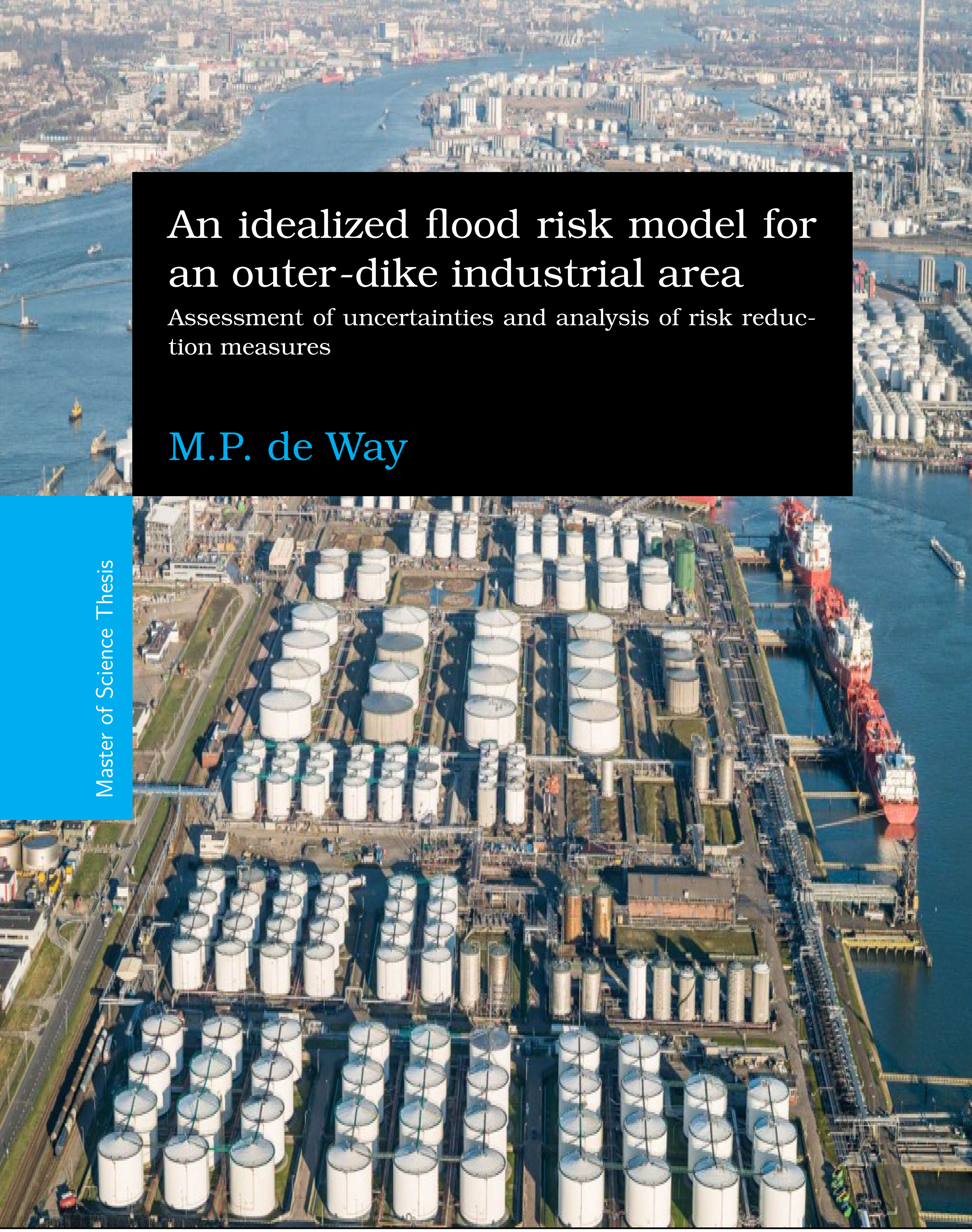

An idealized flood risk model for an outer-dike industrial area

Assessment of uncertainties and analysis of risk reduction measures

M.P. de Way

Master of Science Thesis

TU Delft Delft University of Technology

Department of Hydraulic Engineering

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For the degree of Master of Science in Hydraulic Engineering at Delft University of Technology

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November 2, 2016

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Finally I want to thank my family for supporting me throughout the years.

Martijn de Way
Delft, November 2, 2016

Executive summary

The Dutch coast is very well protected against flooding. The majority of the Netherlands is protected to set safety standards, which are embedded in Dutch law. Outer-dike areas are an exception to this protection. These areas are defined as the areas that do not lie behind water retaining structures. As some of these outer-dike areas contain valuable industry, knowledge of the current and future risks of these areas is important. Knowledge is needed of the possible material damage and social impact due to business interruption for these important harbour areas. The goal of this thesis is to get an answer to the question: How does the risk profile behave for an outer-dike industry and how do uncertainties, environmental damage and flood reduction measures affect the risk profile?

To analyse the behaviour of a risk profile, an idealized approach is taken to create a flood risk model. This idealized approach is used to provide better interpretation leading to insight into the effects of uncertainties, environmental risks and risk reduction measures. The area investigated is modelled after the situation of the Rotterdam harbour. However, due to simplification and idealizations is not a direct representation. It describes a flat area where flooding can occur from a single direction. Only flooding scenarios from sea are taken into account. With this model a reference calculation is made that describes the risks per square meter for the idealized situation. This reference calculation is used to describe the effect of various uncertainties on the expected outcome. The expected risk was described in Euro per square meter in net present value over a lifetime of 100 years. The results are slightly higher, but in the same order of magnitude of what is currently accepted in inner-dike modelling and the values of a more detailed calculation.

The uncertainties that are investigated are the knowledge uncertainty in direct damage estimators and indirect damage estimators. The effect of the knowledge uncertainty in water level predictors is an important factor in calculating the expected risk and is therefore considered in the uncertainty analysis. The influence of interest rate in the calculated expected risk is also considered. The knowledge uncertainty with the largest influence was the water level predictor. The knowledge uncertainty band of this water level predictor had the smallest coefficient of variance. However, the expected risk when taking this knowledge uncertainty into account increased with 350% in relation to the reference model without knowledge uncertainties. The influence of the direct damage estimator, indirect damage estimator and interest

rate uncertainties increased the expected risk by respectively 5%, <1% and 5% in relation to the reference model. In comparison to the water level predictor these are very small.

Based on this idealized flood risk model another model is made that analyses risks relating to environmental damage. For this research, the emphasis has been on cleaning of pollution created by an oil leak. Clean-up related costs are found to be large with an expected value of 400 Euro per square meter. However, the probability of a high water event being present combined with the fragility curve of a storage tank led to very small expected risks. In addition, the higher the fill of the tanks the lower the probability of failure and the lower the fill of the tank the lower the consequences. The risk assessment does not consider the ecological impact an oil leak can have on marine life, bird life and vegetation. On top of that, the ignition of flammable liquids can add to the risk profile, this needs to be examined more thoroughly to give a quantitative advice.

With the existing risk, flood risk reduction measures are also part of this research. The following three flood risk reduction measures have been considered: placing of a ring dike, using the containment dikes around tanks as retaining structures and gradually flood proofing the entire industrial area over 100 years. All three of these measures have a positive benefit/cost ratio. Placing a ring dike is the most efficient measure.

The use of the idealized modelling was helpful to gain insight into the effect of uncertainties, environmental risks and flood reduction measures. With this insight it is advisable to invest in improving the accuracy of the water level predictors. Environmental risks are estimated to be low. Further research should be done in the areas of oil dispersion and risks relating to flammability and corresponding domino effects as well as risks relating to ecological systems. In this idealized situation a ring dike is the most efficient flood risk reduction measure. However, the model is not a direct representation of the Botlek area.

Samenvatting

De Nederlandse kust is goed beschermd tegen overstromingen. Het grootste gedeelte van Nederland is beschermd met in de Nederlandse wet vastgestelde veiligheidsnormen. Echter zijn er ook buitendijkse gebieden, dit zijn gebieden die niet genieten van kust-en rivier bescherming. Op veel van deze buitendijkse gebieden ligt nog wel waardevolle industrie. Hierdoor is het belangrijk om een beeld te krijgen van de huidige en toekomstige risico's betreffende overstromingen. Kennis is noodzakelijk om de mogelijke materiele schade en schade door het stilliggen van industrie in te schatten. Het doel van deze thesis is om een antwoord te krijgen op de vraag: Hoe gedraagt een risico profiel van een buitendijks industrieel gebied zich en wat voor invloed hebben kennis onzekerheden, milieuschade en beschermende maatregelen op dit risico profiel?

Om te analyseren hoe een risico profiel zich hier gedraagt is een geidealiseerde aanpak gekozen om een overstromingsrisicomodel in elkaar te zetten. Deze geidealiseerde aanpak is gekozen om beter inzicht te verlenen in het effect van kennis onzekerheden, milieurisico's en risico reducerende maatregelen. Het gebied is gemodelleerd op basis van de situatie in de Botlek, Rotterdam. Het model beschrijft een vlak gebied waar er sprake is van eenzijdige overstroming. Met dit model is een referentie berekening gebruikt om de risico's per vierkante meter te inventariseren. Deze referentie berekening wordt gebruikt om het effect van verschillende kennis onzekerheden op de verwachte risico's te analyseren. De verwachte risico's zijn uitgedrukt in Euro per vierkante meter in Netto Contante Waarde(NCW) over een levensduur van 100 jaar. De gevonden resultaten zijn wat hoger, maar in dezelfde orde van grootte als wat er momenteel binnendijks wordt geaccepteerd en komen in order grootte overeen met waarden die gevonden zijn in een meer gedetailleerde berekening.

Een aantal kennis onzekerheden die onderzocht waren zijn de kennis onzekerheden die in de directe en indirecte schade schatters mee spelen. Ook het effect van de kennis onzekerheid in waterstands voorspellers is onderzocht. Daarnaast is de kennis onzekerheid van de rentevoet meegenomen en de keuze voor welk type indirecte schade schatter gebruikt kan worden. De invloed van elke kennis onzekerheid op het verwachte risico geeft aan welke kennis onzekerheden prioriteit hebben om verbeterd te worden. De grootst gevonden invloed is de kennis onzekerheid in de waterstandsvoorspeller. Deze verhoogde het verwachte risico met 350 %.

De kennis onzekerheden in direct, indirect en rentevoet waren respectievelijk 5%, <1% and 5%.

Gebaseerd op dit geidealiseerde overstromingsrisico model is een model gemaakt die de mileu risico's analyseert. In dit onderzoek ligt de nadruk op de schoonmaak gerelateerde kosten in het geval van een olielek. Deze kosten waren vrij groot, met verwachtingswaarde van rond de 400 Euro per vierkante meter. Daarentegen waren de kansen waarop hoog water op treedt en de tank faalt zo klein dat het gevonden risico marginaal klein was. Bijdragend hieraan is het effect dat volle tanks een lagere faalkans hebben en legere tanks lagere consequenties hebben. Deze risico analyse neemt echter nog niet de ecologische impact van zo'n olielek mee. Daarnaast zijn risico's gerelateerd aan vuur als gevolg van het ontsteken van gelekte olie ook niet gekwantificeerd in deze risico benadering.

Door de aanwezigheid van risico's, die vooral gerelateerd zijn aan directe schade, zijn risico reducerende maateregelen bekeken om het risico profiel te verminderen. Drie risico reducerende maatregelen zijn behandeld: Het plaatsen van een ring dijk, het gebruik van putdijken als stormvloedkeringen en het floodproof maken van de industrie over een tijdbestek van 100 jaar. Alle maatregeln hadden een positieve voordeel/kosten ratio. Het plaatsen van een ring dike is het meest kosten efficient.

Het gebruik van het geidealiseerde model was behulpzaam in het snel verkrijgen van inzichten wat betreft de invloed van kennis onzekerheden, milieu risico's en risico reducerende maatregelen. Met dit inzicht is het verstandig te investeren in het verbeteren van waterstands voorspellers. Risico's rondom milieu schade zijn gering. Echter, meer onderzoek is nodig naar de verspreiding van olie in een havengebied in verband met risico's gerelateerd aan ontvlambaarheid en domino effect zowel als risico's die optreden richting ecologische systemen. Een ringdijk is in deze gesimplificeerde situatie het meest voordelig.

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Glossary

List of abbreviations

NAP:	Normaal Amsterdams peil
EPK:	Europoort kering
MHW:	Mean high water
KNMI:	Koninklijk Nederlands Meteorologisch Instituut
RWS:	Rijkswaterstaat
NPV:	Net present value
RHDHV:	Royal HaskoningDHV
VNK:	Veiligheid Nederland in kaart
GNP:	Gross National Product

List of symbols

S:	Damage
E:	Expected value
c_v:	Coefficient of variance
σ:	Standard deviation
μ:	Mean
P:	Probability
P_f:	Probability of failure

Chapter 1

Introduction

1-1 Flood risk outer-dike areas

The Netherlands is a country that is specialised in flood protection. This position comes from a history of water related problems and a necessity due to the low elevation of the Netherlands. Over 60 percent of the country is estimated to be flood prone.

Currently, the Netherlands has a high level of flood protection. The protection level for large-scale coastal and riverine flood return periods are typically as low as 1,250 to 10,000 years. This protection level is based on loss of life as well as economic considerations and social disruption. The protective measures primarily consist of dikes, dunes and barriers protecting the hinterland.

