure D.2. In this plot, the lowest point indicates the lowest total costs and therefore the optimal combination. For the optimal ΔZ and $t*$ the development of the total cost is indicated with lines in Figure D.2. In Figure D.3 this is plotted in more detail. Here, one is able to see the influence of the costs of the risk before, after and of the investment.

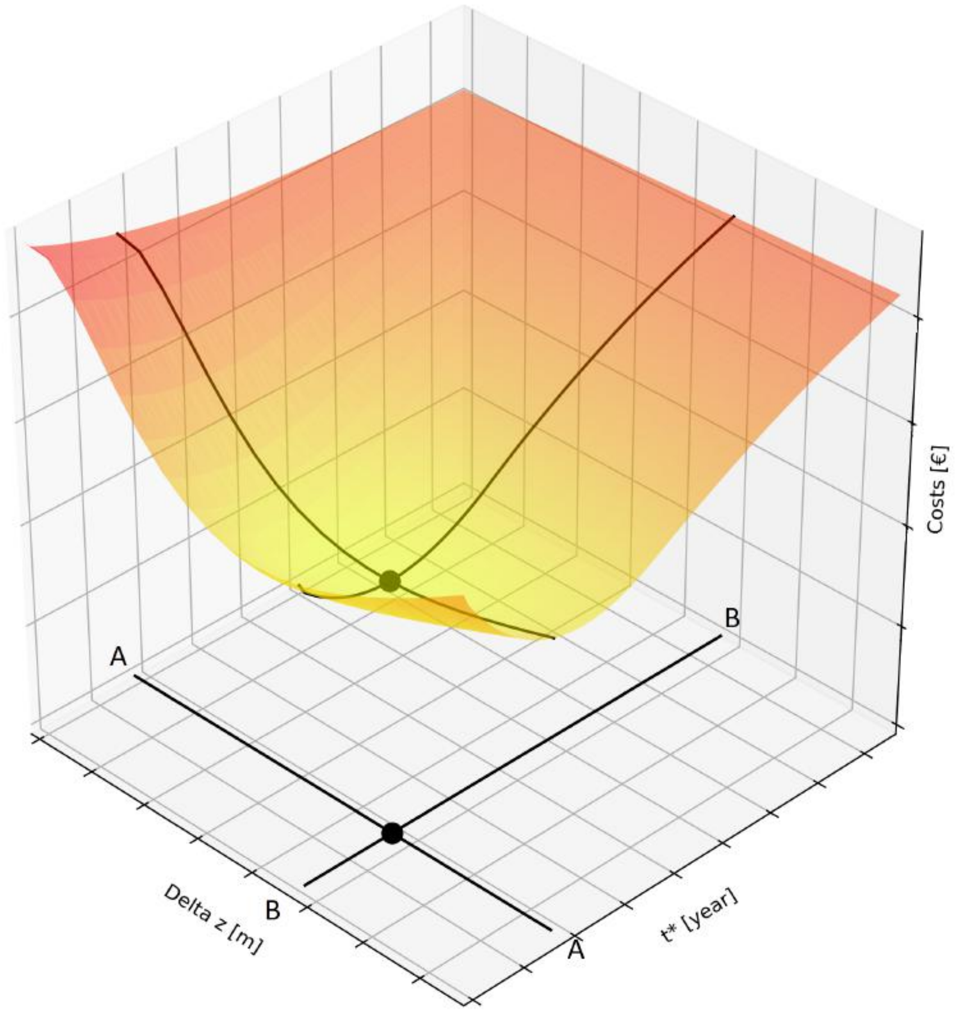
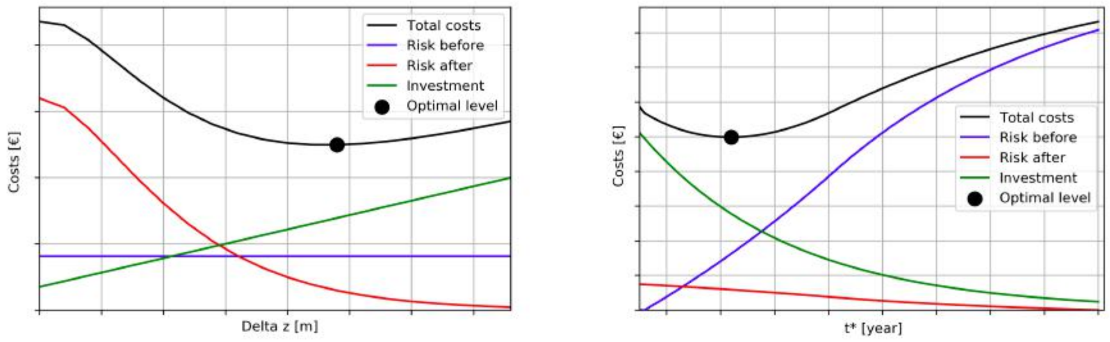