The Netherlands is not completely protected against inundation. There are areas located outside of the dike protection. These are called outer-dike areas. Inner-dike areas are part of the protection by the Dutch government, where it takes precautionary measures to protect the Dutch citizens against flooding. The outer-dike areas are not part of this arrangement. In these areas, the users bare the risk of damage by flooding.

Figure 1-1: Example of a Botlek quay

The harbour and industrial complex of Rotterdam is largely an outer-dike area, an example of how such an area looks is shown in figure 1-1. This area is of high economic and strategic importance to both the Netherlands and Europe. The port authority estimates the contribution to the gross national product of the Netherlands to be around 3 percent and employs roughly 150.000 employees[25].

Due to its high societal importance and uncertainties relating to the social impact a flood could have, the Port Authority, Rijkswaterstaat West-Nederland Zuid (RWS WNZ), the municipality of Rotterdam and the ministry of Infrastructure and Environment(I&M) - hereafter called the project group - started a pilot to investigate the effects of a flood on outer-dike areas. In cooperation with interested parties, the pilot study Flood Risk Botlek aims to analyse the risk of flooding. The aim is to develop an adaptive strategy for the outer-dike area, taking climate change scenarios into account. By conducting these activities in cooperation with interested companies flood risks are shown, as well as how these risks relate to other company related risks. This has led to increased interest by stakeholders in the flood risks in the present and in the future. The current stage (2016) of the pilot is to develop an adaptive strategy which the government and/or companies can undertake to reduce the risks present. The pilot is part of the 'Deltaprogramma Rijnmond Drechtsteden' and is co-financed by the ministry of I&M.

The pilot area, the Botlek (including the Vondelingenplaat) shown in figure 1-2, that is chosen by the projectgroup is a high value area and is completely located outer-dike. It primarily consists of petrochemical, oil refinery, oil storage, bulk and container terminals. It contains possible environmental hazards as a significant amount of hazardous material is present in the area, which could lead to high environmental consequences in case of a flooding.

HKV Lijn in water and VU Amsterdam have started the pilot with the analysis of flood probabilities based on work of Deltares. A consequence analysis has been conducted in cooperation with companies, governments and experts based on the following quantitative aspects:

- Direct economical damage
- Indirect economical damage
- Loss of life
- Social disruption

Parallel to this, Royal HaskoningDHV has conducted a qualitative analysis on environmental damage and inundation of individual objects. Herein, an assessment framework is created, in which they can compare the flood related risks to other risk levels for which assessment frameworks already exist. The results from this first stage of the pilot have initiated a second phase, in which an adaptive strategy will be developed.

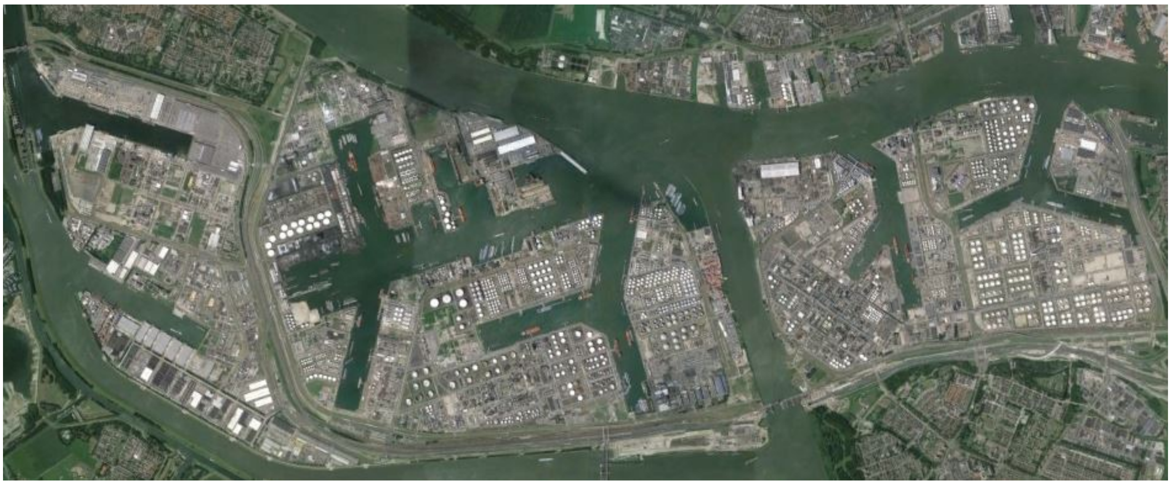


Figure 1-2: Botlek area

The phase one pilot results are currently available (2016). Deltares has used a flow model, which shows the probabilities of flooding and inundation levels with the current and future climate scenarios. These show that inundation has a small chance of occurring. However, taking climate change into accounts these risk levels will increase. Based on these results a risk assessment was necessary to assess the actual and future risk. This risk assessment was done by HKV Lijn in water and VU Amsterdam, and has involved an assessment of the direct and indirect damage, loss of life and social impact.

The result of the risk assessment is that the risks of a flood in the Botlek are comparable to current inner-dike risk levels. However, not all consequences of a flood have been considered. Uncertainties and environmental damages are not extensively assessed. These can occur due to failure of an oil storage tank resulting in a release of pollutants and contamination of the environment. This could have high influence on what possible measures are advised to be taken. This is a difficult aspect as quantifying or monetising environmental damage is an aspect, of which little information is present. More insight into how this environmental aspect can be considered into the risk model is beneficial for an adaptive strategy.

For the next phase of the pilot, in which an adaptive strategy is formulated, insight into what effect different protective measures have on the risk profile is needed. A thorough examination of each protective measures consist of many calculations and is very detailed. This is costly to perform for various different measures. Currently, adaptive and protective measures are being investigated in the pilot study. However, a parallel research with an idealized approach gives quick insight into the effectiveness of several flood reduction measures.

Finally, the question arises about how large the impact of knowledge uncertainties is on the risk profile. Knowledge uncertainties arise from water level predictors, such as water depth and climate scenarios. Also estimators for the following damage sources are considered: the direct damage for specific companies, the type of damage estimator used for indirect damage, quantifiable environmental damage and the indirect consequences of environmental damage on society. It is necessary to take into account the most relevant sources of knowledge uncertainty when developing an adaptive strategy. A knowledge uncertainty analysis gives additional insights into what knowledge uncertainties influence the outcome the most.

1-2 Research question

The insights obtained from the background information and problem definition have led to the main research question of this thesis.

The main research question of this thesis is:

'How does the risk profile behave for an outer-dike industry and how do uncertainties, environmental damage and flood risk reduction measures affect the risk profile?'

The additional research questions that will lead to achieving this goal are:

a) How do uncertainties in flood indicators and damage estimators influence the estimation of flood risk?

b) In what way can environmental damage caused by a chemical leak be modelled and how does it compare to the existing flood risk profile?

c) What flood risk reduction strategies are possible and which are most effective according to the decision model?

1-3 Report structure and methodology

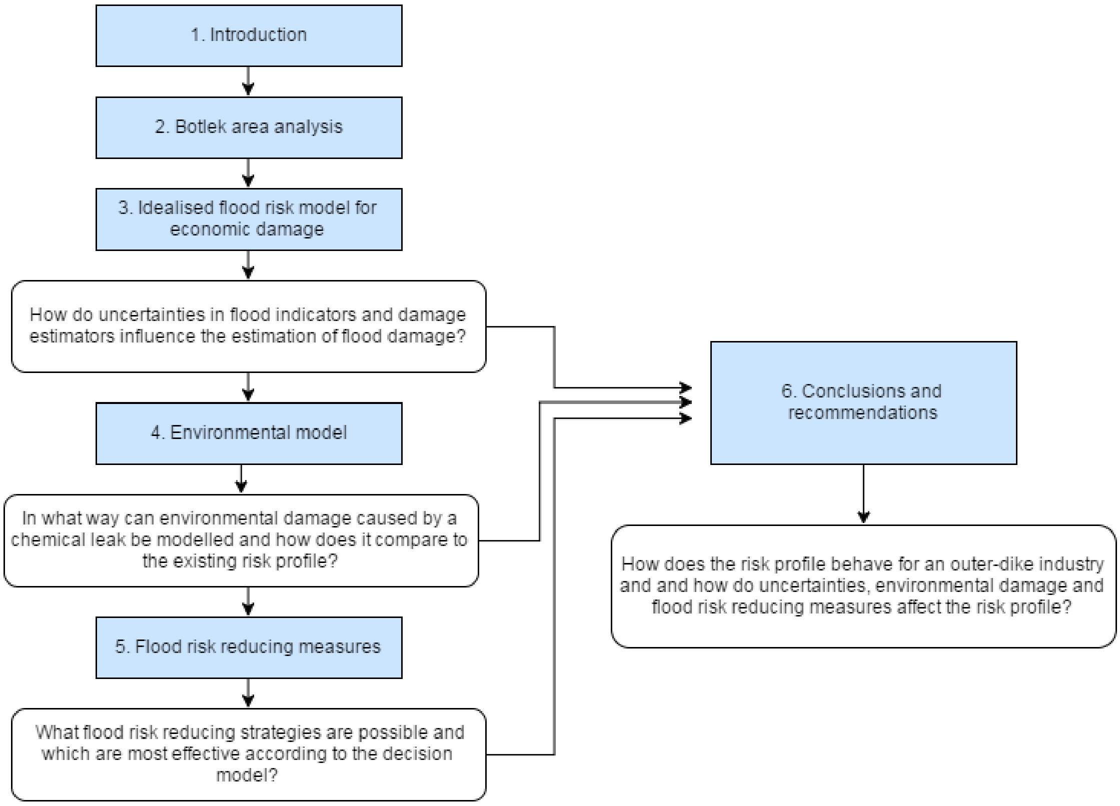
This section gives an overview of the report structure and a short overview of methods that are used to answer the main research question. Each chapter contains a more specific methodology as well, but this chapter explains the general structure.

In chapter 2, an introduction is given about the pilot study area in chapter 2. It gives a short overview of the physical attributes, infrastructure and occupation.

Chapter 3 presents an answer to how uncertainties of several flood and damage estimators influence the outcome of a decision model. To answer this question an idealized model is constructed with a single storage tank. With this the uncertainty distributions are implemented and interpreted. The results are discussed and viewpoints are given.

An environmental damage model is set up in order to answer the question of how the environmental damage can be taken into account in the risk profile. Chapter 4 describes the set-up of this model, where assumptions are made and the model is constructed. The chapter also discusses the results based on the idealized model with a single storage tank.

To find out what the impact of the flood reduction measures is, the risk profiles of each protective measure are generated in the model. Finally, a cost benefit analysis is made to assess which adaptive or protective measure is most beneficial.


1. Introduction
2. Botlek area analysis
3. Idealised flood risk model for economic damage
How do uncertainties in flood indicators and damage estimators influence the estimation of flood damage?
4. Environmental model
In what way can environmental damage caused by a chemical leak be modelled and how does it compare to the existing risk profile?
5. Flood risk reducing measures
What flood risk reducing strategies are possible and which are most effective according to the decision model?
6. Conclusions and recommendations
How does the risk profile behave for an outer-dike industry and and how do uncertainties, environmental damage and flood risk reducing measures affect the risk profile?

Chapter 2

Botlek area analysis

An overview of the Botlek area is given in this chapter. This chapter divides the area in three layers. The first layer consists of the physical properties, the location, elevation, current flood risk and current flood risk reducing measures. The following layer consists of networks of infrastructure, describing the roads, railways and waterways. The final layer describes the occupation of the area, the port activities and governance.

2-1 Physical properties

2-1-1 Location and elevation

The pilot area consists of the Botlek area and the Vondelingenplaat, further in this document merged under the name Botlek. The location is shown in figure 2-1. The Botlek is subdivided in three sections for reference.

(a) Location Botlek in the port of Rotterdam

(b) Zoom in of the Botlek

Figure 2-1: Location of pilot area

The elevation of the land increases from the city of Rotterdam towards sea from NAP+3.4m to NAP+5m in the Maasvlakte 2 as is seen in figure 2-3, where red indicates high elevation and blue low elevation. In the Botlek the elevation ranges from NAP +4.0m to NAP +5.5m. The Botlek III is located most landward and therefore has lower elevation than Botlek I and II. In Botlek I and II there are large differences in elevation where the lowest point is at the south-western side.