Figure D.2: 3D plot of the total costs for different combinations of Δz and $t*$. The lowest point indicates the optimal combination of Δz and $t*$.



(a) The development of the total cost for cross-section A-A. For this cross-section, $t* = t*_{optimal}$ and from Δz ranges from 0 to 2 m.

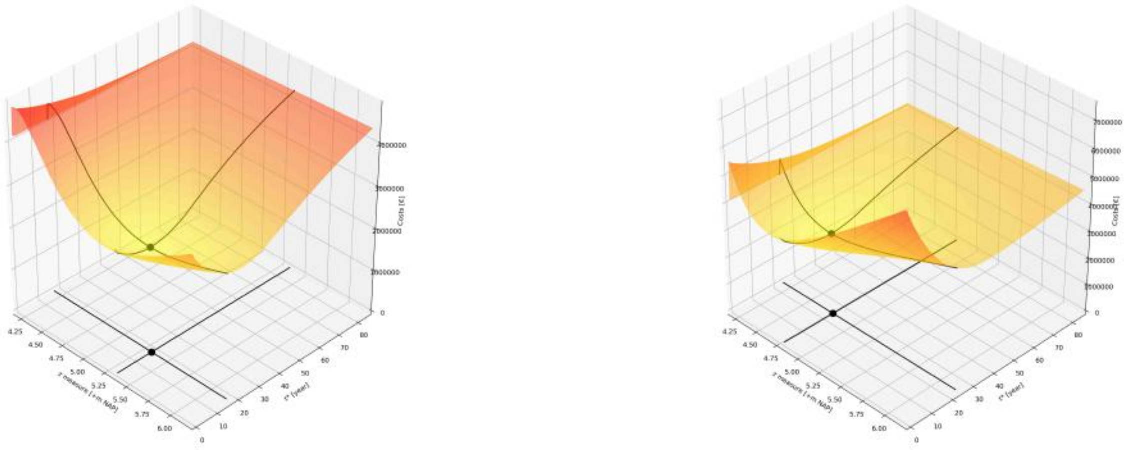
(b) The development of the total cost for cross-section B-B. For this cross-section, $\Delta z = \Delta z_{optimal}$ and from t* = 2015 to t* = 2100.

Figure D.3: A more detailed view on the development of total cost. In each plot, one parameter (Δz or $t*$) is optimal and the other is variable. Also, the

E

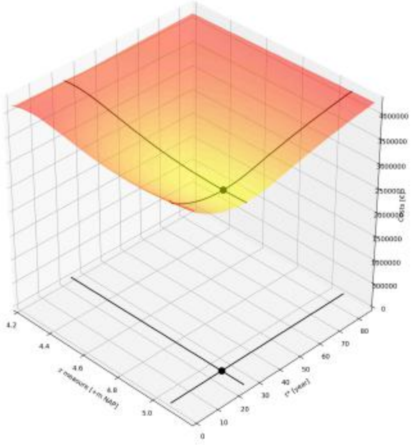
Sensitivity analyses plots

E.1. Measure & size



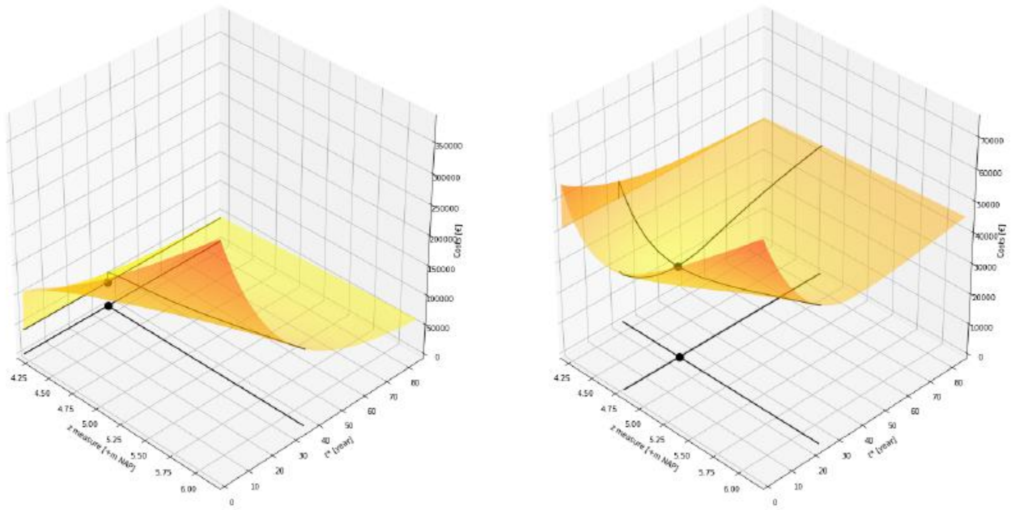
(a) Dike - large area

(b) Land fill - large area



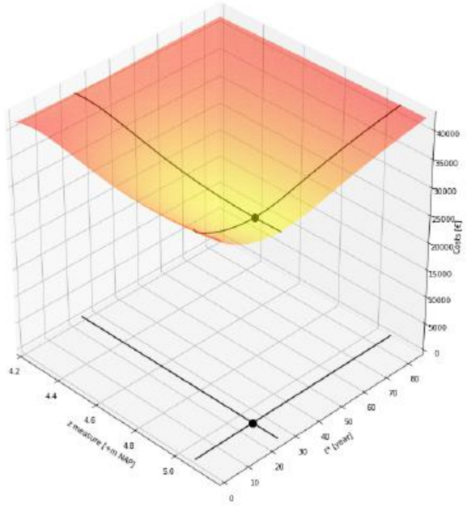
(c) Flood proofing - large area

Figure E.1: Plots for the sensitivity analysis on different kinds of measures for the large area.