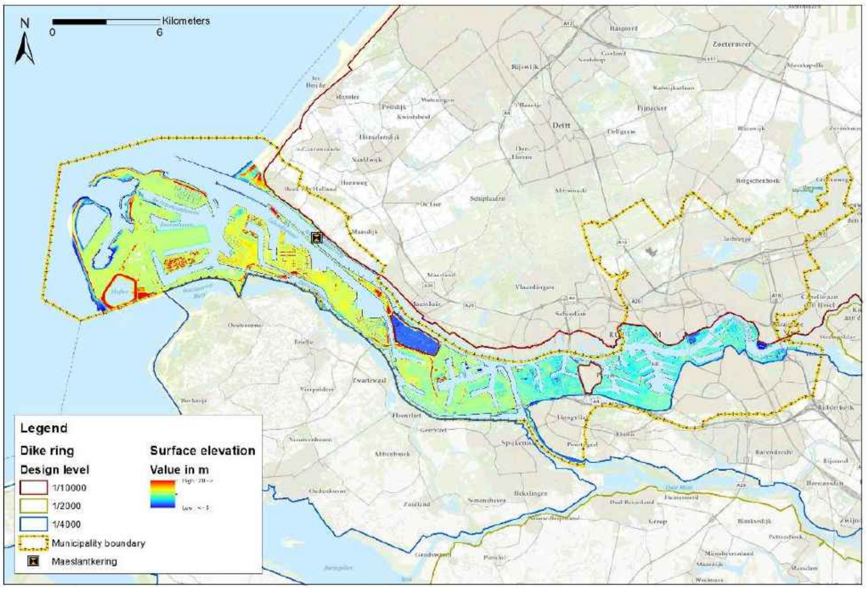


Figure 2-2: Elevation of Rotterdam harbour

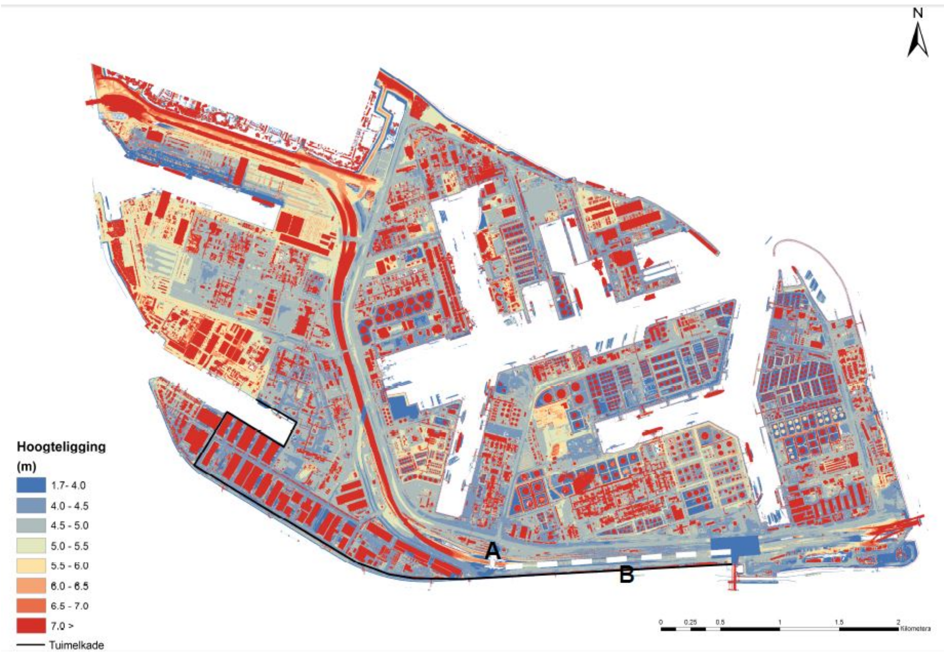


Figure 2-3: Elevation maps of Botlek I and II [2]

2-1-2 Current flood risk

The current flood risk in the Botlek is primarily related to flooding originating from sea. The water can enter the Botlek via the Hartelkanaal, which since the opening of the Beerdam, is in open connection with the sea. In figure 2-4 the water level exceedance graph is shown for 2015 for the Hartelkanaal. From this graph can be deduced that for an area as the Botlek the probabilities of flooding are limited. Water level predictions of NAP+4.5m, corresponding with inundation, have a probability of exceedance of 1/550 per year. For sea level rise the probability of exceedance increases. In this analysis waves and seiches are not considered.

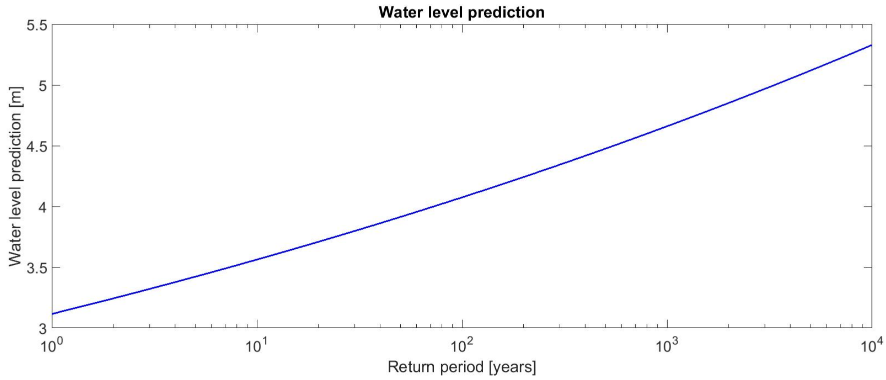
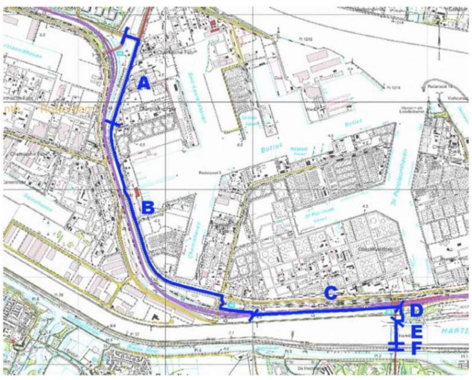


Figure 2-4: Water level exceedance graph for 2015

2-1-3 Flood risk reducing measures

There is an elevated road that functions as part of a retaining structure, the Europoortkering(EPK) which is shown in figure 2-5. It contains sections with relatively low elevation going as low as NAP + 4.5m at section C. It contains passages through which flow can pass during storm conditions.



Naam [-]	Sectie [-]	Omschrijving [-]
EPK-II	A	Aansluiting Europadijk 1000 m
	B	Kortsluiting A15 – Botlekweg 3100 m
	C	Rijksweg A15 – 1740 m
	D	Oeveraansluiting noord 260 m
	D1	Erosiebestendige strook 100 m
	D2	Kade in basalton t.p.v. oude sluis 100 m
	D3	Damwand 60 m
SVKH	E	Hartelkering en sluis
	F	Oeveraansluiting zuid op Brielse Maasdijk 50 m

Figure 2-5: Location and sections of the Europoortkering with corresponding lengths [5]

In order to reduce the chance of flooding in the Botlek the municipality of Rotterdam has constructed a low dike section along the northern side of the Hartelkanaal, called the Tuimelkade. The Tuimelkade was created out of necessity as the Beerdam was openened increasing the governing high water(GHW). The quay ranges from the Hartelkering to the Seinehaven as is shown in figure 2-1b by the yellow line. It is constructed out of clay material with a grassy slope as a cover. The Tuimelkade has an elevation ranging between NAP +5.20m and NAP +5.35m [1] and was designed to repel the GHW, but no wave overtopping and seiches calculations were taken into account for the stability[3].

2-1-4 Soil subsidence and climate change

Due to gas extraction and consolidation, subsidence should be taken into account. This is shown in figure 2-6, where green represents little to no settlement and red indicates high amount of settlement. According to figure 2-6 the effects are limited in Botlek I and II and the effects are relatively higher in Botlek III.

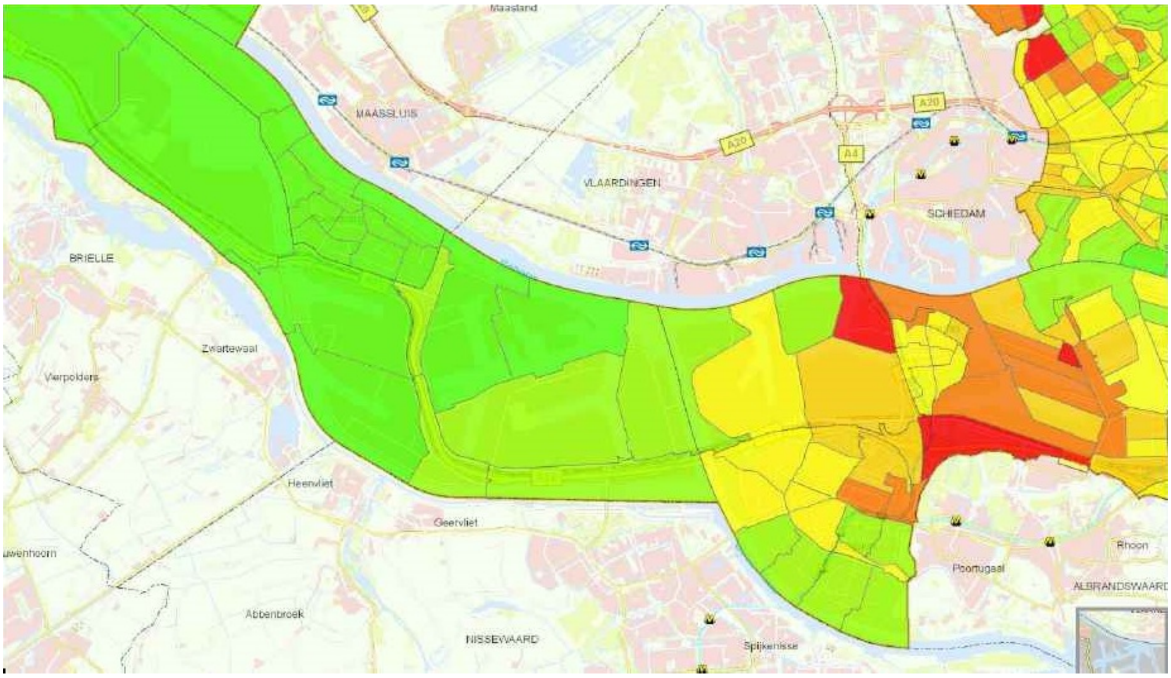


Figure 2-6: Soil subsidence (Bron:Gemeente Rotterdam)

Next to the ground subsidence, also the effects of sea level rise due to climate change have a large influence on the flood sensitivity of the Botlek. The KNMI has published several climate scenarios in 2014, these give an estimation of what the sea level rise is in 2050, 2085 and 2100. The sea level rise increases with 0.35m in 2050(W+) and can be as high as 0.85m in 2100(W+)[2]. These consider the highest rising sea level rise and therefore possibly lead to an overestimation of risk.

2-2 Networks of infrastructure

2-2-1 Waterways

The Botlek is situated between four waterways, in the north the Nieuwe Waterweg, the Calandkanaal to the west, the Hartelkanaal in the south and the Oude Maas to the east.

The Nieuwe Waterweg is connected to sea and can be closed off by means of the Maeslantkering. The Maeslantkering keeps the Nieuwe Waterweg at NAP +3.00m during storm conditions. This measure protects the largest area of Botlek II and III. However, the probability of failure for the Maeslantkering, according to Rijkswaterstaat [29] is 1 in 100 closures.

The Calandkanaal has an open connection to sea until it meets the Rozenburgsesluis (dark blue line, figure 2-1b). It directly connects parts of Botlek I to the sea.

The Hartelkanaal also has an open connection to sea, but can be closed off by the Hartelkering(light blue line, figure 2-1b). This, however, does not ensure protection to Botlek I and Botlek II.

2-2-2 Roads

There is one main road corridor on the Botlek, the roadway A15. This is the connecting element to the Europoort and the Maasvlakte as well as the Botlek. The A15 acts as the main road for this area and connects it with the western harbour area.

The road lies on top of the Europoortkering, which is shown in figure 2-5. Because of the low elevation this road can flood in case of severe storm events. This shuts down transport during an event, and possibly leads to repair time, which shuts down a large part of the industry.

There are scheduled future additions to the road system. The Blankenburg connection will consist of a connection between the A15 east of Rozenburg with the A20 between Maassluis and Vlaardingen. This connection will be constructed underneath the Nieuwe Waterweg and will increase the access to the area.

2-2-3 Railway

The railway system that lies on the Botlek is part of the Betuwelijn connecting all the transport from the harbour of Rotterdam to the border of Germany. The railway system is therefore of high importance to the entire harbour area as it consists of one of the main infrastructures that connects the harbour. It is located parallel to the A15.

There are also scheduled future additions that are planned in the case of railways. The Calandbrug is ready to be replaced as it is at the end of its technical life expectancy. As replacement a railway viaduct will be constructed on the Theemsweg, which will reduce hindrance between train and boat traffic.

2-3 Occupation of the area

2-3-1 Port activities

The harbour of Rotterdam supports a number of port activities. A subdivision has been made of the various harbour activities, a layout of this is shown in figure 2-8. The Botlek contains around 2.300 ha of industry and therefore includes a quarter of the total surface area of the Rotterdam harbour. It directly and indirectly employs around 150.000 people.

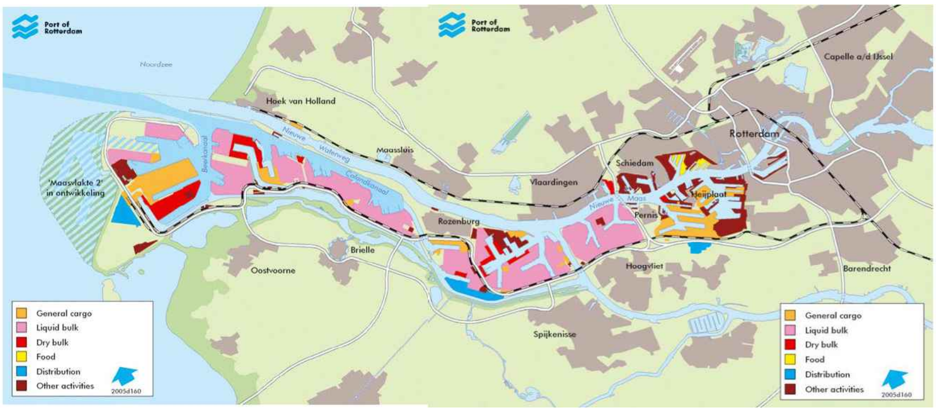


Figure 2-7: Layout of different companies of the harbour of Rotterdam according to www.portofrotterdam.com

The pilot area primarily focusses on liquid bulk refineries. A distribution of the different types of companies that are established in the pilot area is shown in figure 2-8. These liquid bulk companies consist mostly out of oil refineries and chemical industry. The harbour contains the largest petrochemical cluster of north-western Europe.