(a) Dike - small area

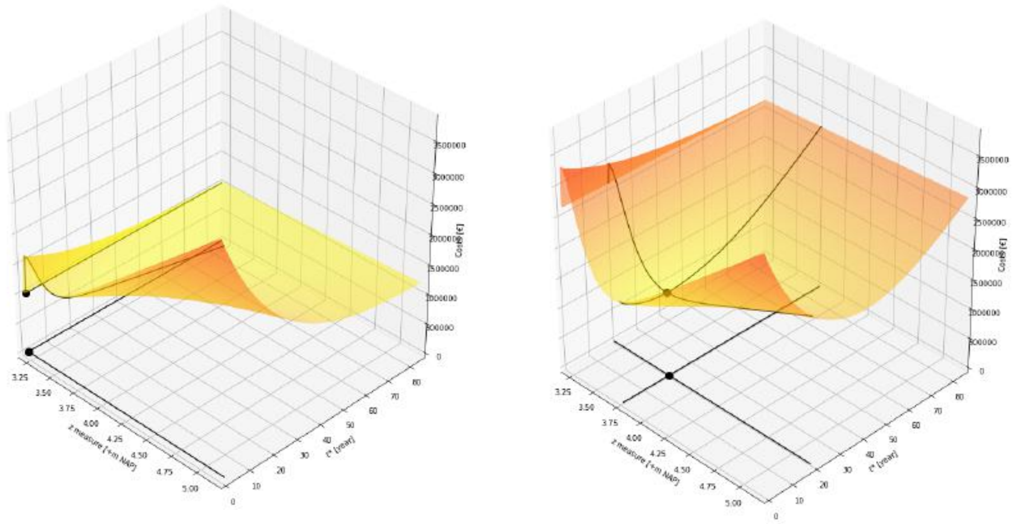
(b) Land fill - small area



(c) Flood proofing - small area

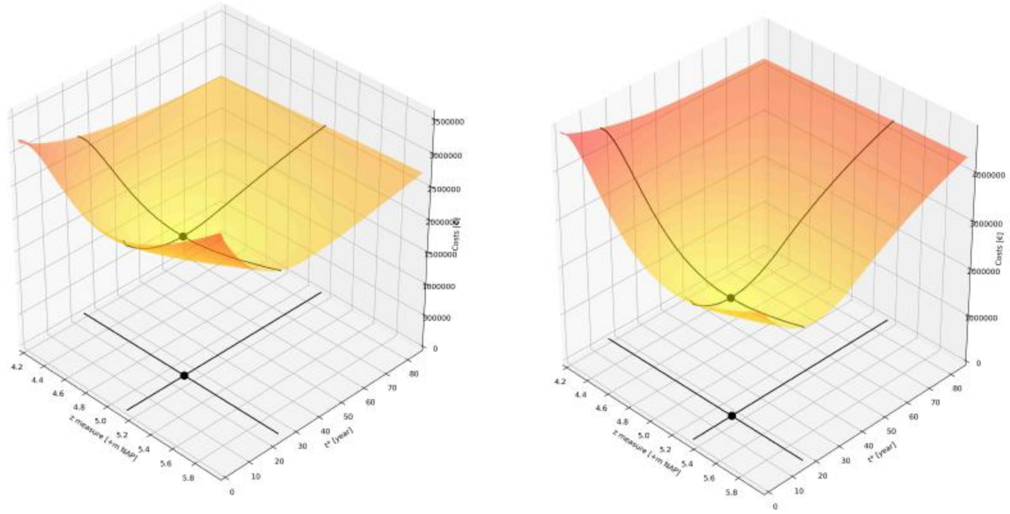
Figure E.2: Plots for the sensitivity analysis on different kinds of measures for the small area.

E.2. Climate & location



(a) Inside the Maeslantbarrier, G+ (moderate) climate

(b) Inside the Maeslantbarrier, W+ (warm) climate

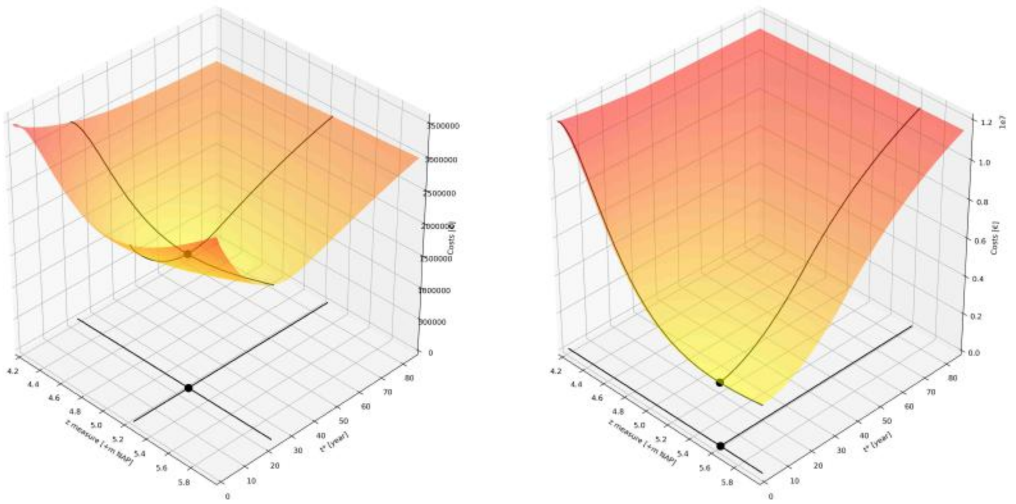


(c) Outside the Maeslantbarrier, G+ (moderate) climate

(d) Outside the Maeslantbarrier, W+ (warm) climate

Figure E.3: Plots for the sensitivity analysis on climate and location.

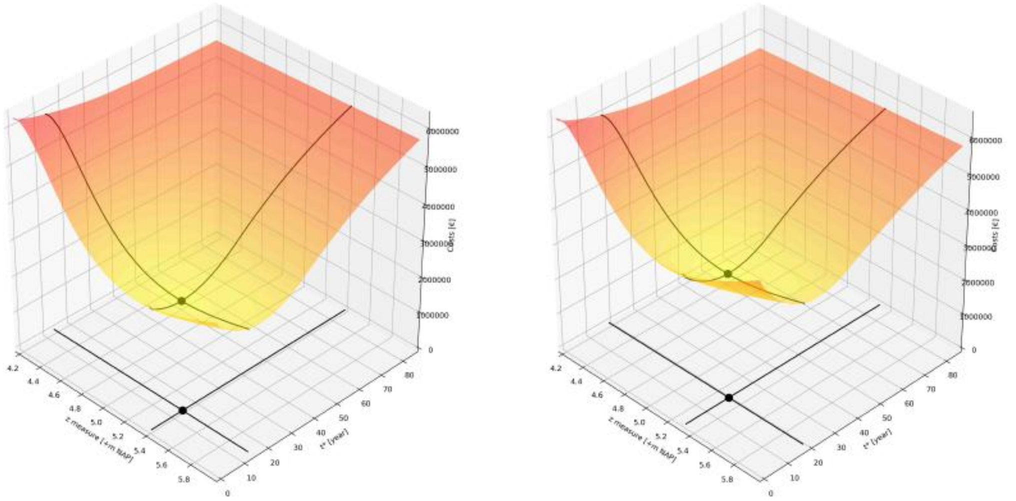
E.3. Sector



(a) Bulk terminal (b) Distribution

Figure E.4: Plots for the sensitivity analysis on sectors.

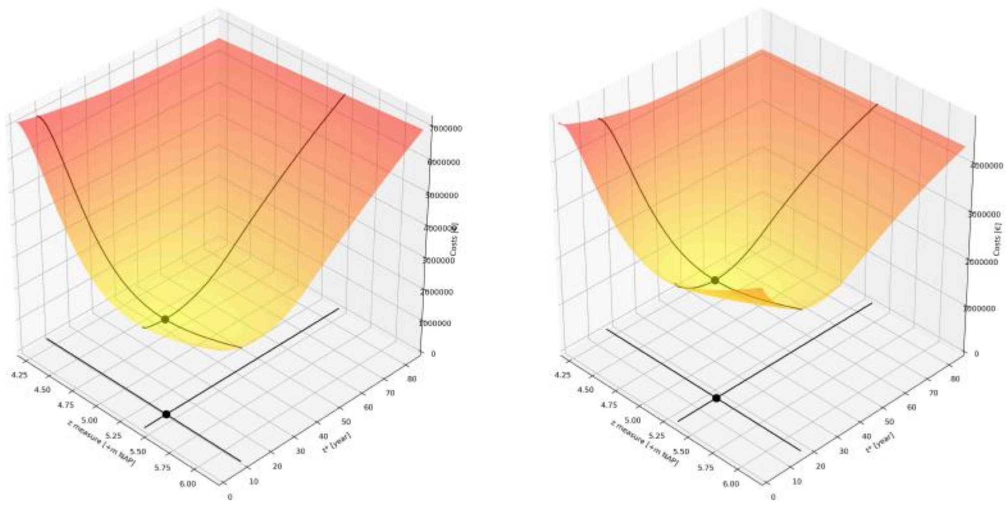
E.4. Shape



(a) Dike: 500 x 400 m (b) Dike: 1000 x 200 m

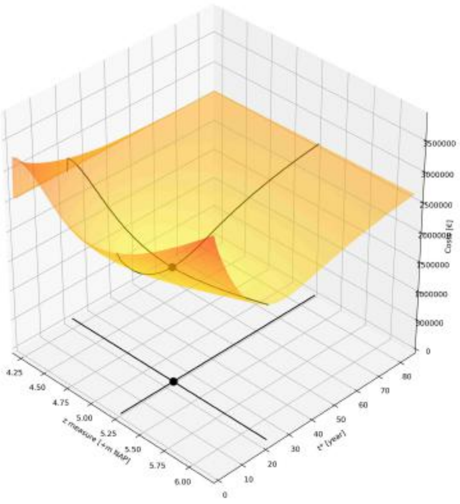
Figure E.5: Plots for the sensitivity analysis on shape.

E.5. Economic prospect



(a) Low discount rate (2,5%)