Industry in this area is very intertwined as many individual companies depend on the delivery of raw materials from other companies. On top of that, many security issues and optimising processes are in cooperation with other companies.

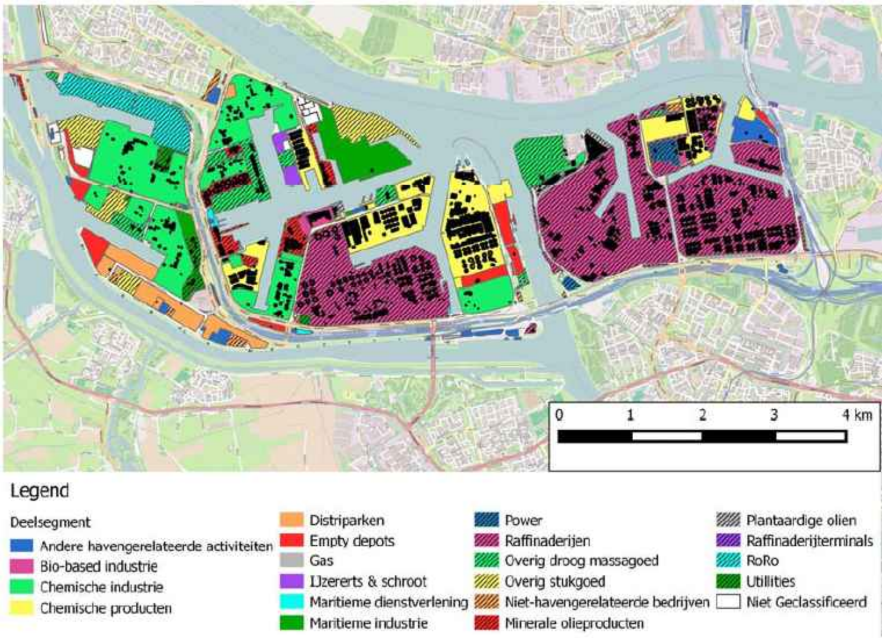


Figure 2-8: Layout of different activities of the harbour of Rotterdam according to www.portofrotterdam.com

Companies do not currently have structural measures against floodings in place. Safety measures against oil leakage are in place, such as the existence of containment dikes around storage tanks. These are designed to contain the amount of released material of that tank facility. Additionally, it is conceivable that it also works as a water retention mechanism in case of flooding. Based on visual observation the containment dikes are approximately 2 meter in height and have a maximum slope of 1:1 [11]. The dike has been designed that it should hold the full volume of the tank in case of an oil leak with an additional safety height of 0.25m [11].

2-3-2 Governance

Several large companies have facilities on the Botlek area. A number of interested parties are listed below. A high level of interest can be expected from these due to expected economic and political consequences. Not only companies have interest, but also other institutions as a variety of situations can occur because of a flood, such as a leakage or a fire.

- Deltalinqs - This organisation represents the interests of over 95% of the harbour and industrial companies in the mainport of Rotterdam. It is therefore a key player in measures and activities taken in the harbour
- Established companies - The companies that are situated in the Botlek have high interest in preventing damage and interruption of business as well as preventing large ecological catastrophes.
- Port Authority / Havenbedrijf Rotterdam - The port authority has a responsibility to the tenants as it is the landlord of the location. It will be interested in knowing whether

its property is at risk and what can be done to prevent it. It also coordinates between different parties.

- Rijkswaterstaat - Even though it is not responsible for outer-dike areas, it is responsible for the Europoortkering, Hartelkering and Maeslantkering, which also has a direct effect on the Botlek. Cooperation is therefore convenient. It also gives information about expected high water levels and grants permits for outer-dike activities.
- Waterboard / Waterschap Hollandse Delta - The waterboard is responsible for all the locks in the area and is responsible for the dikering Rozenburg.
- Province / Provincie Zuid-Holland - The province directs an outer-dike policy with regard to loss of life. With this policy the Municipality of Rotterdam can weigh their decision for possible measures.
- Ministry of Infrastructure and Environment / Ministerie van Infrastructuur en Milieu - This ministry concerns itself about the liveability and accessibility of a structured and safe environment. It also considers the effect of possible events on social disruption.
- Municipality of Rotterdam / Gemeente Rotterdam - The municipality is responsible for controlling the plans regarding water safety. Communication regarding the hazards of outer-dike activities falls mostly on the municipality.
- DCMR - The DCMR is the environmental service in the area of Zuid-Holland. It inspects environmental ruling and safety and grant permits. It also acts when incidents occurs and has a priority of preventing incidents.

Chapter 3

Idealized flood risk model for economic damage

3-1 Introduction

This chapter consists of the set-up and results of the idealized model. The idealized approach is considered as this provides more interpretable results than sophisticated SOBEK and ArcGIS models. It removes complicated geometries and is more equipped to unravel the effect of a single measure. This simpler interpretation enhances the understanding of the application of knowledge uncertainties, environmental risks and flood reducing measures. A more detailed model leads to a costly and time consuming method of calculating the effects and leads to a difficult and more distorted analysis of the results.

First, the type of models that are used are discussed. The physical model assumptions are shown, followed by the assumptions made for the prediction of the flood characteristics, damage models and risk calculations. After this, the computational procedure that is used to run the model is explained. Finally, the results are presented and discussed.

To investigate the effect of multiple knowledge uncertainties, two type of models are used. The first model has no knowledge uncertainties incorporated in it. This model is called the **reference model**. The second model includes several types of knowledge uncertainties and different damage estimators. This is called the **probabilistic model**. The water level prediction and the damage estimators are all based on information of the report of HKV/VU [3].

3-2 Physical characteristics of the model

The outer-dike industry area is modelled as a flat area at a fixed elevation. The area is based on geometry and data relating to Botlek, however, the model is idealized and therefore not an exact representation of the Botlek. The elevation of the industry is based on the Botlek area and is fixed at NAP+4.5m. The modelled area does not contain any flood defences. A sketch is shown in figure 3-1.

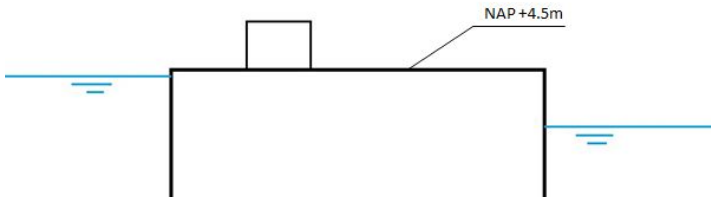


Figure 3-1: Sketch of the model setup

The industry on the area is modelled with a single storage tank that lies on a flat subsurface of the same elevation. The use of storage tanks is not coherent with the Botlek as many of these are not located in areas prone to inundation. However, they are used to assess the environmental consequences in chapter 4 and are therefore considered here. The plate has a channel on each side, similar to the Botlek. The area is assumed to be short enough that the water level on the industry area is equal to the water level in the channel in case of inundation.

3-3 Flood characteristics

The water level prediction in the channel is modelled with the water level exceedance frequencies curve presented in the HKV/VU report[3]. First, the present extreme water level statistics for 2015 are discussed and later the effect of sea level rise is discussed.

The water level exceedance frequency chart shown in figure 3-2 is used in this idealized model. In these water level predictions knowledge uncertainties are present. This is mostly due to lack of data on extreme high water events. For this reason the magnitude of the knowledge uncertainty increases with higher return periods as these events have not occurred and the prediction is more uncertain without data to extrapolate on.

The knowledge uncertainty of the water level predictor in this model has been based on a normal distribution around the predicted exceedance frequency line made by HKV/VU[3].

$$h_p(T) = norm(h(T),\ \sigma(T)) \tag{3-1}$$

$$\sigma(T) = 0.25m + 0.04 \cdot\ h(T) \tag{3-2}$$

Where h is the water level in metres +NAP, T the return period in years and σ the standard deviation. The value for σ is based on the report of HKV/VU[3] where the maximum accuracy for the water level prediction is estimated at 0.25m. This maximum accuracy is assumed for low water levels, which can be predicted most accurately as there is data of occurrence. The coefficient 0.04 is estimated by assuming a water level uncertainty of 0.5m at a water level prediction of 6m with 95% confidence interval. The water level predictions including the 95% confidence bands are shown in figure 3-2.

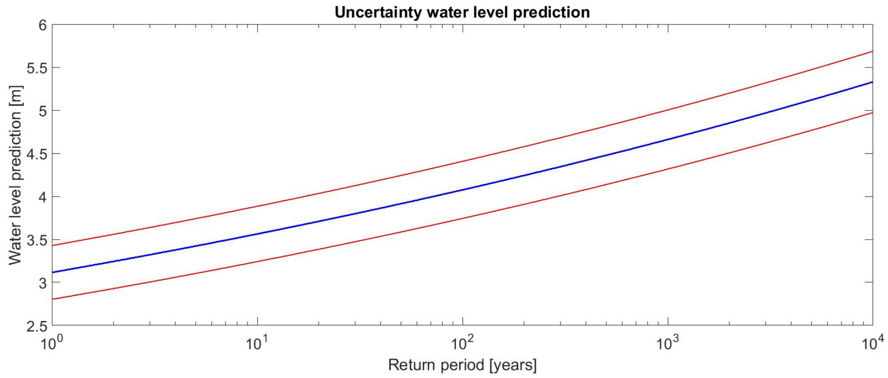


Figure 3-2: Water level exceedance frequencies for 2015

Also sea level rise is an important factor in this analysis. Two general scenarios are considered. The W+ scenario is a fast rising sea level rise scenario and the G scenario a slow rising sea level rise scenario. In this analysis the W+ scenario is taken to illustrate the risks with the highest increase in sea level rise. Three scenarios are modelled: the current climate scenario, the climate scenario for 2050(W+) and the climate scenario for 2100(W+). The scenario of 2050(W+) accounts for a 0.35m increase in sea level and the climate scenario of 2100(W+) accounts for a 0.85m increase in sea level[2]. The sea level rise has effect on the number of inundation events, but can also prove influential in how important knowledge uncertainties are in the decision model.

3-4 Damage estimators

The water levels are linked to a certain level of damage in case of inundation. Only economic damage is considered herein. Two types of economic damage are considered for this model, direct damage and indirect damage. Direct damage estimates the amount of material damage and product loss. Indirect damage estimates the costs of business interruption, social impact and damage due to loss of supply chains.

3-4-1 Direct damage estimators

With the use of damage graphs by Tebodin[8] (refined by HKV/VU[3]), the water level can be linked to a direct damage factor. This damage factor depends on the inundation depth. A higher inundation leads to a higher damage factor until maximum damage is reached. A simplified version is illustrated in figure 3-3. The damage factor is then multiplied with a maximum direct damage value per m^2. The maximum direct damage for tank storage is 823 Euro/m^2[3], but this value is different per type of land use. This value also contains a lot of knowledge uncertainty as it is based on expert judgement and is not case specific. This knowledge uncertainty is currently not taken into account.

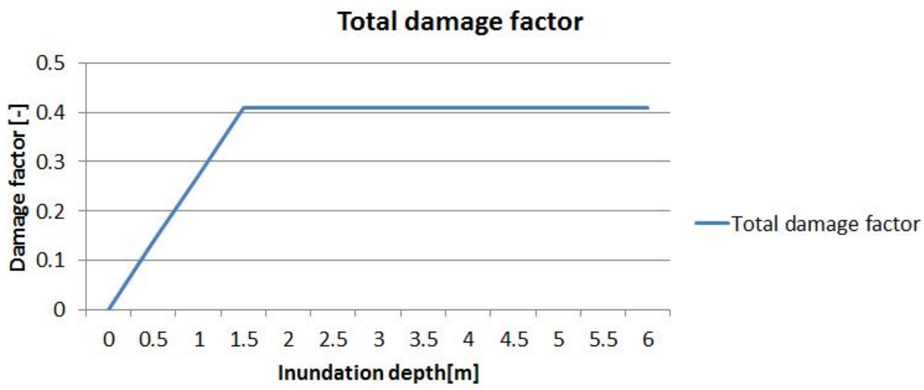


Figure 3-3: Simplified damage factor graph

The damage curves also contain knowledge uncertainties. Three points along the damage curve are considered in the uncertainty analysis: the initiation of damage h_0, the water level where maximum damage is reached h_{max}, and the maximum damage factor f_{max} that can be accredited to damage due to floods. Since there is limited information about the knowledge uncertainties in damage estimators a uniform distribution is used. The used values are based on the damage curves made by HKV/VU[3].

- Initiation of damage, h_0: The range for the knowledge uncertainty of the initiation damage is uniformly distributed between 0m and 0.5m. The knowledge uncertainty band of the initiation of damage h_0 is based on the fact that at an inundation depth of 0.5m a high amount of electronics will be damaged. Therefore at this point there is initiation of damage with a high likelihood.

- Inundation level for maximum damage, h_{max}: The inundation level where the maximum damage factor is reached is distributed uniformly from 0.5m till 1.5m. This is based on the assumption that at 0.5m a high amount of electronics is already inundated and at that point also installations can be affected. At 1.5m floatation starts to become more probable and maximum damage is more likely.

- Maximum damage factor, f_{max}: Lastly, the maximum damage factor has a large range depending on what kind of storage tank it is and whether it is full of material or empty. Floatation plays a key role in this assumption. The estimation from HKV/VU[3] is 0.41, as this has been refined quite recently the uncertainty in this is assumed to be relatively low. The range for this factor is therefore 0.32 - 0.5.

In the reference model, where no knowledge uncertainties are present, the values on the left are used. For the probabilistic model where knowledge uncertainty is present the values on the right are used.

$$\begin{aligned} &Reference\ model & &Probabilistic\ model \\ h_0 &= 0.25m & h_0 &= [0 - 0.5] \\ h_{max} &= 1m & h_{max} &= [0.5 - 1.5] \\ f_{max} &= 0.41 & f_{max} &= [0.32 - 0.50] \end{aligned}$$

3-4-2 Indirect damage estimator

Besides the direct damage there is also indirect damage. The estimation of the indirect damage is a difficult process and several models have been developed. These give some insight to the magnitude of the indirect damage, but it is a very uncertain estimation.

The indirect damage is therefore analysed in two ways. The first approach is to look at the indirect damage as a constant factor of the direct damage. Building on this, the second method looks at the recovery times that are paired with certain amount of direct damage. The last addition is looking at the specific shape of the currently used recovery time function. This recovery time function has been part of the pilot study performed by HKV/VU[3] where it has been based on expert judgement and corresponding damages were calculated. In this study, they have estimated the recovery time based on inundation depths using expert judgement.

Indirect damage factor method

For the indirect damage, a constant factor α, is generated for which the indirect damage depends on the direct damage. The α value is therefore independent of water level.

$$S_{indirect} = \alpha \cdot S_{direct}$$

The factor with which the indirect damage is calculated in the reference model is equal to the direct damage, $\alpha = 1$.

In countries such as the United States of America the factor for indirect damage, α, can be as high as a factor 10. However, this is not a widely used factor for the Netherlands, most likely due to lower recovery times due to a lower inundation pattern. In the Netherlands, factors of 2 are more common. The factor α is implemented in the model uniformly between 0.5 and 2 for the knowledge uncertainty.

Recovery curve method

A different approach to the indirect damage is looking at the recovery times. This method was applied by HKV/VU[3]. The method describes the use of assumptions for recovery times for certain inundation depths. This means that with increasing inundation depths there is more recovery time and more indirect damage. Herein, the calculated indirect damages of HKV/VU[3] and dividing it by the direct damage calculated by HKV/VU is taken as a starting point and compared with the direct damage. This leads to an estimated α for different return periods with their corresponding inundation depths. An extrapolated trendline of this is used to get an α that is dependent on inundation depth.

For each type of industry different recovery times are expected. For the pilot area, a convex recovery curve is used. This recovery curve is based on expert judgement with the local companies. The resulting curve has a convex shape. However, there are other possible recovery curves as is seen in figure 3-4.

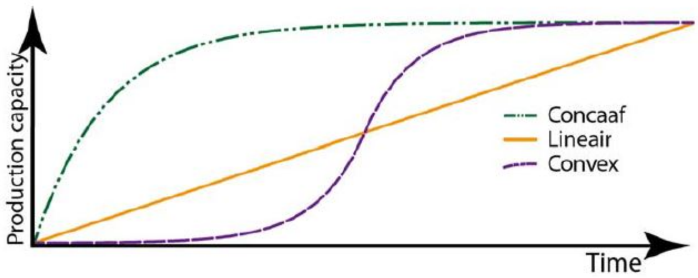


Figure 3-4: Type of recovery curves used, source: HKV/VU [3]

The effect of the choice of one of these is investigated by implementing all three in the model. This is done by comparing the damages for the climate scenario 2015. The indirect damage is calculated for each of the three recovery curves. The indirect damage is divided by the direct damage and this leads to an α value that is dependent on the inundation depth. The result is α as a function of inundation depth for each recovery curve.

With the convex recovery curve of the report of HKV/VU[3] the α value is determined. This is shown in figure 3-5. Noticeable is that the α values increase dramatically between the return period 1000 years and 4000 years. This is not the case for the concave or linear recovery curve.

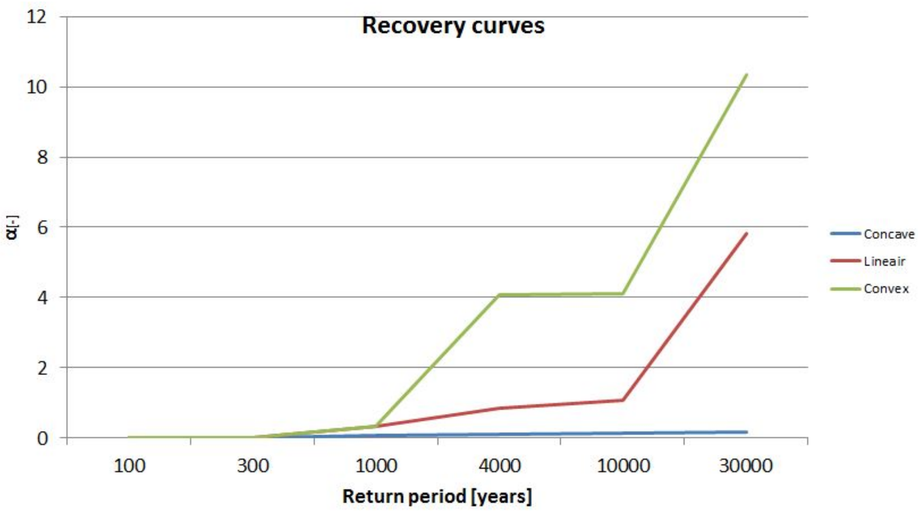


Figure 3-5: Alpha trendlines for recovery curves

As the calculation has been done for limited return periods it is unclear where this 'jump' is located exactly. This turning point could prove to be influential and thus an uncertainty analysis is made.

First, the graph is divided into two parts. The first part is a linear trendline following the lower α values for low inundation depths. The second part is a polynomial trendline which leads to very high α factors. The turning point is the point where the determination of the α factor follows the first or the second trendline. It is uniformly distributed between 1000 year return period and 4000 year return period with a mean of 0.75m.

3-4-3 Risk in net present value

The actual risk level of an industry also depends on the time when a storm event occurs. Due to future value of cash being less than the current value, the damage that occurs at a certain point in time has to be discounted. The rate used to discount the future value of damage, the interest rate, is a key variable. This is taken as 3 % in the model, with a knowledge uncertainty band between 1.5% and 4.5%. The summation of the discounted values of each damage event is the total Net Present Value(NPV) and gives a representation of the actual risk over a certain lifetime.

To calculate the total NPV a lifetime must be estimated. For the industry in place a lifetime expectancy of 100 years is taken as it can be interpreted as an infinitely long time horizon.

3-5 Computational procedure

In this section the computational procedure is explained that is used in the model. The process is explained for both the reference model and the probabilistic model. To further demonstrate the procedure an illustration is made in figure 3-6. Each step is explained in detail in the following paragraphs.

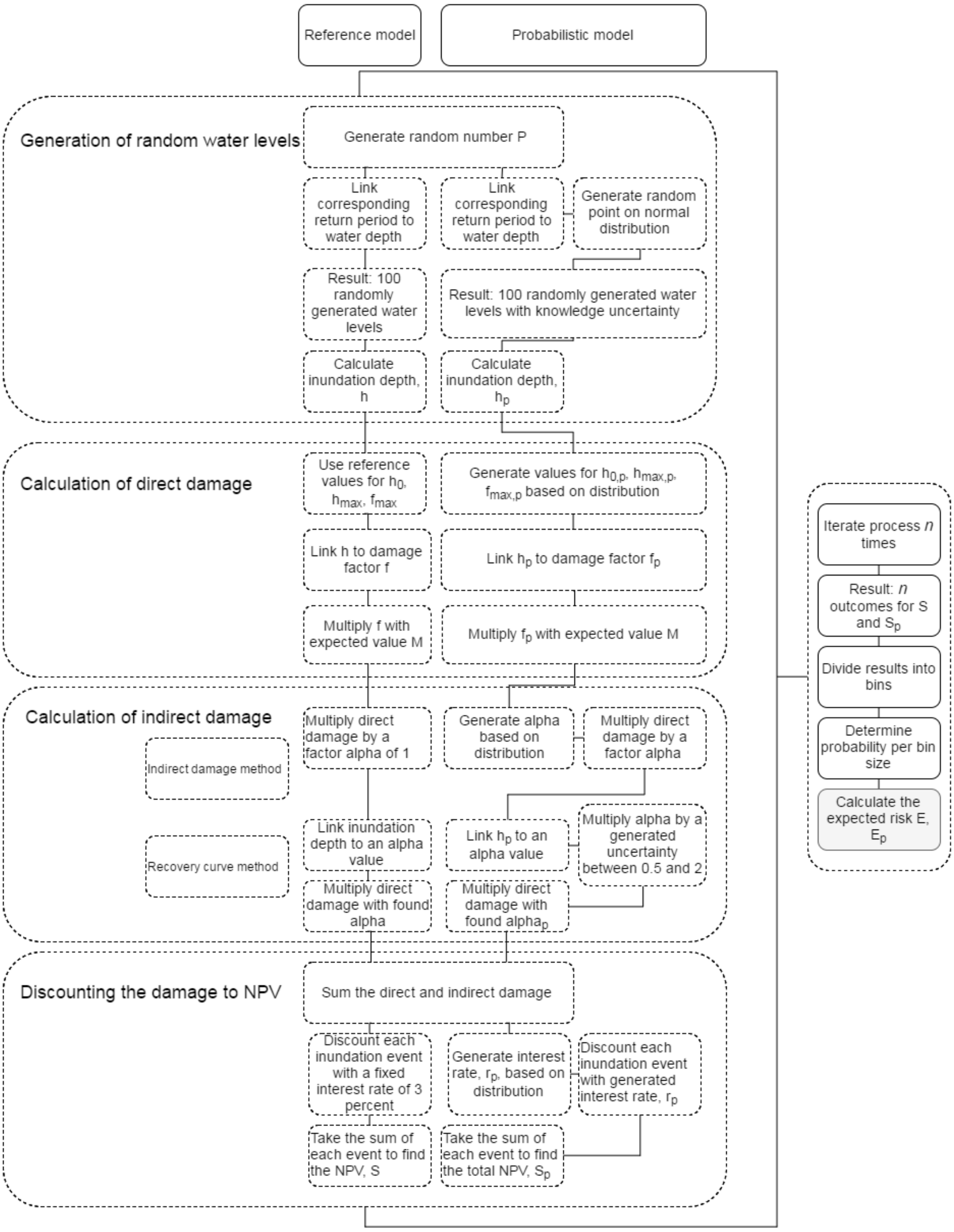


Figure 3-6: Illustration of computational procedure

3-5-1 Generation of random water levels

Over the course of a lifetime random water level events are modelled according to the flood characteristics that have been discussed. The approach for the generation of random water levels for the reference model and probabilistic model is similar.

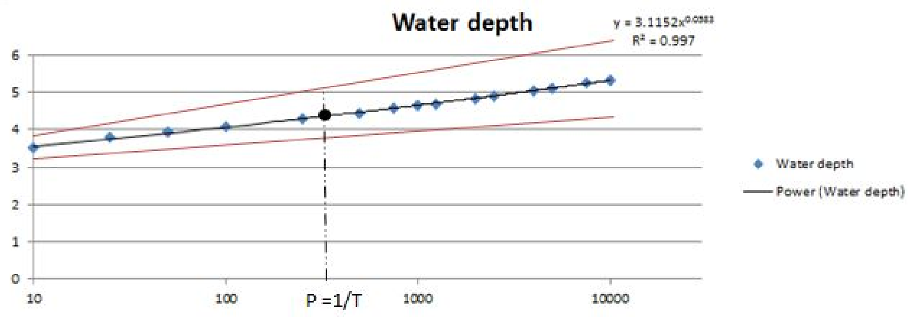


Figure 3-7: Generation of random water levels

In the reference model, each year of the lifetime a value P is chosen at random of a uniform distribution between 0 and 1. This value is converted to the return period. With the return period and the trendline h(T) a random water level is generated.

$$P = rand[0,1], \quad T = 1/P, \quad h(T) = random \quad water\ level \tag{3-3}$$

This process is repeated $n_{lifetime}$ times and leads to $n_{lifetime}$ random water levels, one for each year. An example of such a result of one lifetime of 100 years is shown in figure 3-8.