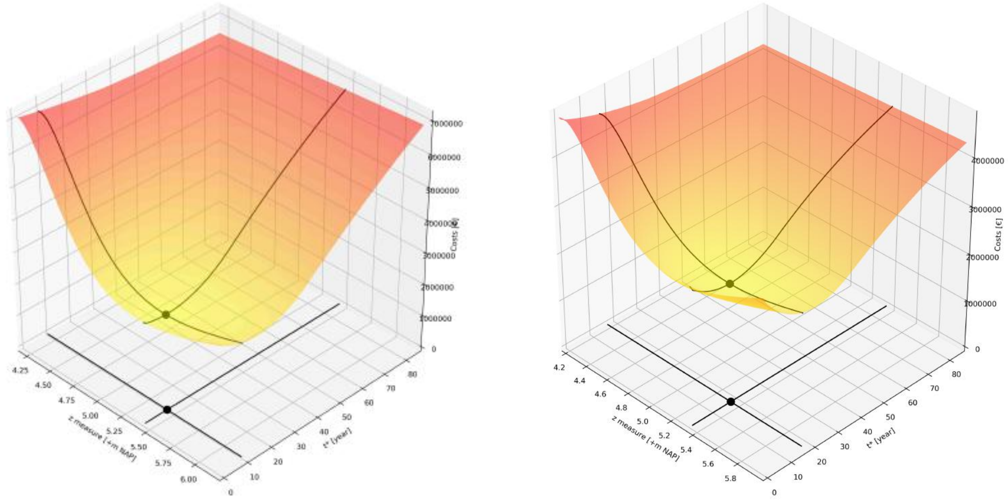
(b) Average discount rate (3,6%)



(c) High discount rate (5%)

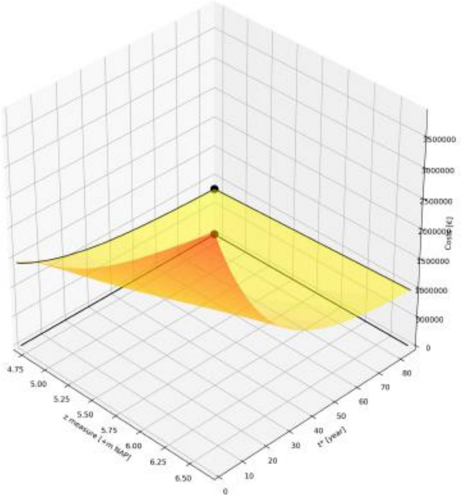
Figure E.6: Plots for the sensitivity analysis on economic prospect and the discount rate.

E.6. Original terrain



(a) Low original terrain (3,7 m)

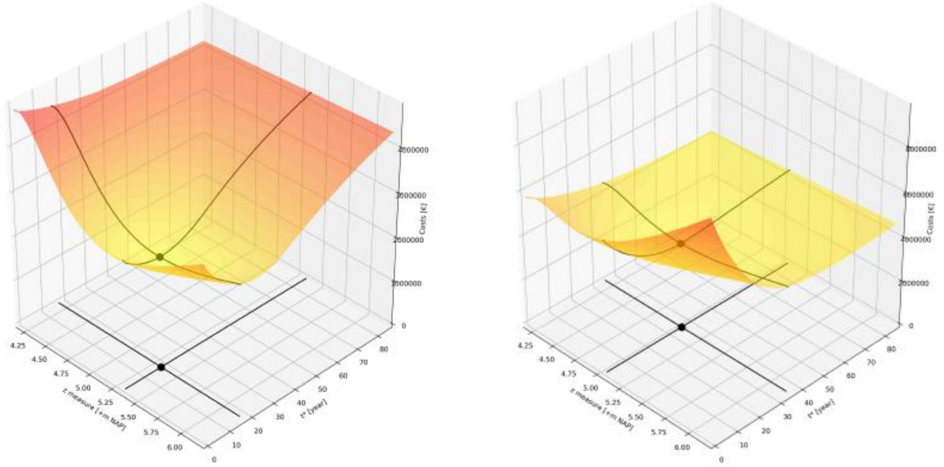
(b) Medium original terrain (4,2 m)



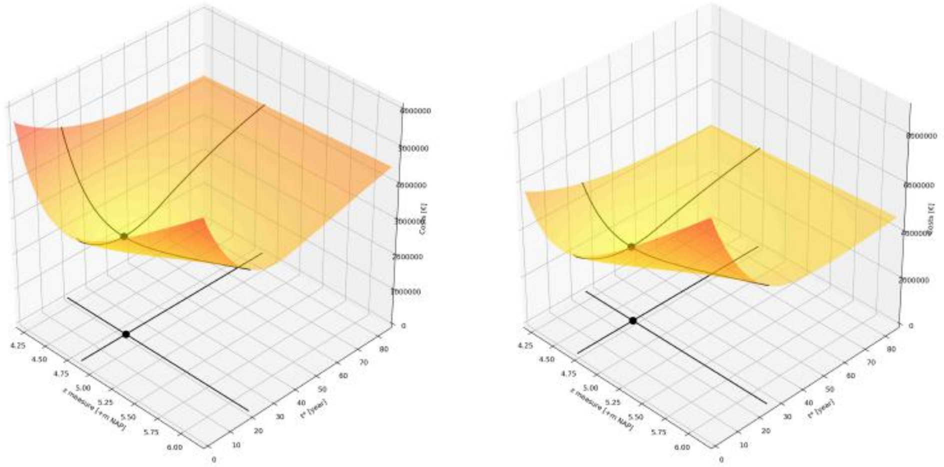
(c) High original terrain (4,7 m)

Figure E.7: Plots for the sensitivity analysis on the ground level.

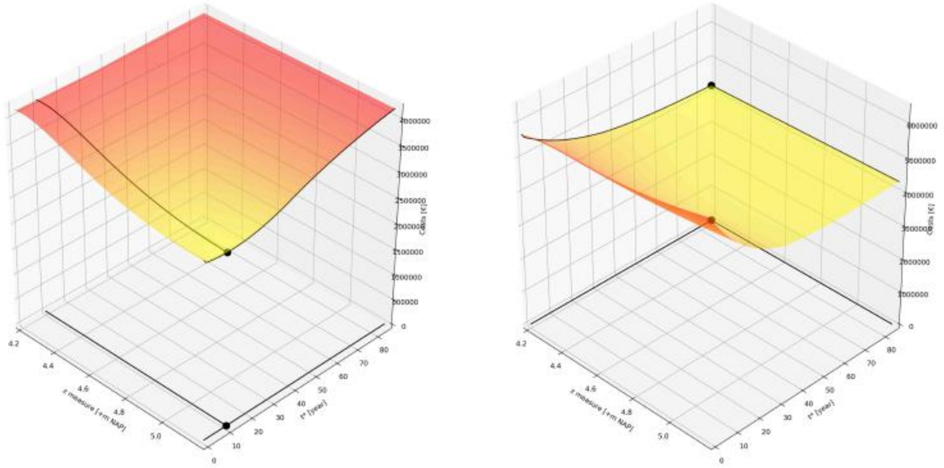
E.7. Investment costs



(a) Dike low investment cost (b) Dike high investment costs



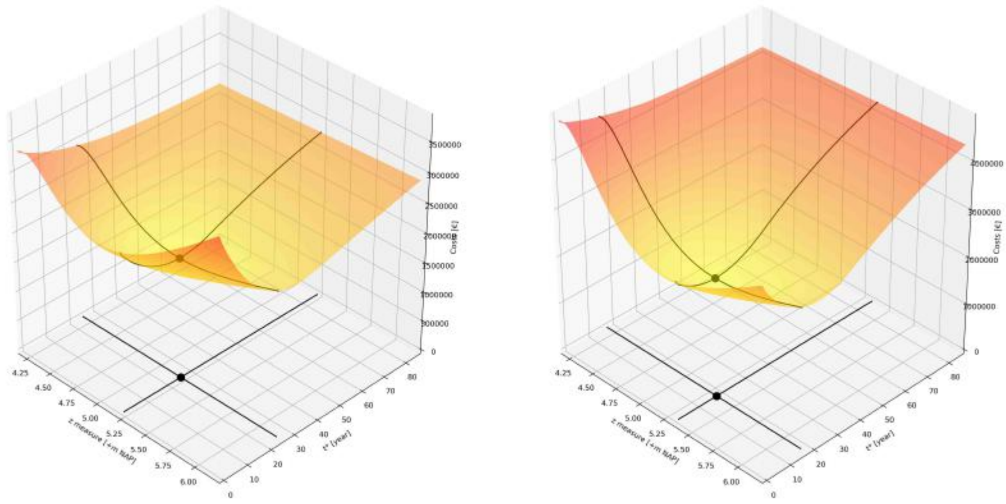
(c) Land fill low investment cost (d) Land fill high investment costs



(e) Flood proofing low investment cost (f) Flood proofing high investment costs

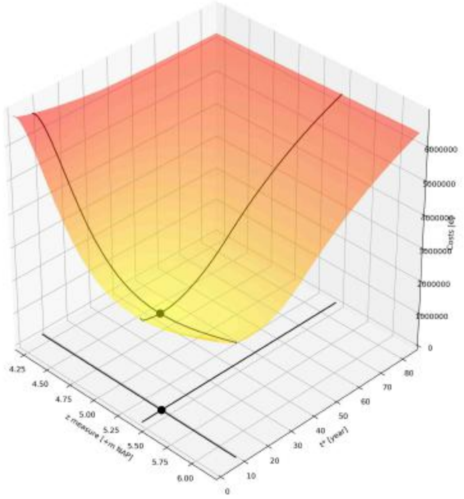
Figure E.8: Plots for the sensitivity analysis on investment costs.