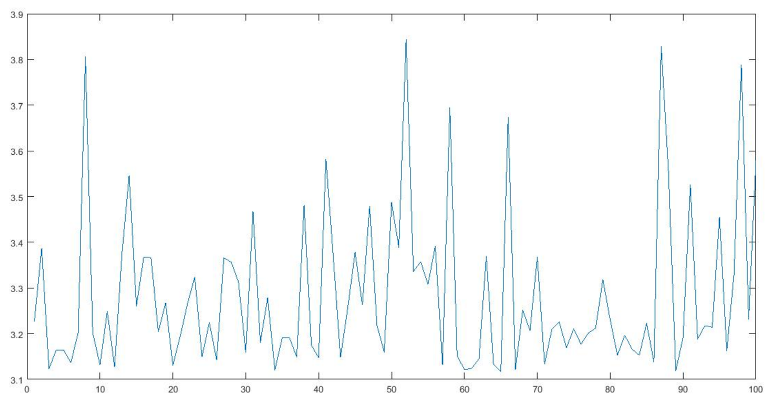


Figure 3-8: Random water level generation for the reference model

For the probabilistic method this is done similarly, but the knowledge uncertainty must be taken into account. Therefore, a random value P is selected and the corresponding water level is calculated. Two steps are taken to include the knowledge uncertainty in the water level.

First, a normal distribution is generated according to equation 3-2. This creates a normal distribution for each value of the exceedance graph. The second step is the random picking of a random value on the probabilistic exceedance graph. This is done by first generating a random water level based on the standard exceedance graph. When this is selected the next step is to generate a random point on the normal distribution, where the selected random water level is the mean and the standard deviation is determined as a function of the random water level. This random point on the normal distribution shows the water level with knowledge uncertainty. This process is again repeated $n_{lifetime}$ times and leads to $n_{lifetime}$ independent random water levels including knowledge uncertainty.

Now there are $n_{lifetime}$ of reference water levels and $n_{lifetime}$ of probabilistic water levels. This is done for a number of simulations, which results into n_{sim} of random water levels as is seen in figure 3-9.

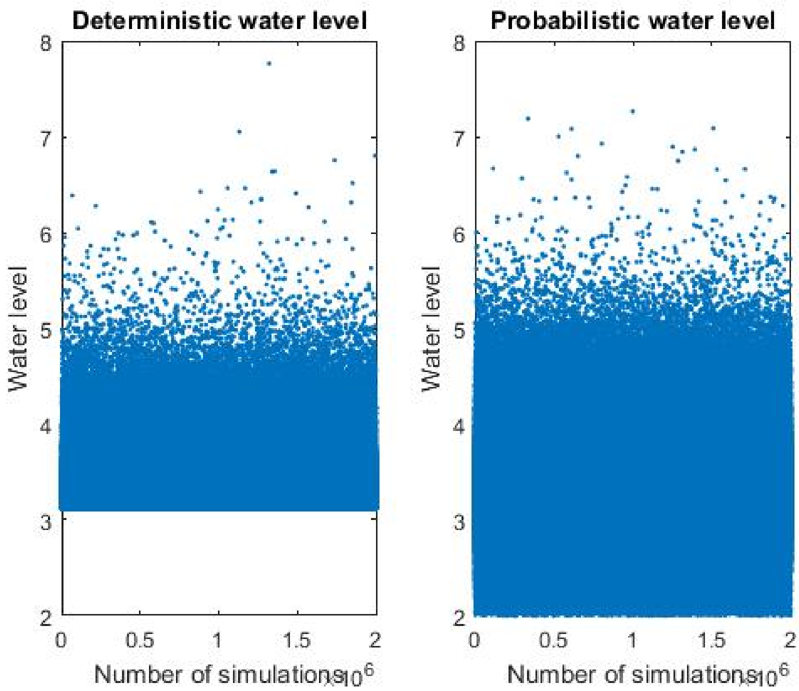


Figure 3-9: Random water level generation for both the reference and the probabilistic model

The effect of sea level rise is implemented by simply adding the forecasted increase in water level during the lifetime of 100 years. For the scenarios 2015, 2050(W+) and 2100(W+) these are respectively +0, +0.35 and +0.85m.

3-5-2 Link water level to damage function

Direct damage

The damage functions, that have been discussed in section 3-4, are used to calculate the damage for each of the randomly generated water levels. First, the damage functions have to be defined. Three points are needed, h_0, h_{max} and f_{max}. In the reference calculation these are set at respectively, 0.25, 1.5 and 0.5. However, for the probabilistic calculation there is knowledge uncertainty about the value of these parameters. Therefore for the duration of the lifetime, a randomly selected value is generated independently on the uniform distribution of the corresponding variable.

When these values have been generated, the functions which calculate the damage factors are put into three intervals:

$$\begin{aligned}
f_{damage} &= 0 && for && h < h_0 \\
f_{damage} &= f_{max}/(h_{max} - h_0) \cdot h && for && h_0 > h < h_{max} \\
f_{damage} &= fmax && for && h > h_{max}
\end{aligned}$$

In this manner the damage factor is determined for each water level. The damage factor is then multiplied with the maximum amount of damage for a storage tank, 823 Euro/m^2.

Indirect damage

With the direct damage known the indirect damage can now be calculated. Two methods are used to compute the indirect damage.

The direct factor method uses a factor α times the direct damage to compute the indirect damage. Where α is 1 for the reference model and uniformly distributed between 0.5 and 2 times for the probabilistic model. The value for α is randomly generated for the probabilistic calculation and is fixed over a single lifetime.

The recovery curve method uses a predefined α function, which depends on the inundation depth. In case of sea level rise the alpha trendline found in the convex, concave and linear recovery is different and have been implemented in separate models.

3-5-3 Calculating NPV over lifetime

The NPV of the damages is determined by discounting the damage. The interest rate is at a fixed 3% for the reference calculation and is determined by a randomly generated number on the uniform distribution between 1.5% and 4.5% for the probabilistic calculation.

With the selected interest rate the damage in case of inundation is discounted in the following way:

$$S_{discounted} = S_{total}/(1+r)^t \tag{3-4}$$

Where t is the year in which the damage occurs. With the discounted value the total NPV is calculated by taking the sum of the discounted damages during a lifetime.

$$S_{NPV} = \Sigma S_{discounted} \tag{3-5}$$

3-5-4 Computational repetition

Because the results for a single lifetime are influenced by the knowledge uncertainties and the generation of random water levels, this process is repeated multiple times. The following values change every run in the probabilistic calculation:

- Generated water levels
- Water level for which initiation of damage occurs, h_0
- Water level for which maximum damage occurs, h_{max}
- Maximum direct damage factor, f_{max}
- Indirect damage factor, α
- Interest rate, r

Because these variables are changing every run there is a variety of outcomes. The outcomes are divided into bins with automated ranges. This gives insight into the probability with which a certain outcome is generated. This is shown in figure 3-10.

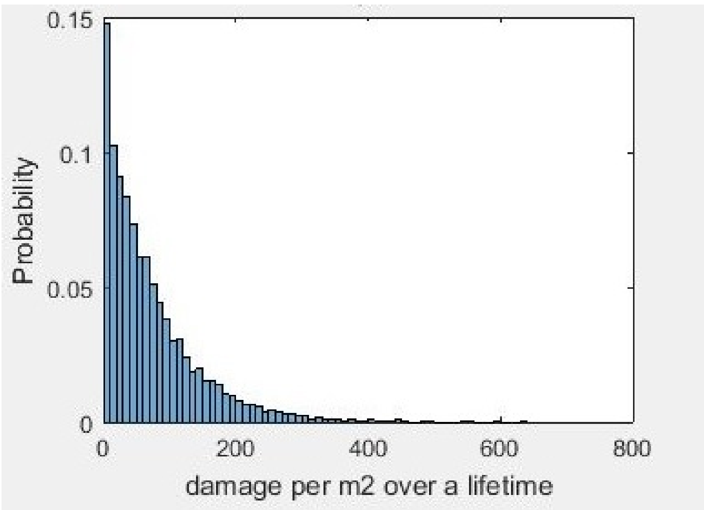


Figure 3-10: Distribution of outcome (lower elevation is used to illustrate the distribution, in the actual model most values would be zero leading to a difficult to read distribution)

This distribution does not give accurate insight into the actual risk profile. To get a more insightful answer the expected value is calculated. The expected value multiplies each outcome with its corresponding probability and sums them to give the average expected value.

$$E[X] = \Sigma(S(i) \cdot P(i)) \tag{3-6}$$

i=number of runs

The total amount of runs necessary is attained when the distribution no longer varies when the number of runs increases. This number has been reached at 2.000.000 simulations. At this number the distribution no longer varies.

3-6 Results of the reference model

First, a validation of the results is made to check if the model is running correctly. The model on which this validation is based is the recovery curve model. The recovery curve method is used in more detailed calculations and is therefore estimated by expert judgement to be more realistic. This validation calculation has been performed in Appendix D. From this can be concluded that the model is accurate as the order of magnitude is the same as that of the hand calculation.

Two versions of the results are shown in this section. The results using the indirect damage factor, α, in table 3-1, and the results using the recovery curves in table 3-2. The plots of the distributions for each calculation can be found in Appendix A.

Table 3-1: Results of the indirect damage factor method

	Expected value of NPV over lifetime [Euro/m^2]	Relative increase i.r.t. reference calculation [-]
Reference calculation	10,1	1
Uncertainty in water level	36.2	3.59
Uncertainty in indirect damage	11.3	1.12
Uncertainty in direct damage factor h0	9.8	0.97
Uncertainty in direct damage factor hmax	10.9	1.08
Uncertainty in direct damage factor fmax	10.1	1
Uncertainty in direct damage all uncertainties	10.6	1.05
Uncertanty in interest rate, r	10.61	1.1
Combination of all uncertainties	45.6	4.5

Table 3-2: Results of the recovery curve analysis

Variable	Expected value of NPV over lifetime [Euro/m^2]	Relative increase i.r.t. reference calculation [-]
Reference calculation with convex trendline	5.1	1
Uncertainty in water level prediction	18.1	3.6
Uncertainty in convex trendline	5.1	1
Convex trendline	5.1	1
Concave trendline	5.1	1
Linear trendline	5.1	1
Uncertainty in direct damage factor, h_0	5.0	0.97
Uncertainty in direct damage factor, h_{max}	5.5	1.08
Uncertainty in direct damage factor, f_{max}	5.1	1
Uncertainty in direct damage all uncertainties	5.37	1.05
Uncertanty in interest rate, r	5.4	1.05
All uncertainties	20.2	4.0

The results in table 3-1 and 3-2 show a large difference in the outcome of the two models. For the indirect damage factor the expected risk is twice as large as for the use of recovery curves. This is without the implementation of any knowledge uncertainties. The effect of the use of indirect damage method is clear when only the indirect damage is modelled. This is done for both the indirect damage factor technique as well as the recovery curves. The results are shown in table 3-3.

Table 3-3: Total indirect damage for a simulation using a convex recovery curve for the base knowledge uncertainties in case of a recovery curves and a fixed alpha value for the indirect damage factor method

	Indirect damage using recovery curve [Euro/m^2]	Rel. increase i.r.t. reference[-]	Indirect damage using fixed alpha value [Euro/m^2]	Rel. increase i.r.t. reference[-]
Reference calculation	0.015	1	5.36	1
Uncertainty in water level	0.05	3.41	20.63	3.56
Uncertainty in indirect damage	0.02	1.22	5.78	1.07
Convex recovery curve	0.015	1	-	-
Concave recovery curve	0.016	1.06	-	-
Linear recovery curve	6.1E-4	0.04	-	-
Uncertainty in direct damage factor, h_0	0.015	1	5.18	0.97
Uncertainty in direct damage factor, h_{max}	0.015	1	5.89	1.08
Uncertainty in direct damage factor, f_{max}	0.015	1	5.36	1
Total direct damage uncertainty	0.015	1	5.68	1.05
Uncertainty in discount rate, r	0.02	1.31	5.68	1.05
All combined uncertainties using convex curve	0.06	3.62	21.4	3.99

This table shows, that using the recovery curve model the influence of the indirect damage is very marginal as the indirect damage reduces to almost zero. The different recovery curves,convex, concave and linear are investigated for their relative influence. Two aspects are observed.

Whilst using the actual recovery curves, the total damage reduces by a factor 2 compared to the indirect damage factor that ranges between 0.5 and 2. This can be explained as the α values for low inundation levels are low with a high probability of occurring and the α value for high inundation levels are high, but with a low probability of occurring. This leads to an average lower use of the α value that is implemented.

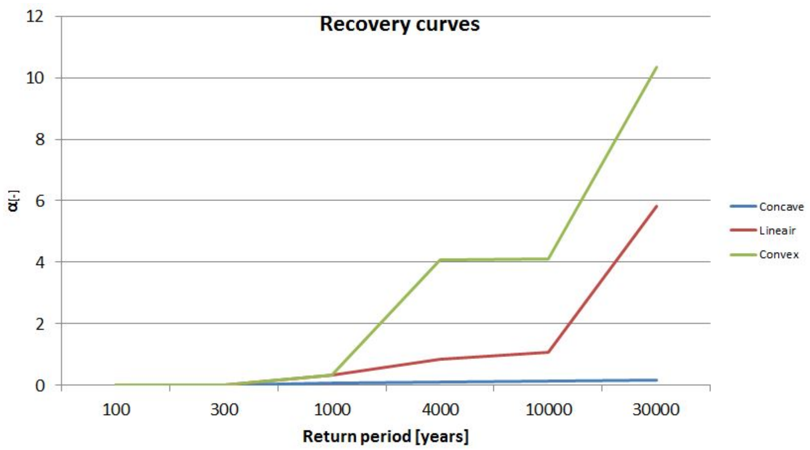


Figure 3-11: Alpha values for the different recovery curves 2015

The results shown in table 3-2 also show that the influence of different recovery curves is almost non-existent. The marginal effect can be contributed to the fact that for all three curves, the α values are relatively the same until an inundation depth is reached with a return period higher than 1000 years as is seen in figure 3-11. This in addition to the already lower α values and the therefore reduced impact on the outcome leads to a marginal difference.

3-7 Results of the probabilistic model

In this section the influence of each knowledge uncertainty is discussed. The model used for this is the model using recovery curves as this is deemed most accurate according to expert judgement. Each influence is discussed at length and finally compared to what the largest influences are. The results of each distribution are shown in Appendix A. A final recommendation is done for what can be improved in the model.

The relative influence of each knowledge uncertainty in relation to the reference calculation is shown in the tables above. However, this is not the only important parameter to interpret the results with. Logic follows, that the higher the range of knowledge uncertainty is implemented, the higher the influence on the outcome is. To get an indication of the relative influence, the method of the coefficient of variation(CV) is used. The method is described by dividing the standard deviation by the mean to compare the different knowledge uncertainties in the model.

$$c_v = \frac{\sigma}{\mu}, \quad \sigma_{uniform} = \sqrt{\frac{1}{12} \cdot (r_2 - r_1)^2} \tag{3-7}$$

The standard deviation is known for the water level prediction, however for the other distribution it has to be determined. The standard deviation for a uniform distribution can be described with equation 3-7. With the standard deviation known, the coefficient of variation can be determined for all the uniform distributions as well.

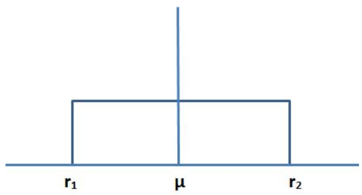


Figure 3-12: Relative spread of distribution

Table 3-4: Coefficient of variation for each uncertainty implemented

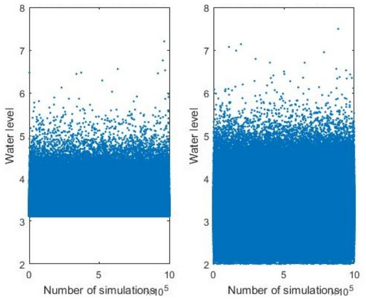
Variable	Coefficient of variation [-]
Uncertainty in water level prediction	0.12
Uncertainty in indirect damage factor	0.43
Uncertainty in convex trendline	0.58
Uncertainty in concave trendline	0.29
Uncertainty in linear trendline	0.13
Uncertainty in direct damage factor, h_0	0.13
Uncertainty in direct damage factor, h_{max}	0.29
Uncertainty in direct damage factor, f_{max}	0.30
Uncertanty in interest rate, r	0.17

The coefficients of variance shown in table 3-4 show that the knowledge uncertainty in water level prediction has the lowest coefficient of variation and the knowledge uncertainty in the convex trendline has the largest.

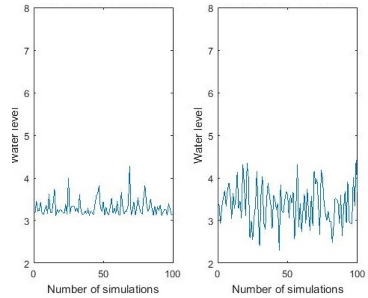
3-7-1 Influence of knowledge uncertainty in water level

A first examination of table 3-2 is that the outcome is highly influenced by the knowledge uncertainty in the water level prediction, by a factor of 3.55. Most lifetimes in the model do not have an inundation event during the lifetime due to the high elevations. With a knowledge uncertainty band, the chance of an inundation event increases as the probability of a high water level that causes inundation increases, as is explained below. In addition, the inundation depth increases directly with the water level. This contributes to the influence of the knowledge uncertainty. As the water levels become more frequent with knowledge uncertainty implemented, the water level per return period increases. This directly translates in more damage and thus more risk. For an inner-dike situation inundation behaves much more binary, instantly leading to high damages in case of inundation.

When comparing the number of events of inundation the effect of the knowledge uncertainty is shown. The number of events of which the water level is higher than 4.5m in the 2 million simulations is 3,540 in the reference calculation. With the knowledge uncertainty band taken around the water level the number of events increase to 14,854. The number of events therefore increases with a factor 4.196. This can be seen in figure 3-13 as well.



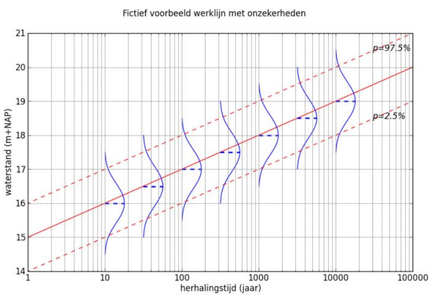
(a) All simulated water levels for the reference calculation on the left and the probabilistic calculation on the right



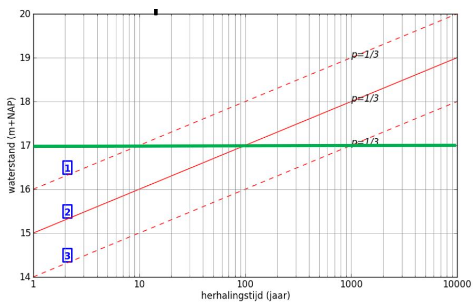
(b) Created water levels for a single lifetime for the reference calculation on the left and the probabilistic calculation on the right

Figure 3-13: Water levels of reference(left) against probabilistic model(right)

This increase in events seems disproportionally large for the knowledge uncertainty that is implemented, looking at the coefficient of variation. However, looking at a simplified example that is performed by Rijkswaterstaat [29] it is reasonable. Figure 3-14 is a result of when a knowledge uncertainty band is implemented and one looks at the 97.5 % confidence interval. Looking at a certain water level and doing a single calculation to the reference value and the outer edges of the distribution figure 3-14 is formed.



(a) Uncertainty band around frequency chart



(b) Pick of a certain water level

Figure 3-14: Integrating new probability from uncertainty band[29]

With a simplified calculation, shown in table 3-5, the implemented knowledge uncertainty shows the new probability of the selected water level has gone up from 1/100 to 1/27. This increase by a factor 4 shows that the results from the model, a factor of 4.196, are indeed reasonable.

This assessment is carried out for the exceedance graph for the climate scenario 2015. The above method is applied with numerous confidence intervals and for four different water levels. A trendline is plotted between these points and is shown in figure 3-15. For each water level,

Table 3-5: Example calculation

Water level line	Probability	Exceedance probability water level	Product
Lower boundary	1/3	0.1	3.33E-02
Deterministic value	1/3	0.01	3.00E-03
Upper boundary	1/3	0.001	3.00E-04
New probability water level			0.04

lower corresponding return periods are found in reference to the exceedance graph without knowledge uncertainties. This results into a new graph that has shifted upwards and thus higher probabilities for higher water levels than the reference model are expected.

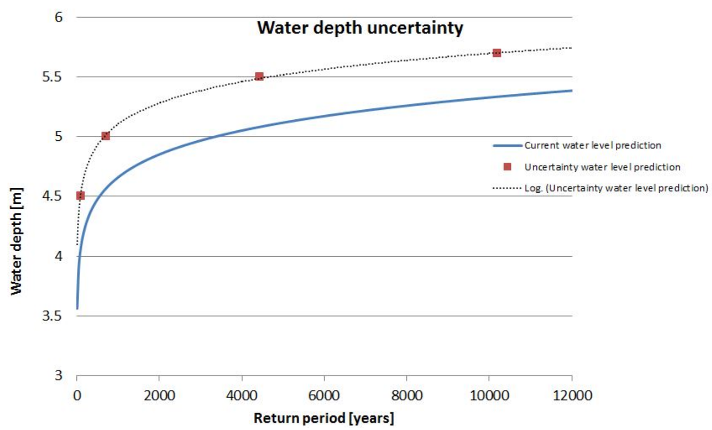


Figure 3-15: Water depth graph including uncertainties

3-7-2 Influence of uncertainty in the direct damage

The direct damage is subdivided in to three knowledge uncertainties, h_0, h_{max} and f_{max}. They are discussed in separate sections.

Initiation of direct damage

The initiation of damage, h_0, has the largest coefficient of variation. The relative influence however is not that large, by a factor of 0.97. The expectation that this is the leading knowledge uncertainty in case of direct damage estimation is therefore not true. This expectation was based on the low inundation depths and therefore uncertainty in the threshold value was expected to be influential.

This is because of two counteracting aspects. The first is that the outcome would rely heavily on the probabilistic aspects of the water levels. It is expected that more frequent lower inundation levels (of 0m-0.25m) can benefit from the knowledge uncertainty in initiation of damage more than the less frequent higher inundation levels as the threshold is reached more often in case of higher likely events.

The second aspect is that the average initiation of damage in case of a uniform distribution is higher than the mean of the uniform distribution. This is explained by looking at the damage functions explained in section 3-5-2. In case of initiation of damage the damage function is $f_{max}/(h_{max} - h_0)$. Figure 3-16 shows which three damage function are followed when three bins are selected as a simplified method of explaining the knowledge uncertainty.

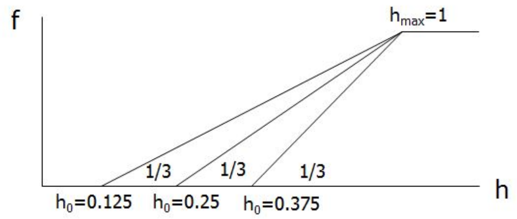


Figure 3-16: Water depth graph including uncertainties

When the average function is calculated the following procedure is done.

$$\frac{1}{3} * \frac{f_{max}}{h_{max} - 0.125} + \frac{1}{3} * \frac{f_{max}}{h_{max} - 0.25} + \frac{1}{3} * \frac{f_{max}}{h_{max} - 0.375} = \frac{f_{max}}{h_{max} - h_{0,average}} \tag{3-8}$$

Where $h_{0,average} = 0.28$ is found. This is higher than the mean of the distribution, 0.25, and therefore less damage is expected.

The end result is a balance between these two aspects leading to a relatively low effect on the outcome. The increase found in the average initiation of damage is predominant leading to a reduction in expected risk.

Maximum direct damage depth

The inundation depth, h_{max}, for which the maximum value is attained is of higher influence, by a factor of 1.08. It also has a lower coefficient of variation and therefore the relative influence is even higher. The knowledge uncertainty in this parameter leads to a higher risk profile. This is explained using the same method as the in the equation 3-8 only now with h_{max} as the variable. This leads to a $h_{max,average} = 0.74$ which is smaller than the mean of 1, which explains why more damage is expected.

Maximum direct damage factor

Uncertainty in the maximum damage factor, f_{max}, has no effect as the influence factor is equal to 1. This is logical as the further maximum damage factor does not increase the amount of events or the speed in which more damage is attained. With a symmetrical distribution the value should stay equal. Including all knowledge uncertainty, the direct damage knowledge uncertainties lead to a 5% increase in risk. This is mostly due to the influence of the knowledge uncertainty of the h_{max} parameter.

3-7-3 Influence of knowledge uncertainty in indirect damage

The indirect damage is divided into two sections. The indirect damage factor and the recovery curves.

Indirect damage factor

The influence of knowledge uncertainty in the indirect damage factor is the largest of the knowledge uncertainties other than the water level knowledge uncertainty, as is seen in table 3-1. This is due to the relatively large coefficient of variation, the second largest of all the knowledge uncertainties. The σ is, however, a conservative estimation of the distribution of knowledge uncertainty. Therefore, the influence of the indirect damage is essentially large. This could mean that better models are needed to assess this problem, which could benefit up to a 12% reduction in risk.

The current assumption is that the indirect damage is a multiplication of the direct damage. However, indirect damage is also possible to stand alone of the direct damage. This assumption causes it to have a larger influence then it actually could have. If it would be a stand alone source of damage, the knowledge uncertainty might bring much lower influence in the model.

Recovery curves

The convex recovery curve is determined to be most accurate for an industry such as the Botlek (according to expert judgement). Therefore, it is interesting to see how knowledge uncertainties actually influence the outcome using this recovery curve. A knowledge uncertainty band is implemented of 0.5 - 2 times the recovery curve.

What is noticeable is that the knowledge uncertainty in indirect damage decreases with lower α values. Where a factor of 0.5 - 2 in the α value in the indirect damage factor leads to a relative influence of 1.12, with the recovery curve method the influence is close to zero. Because of this lower α value the influence of the indirect damage on the outcome is lower. When knowledge uncertainty is implemented in the indirect damage estimator this causes a lower level of impact than in the previous analysis as the α is much lower for the majority of the events.

The results show that the turning point knowledge uncertainty has no effect on the outcome as it is uniformly distributed resulting in the relative influence factor of 1 as is seen in table 3-6.

Table 3-6: Results of the turning point analysis

Variable	Expected damage NPV [euro/m2]	Relative influence [-]
Expected value without uncertainties turning point method	5.08	1
Uncertainty in water level prediction	18.3	3.60
Uncertainty in turning point	5.07	1
Expected damage with all uncertainties	20.3	3.99

3-7-4 Influence of interest rate

The interest rate has an influence factor of 5 percent, see table 3-3. For the same reason as the direct damage factor h_{max} the influence of the knowledge uncertainty in the interest rate increases the total expected risk. The influence of 5 percent is relatively high and therefore this knowledge uncertainty can be important. It, however, is not a knowledge uncertainty that is easily improved as it depends on many uncertain economic predictions.