E.8. Indirect damage



(a) Concave recovery

(b) linear recovery

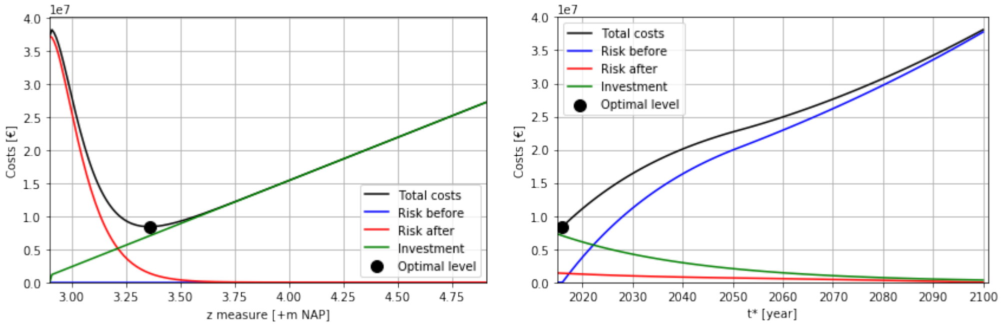


(c) Convex recovery

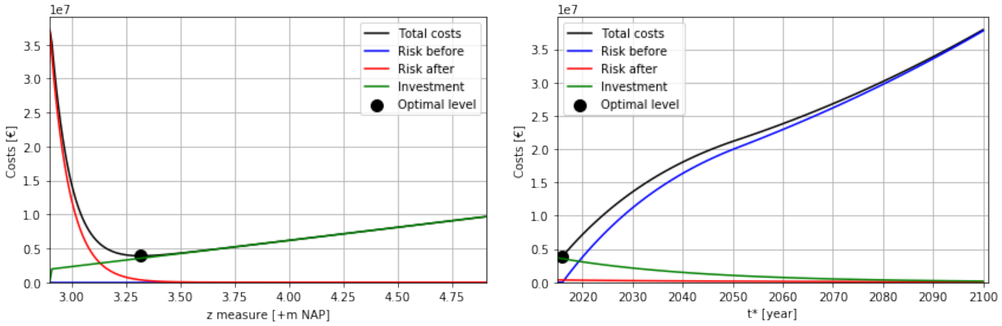
Figure E.9: Plots for the sensitivity analysis on indirect damage and recovery of flooded area.

F

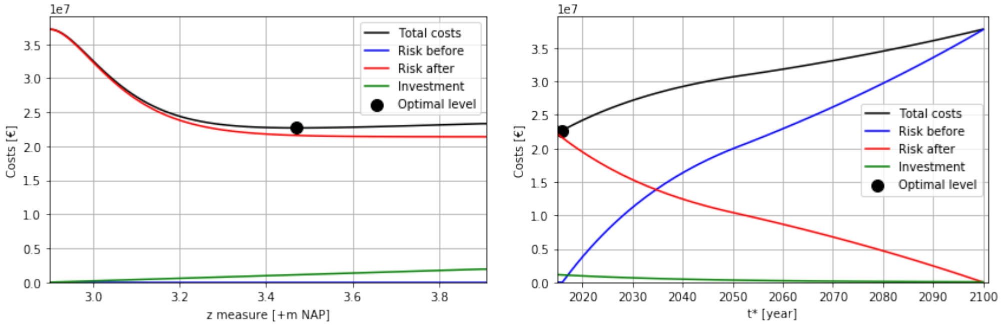
Case study cross sections



(a) Dike: t* = constant, $z_t < \delta z < z_t + 2$ (b) Dike: Δz = constant, 2015<t*<2100



(c) Land fill: t* = constant, $z_t < \delta z < z_t + 2$ (d) Land fill: Δz = constant, 2015<t*<2100



(e) Flood proofing: t* = constant, $z_t < \delta z < z_t + 1$ (f) Flood proofing: Δz = constant, 2015<t*<2100

Figure F.1: Cross section plots of the 3D plots from Figure 4.6. From this cross sections