3-8 Results including the effect of sea level rise

Lastly, the effect of sea level rise is taken into account. Sea level rise is analysed only for the model using recovery curves as this is the more accurate model used in more detailed calculations. Two sea level rise scenarios have been looked at, 2050(W+)/2100(G) and 2100(W+), where the corresponding sea level rise is 0.35m and 0.85m. The sea level rise has been implemented with the same exceedance graph but with the sea level rise added.

The first results are clear as the expected risk increases from a value of 5.1 Euro per square meter in 2015 to a value of 140 Euro per square meter in 2100. This is expected as higher water levels are expected and relatively more inundations occur. When including the knowledge uncertainties the values increase even more.

Table 3-7: Outcome of the recovery curve model for the different climate scenarios

	Results					
	2015		2050		2100	
	[Euro/m^2]	Rel.increase[-]	[Euro/m^2]	Rel.increase[-]	[Euro/m^2]	Rel.increase[-]
Reference calculation	5.1	1	18.4	1	140.3	1
Uncertainty in water level	18.1	3.56	81.3	4.41	683.3	4.87
Uncertainty in indirect damage	5.1	1	18.5	1	140.7	1
Covex recovery curve	5.1	1	18.4	1	140.3	1
Concave recovery curve	5.1	1	18.4	1	139.1	1
Linear recovery curve	5.1	1	18.4	1	138.9	1
Uncertainty in direct damage factor, h_0	4.97	0.98	18.0	0.97	137.2	0.98
Uncertainty in direct damage factor, h_{max}	5.5	1.08	20.0	1.09	154.2	1.1
Uncertainty in direct damage factor, f_{max}	5.1	1	18.4	1	140.3	1
Uncertainty in direct damage all uncertainties	5.4	1.05	19.5	1.06	150.7	1.07
Uncertanty in interest rate, r	5.36	1.05	19.4	1.05	147.5	1.05
All uncertainties	20.2	3.97	91.6	4.97	758.1	5.4

The relative increase or decrease of the influence of knowledge uncertainties with the sea level scenarios of 2050 and 2100 are compared to the current climate scenario 2015. A factor is given for which the relative difference in table 3-8.

As is seen in table 3-7, the knowledge uncertainty in water level prediction plays an increasing role with sea level rise. The expected risk increases as the sea level rise is implemented. This can be understood as the effect of a higher water level also increases the knowledge uncertainty bands around the water level and relatively a higher reduction of probability is attained per water level. This in turn increases the expected risk. The other knowledge uncertainties remain approximately the same as is expected due to the independence of the knowledge uncertainty on water level.

Table 3-8: Relative influence of the effect of sea level rise in relation to the outcomes without sea level rise in the case of the model using recovery times

	Relative influence compared to 2015	
	2050	2100
	Rel.increase [-]	Rel.increase [-]
Reference calculation	1	1
Uncertainty in water level	1.24	1.37
Uncertainty in indirect damage	1	1
Convex recovery curve	1	1
Concave recovery curve	1	1
Linear recovery curve	1	1
Uncertainty in direct damage factor, h_0	1	1
Uncertainty in direct damage factor, h_{max}	1	1
Uncertainty in direct damage factor, f_{max}	1	1
Uncertainty in direct damage all uncertainties	1	1
Uncertanty in interest rate, r	1	1
All uncertainties	1.25	1.36

3-9 Relation to different flood scenarios

Till now, the emphasis has been on the flood scenarios within the Botlek. The flood characteristics in this scenario are such that the probability of a flood is very low. This is due to the combination of high elevation and low probabilities of a high water event.

The results of the model and the influence of the knowledge uncertainties could provide different results in case of a different harbour scenario, for instance a harbour abroad. Different elevations and flood characteristics could lead to more impact of the indirect damage in relation to the reference model. The effects of knowledge uncertainties other than the water level prediction could be larger and the effects of possible environmental damages could be more substantial.

For this reason the model is run for the same flood characteristics, but with different elevations. This demonstrates the effect of having a harbour that is located at a much lower elevation and is therefore more flood sensitive. The elevation has been set from NAP+3.5 to NAP+4.5 in steps of 0.25m. The results of these are shown in table 3-9.

Table 3-9: Several varying elevations using the basic model with recovery curves

	NAP+3.5m		NAP+3.75m		NAP+4.0m		NAP+4.25m		NAP+4.5m	
	Exp. Val	Factor	Exp. Val	Factor	Exp. Val	Factor	Exp. Val	Factor	Exp. Val	Factor
Reference calculation	269.8	1	112.4	1	32.7	1	12.6	1	5.1	1
Uncertainty in water level	1020	3.78	477.2	4.25	138.7	4.24	48.85	3.86	18.1	3.6
Uncertainty in indirect damage	269.4	1	115.6	1.03	33.4	1.02	12.8	1.01	5.1	1
Convex recovery curve	269.1	1	112.1	1	32.6	1	12.6	1	5.1	1
Concave recovery curve	268.9	1	112	11	32.6	1	12.6	1	5.08	1
Lineair recovery curve	268.7	1	112	1	32.5	1	12.6	19	5.08	1
Uncertainty in direct damage factor, h_0	264.1	0.98	109.9	0.98	31.96	0.97	12.23	0.97	4.97	0.98
Uncertainty in direct damage factor, h_{max}	299.1	1.11	123.2	1.096	35.8	1.1	13.7	1.08	5.5	1.08
Uncertainty in direct damage factor, f_{max}	269.8	1	112.4	1	32.7	1	12.6	1	5.09	1
Uncertainty in direct damage all uncertainties	292.3	1.08	120.3	1.07	34.9	1.07	13.3	1.05	5.37	1.05
Uncertanty in interest rate, r	284.7	1.06	118.6	1.05	34.5	1.06	13.2	1.05	5.36	1.05
All uncertainties	1122.2	4.16	529.9	4.7	155.4	4.8	54.9	4.34	20.2	3.97

From this analysis is seen that the effect of a lower elevation definitely increases the expected risk output. This is accredited to the more frequent floodings. When looking at the knowledge uncertainties, it becomes clear that with lower elevations the influence of the knowledge uncertainty of the water level prediction becomes larger. A modelling error causes the results for NAP+3.5m to be inconsistent. This is understood when looking at figure 3-15 the increase in probability is larger for lower water depths than for larger water depths. The knowledge uncertainties for direct damage do not change significantly. This is linked to the increased probability of lower inundation depths and the method which is explained in section 3-7-2.

What becomes clear is that the fraction of damage that is caused by indirect damage does not change significantly. This is seen as the influence of the knowledge uncertainty in indirect damage is still very small. The lower elevation has almost no effect on the influence of the knowledge uncertainties in direct damage estimators, indirect damage estimators and interest rate.

Concluded can be that in case of lower elevations the influence of knowledge uncertainties in water level prediction increase. However, the influence of the other knowledge uncertainties remains small compared to the water level prediction.

3-10 Comparison of outer-dike risk profile to inner-dike safety levels

Part of the pilot study Watersafety Botlek was to investigate how an outer-dike flood risk profile behaves and whether the risk is deemed comparable to inner-dike safety levels. This was done by creating a framework in which acceptable risk levels were determined. This acceptable risk level was used to assess the results of the detailed computation made by HKV/VU[3]. The same framework can be used to determine whether this model is exporting results that are in the same order of magnitude. In addition it can be used to assess if the effects of knowledge uncertainties and sea level rise lead to unacceptable risks.

First, some explanation is given on the way the acceptable risk levels were determined in the assessment framework. Inner-dike safety is based on three aspects: individual loss of life, group risk and economic risk. In this assessment the loss of life is often dominant, but on several occasions economic aspects can also be dominant. Per dike ring the safety levels vary slightly, but based on the VNK[30] assessment there is an estimation of the acceptable risk. This comes down to roughly one million Euro NPV per year, based on research of RHDHV[9]. The values found in the detailed model made by HKV/VU[3] are also in the order of one million Euro per year, this is however an indication of what could be accepted and is not a definitive threshold.

A note must be made that the model is idealized with many simplifications, therefore the comparison to the detailed model is not accurate. However, it does generate insight into how knowledge uncertainties can influence the level of acceptance. Comparing this to the reference model the annual expected risk for the total area must be calculated. This is done by taking the total 5.1 Euro per square metres in NPV and multiplying with the total area. Taking interest rate into account this leads to an estimated 3.7 million Euro per year in NPV. This shows that the risks are not that far apart from the detailed model. These risks without knowledge uncertainties are deemed 'acceptable' based on the used framework. The reference model does result into higher expected risks. This is because it is an idealized model where the elevation is fixed and assumed is that when inundation takes place the entire area is inundated. This overestimates the damage that is considered as in the Botlek only limited areas will inundate. However, it is still in the order of magnitude of the detailed model and is therefore expected to be acceptable.

When the knowledge uncertainties are added, the expected risk increases significantly. From 3.7 million Euro per year in NPV without knowledge uncertainties, the results increased to 14.6 million Euro per year in NPV for including all knowledge uncertainties. The expected risk is much higher, in the order of ten times higher than the acceptable risk levels stated in the framework. This increase would shift the risk level towards 'unacceptable'. However this does not consider that there are knowledge uncertainties in the risk assessment of inner-dike area, to compare this for acceptability these should be taken into account.

In case of sea level scenarios the expected risk increases from 5.1 Euro per square meter to 18.41 Euro per square meter for 2050(W+) and 140.31 Euro per square meter for 2100(W+). These values relate to 13.5 million Euro per year for 2050(W+) and 103.5 million Euro per year for 2100(W+). These are the risk levels without taking knowledge uncertainties into account. With knowledge uncertainties and sea level rise the risks are far larger and definitely in the unacceptable region. These climate scenarios are the most pessimistic, but it would seem that the increase in risk would lead to unacceptable risk levels.

Putting expected risks in this specific case aside, there is also difference in the manner in which an outer-dike behaves compared to an inner-dike. An outer-dike area reacts much more directly as the damage function is strongly dependent on water level. An inner-dike area is very binary as it is either flooded completely or not at all. This is because the 'bath tub' quality of a polder. When the storm event is over, there is a lot of water inside the 'bath tub' that needs to be removed. This causes high delays in recovery time and therefore a lot of indirect damage. An outer-dike area behaves much more direct in both the flooding as the recovery. It floods as soon as the water level is equal to the ground level, instead of having an extra retaining height. This increases the likelihood of a flood, but also reduces the amount of time the water remains. The water can simply flow out the same way that it came in, unlike an inner-dike area. The influence of high probability floods is therefore far larger for outer-dike areas than low probability floods. For an inner-dike area this is exactly opposite.

3-11 Discussion and conclusions

From the results the main conclusion is that the model is highly influenced by the knowledge uncertainties. The effect when all knowledge uncertainties are taken into account can lead to a significant increase of the expected outcome. The total factor is about 4 and is mostly due to the knowledge uncertainty in the water level prediction.

The main influencing aspect in the model is the occurrence of a high water event during its lifetime. Considering that the probability of a high water event during its lifetime is very low the factors that influence the outcome the most are the events that increase the probability of a high water event. The model responds very directly to increasing water levels as it is strongly dependent on the water level. For this reason the knowledge uncertainty in water level prediction has a very large influence of a factor of 3.5. This factor originates from the increased probability of an inundation event taking place due to the shifting of the exceedance graph as is seen in figure 3-15.

The knowledge uncertainty in the direct damage plays a small role, increasing the outcome by approximately 5 percent of the reference calculation. The inundation depth, h_{max}, where maximum direct damage is reached is most influential.

The knowledge uncertainty in indirect damage is the largest influence on the outcome other than the water level knowledge uncertainty if the indirect damage factor method is considered. It ranges from an increase of 12 percent for the indirect damage factor method to less than 1 percent for the recovery curve method. Looking at the influence of the knowledge uncertainty on the indirect damage only, it is much higher for the recovery curve. However the expected risk is much lower.

The lower risk for the recovery curve method is due to the low probability of high water events and the inundation depth dependency of the recovery method. With the highest probability of very low inundation events the indirect damage is therefore low as well. The choice of the type of recovery curve has a slight impact on the indirect damage. However, with the indirect damage being so low using this method for the lower return periods the effect is marginal. The turning point in the recovery curve is of no effect either.

Interest rate plays a small role. This 5 percent increase originates from the same method of calculation as the influence of direct damage factor h_{max} is explained. It is therefore an influential knowledge uncertainty.

Also the effect of sea level rise causes an increase of the effect of knowledge uncertainty on the expected value. The sea level rise scenarios increase the influence of the knowledge uncertainty in water level prediction. Naturally it also causes the expected risk to increase with increasing water levels. In addition the knowledge uncertainties also increase with sea level rise.

Comparing the total risks of an outer-dike industry to an inner dike area, the risks are larger for the outer-dike area, but comparable to a current inner-dike situation. Without knowledge uncertainties they are a factor 3.7 higher, but this increases to a factor of 14.6 with all knowledge uncertainties. With sea level rise these values increase even more, leading to a significant risk in the outer-dike industry. This means that protective measures are worth considering. It is also clear that the risk profiles of outer-dike areas are much more dependent on high probability storm events than inner-dike areas.

Concluding, this analysis leads to the advice that refining the water level statistics can lead to better estimating the expected risk when taking knowledge uncertainties into account. This is a wise investment as it has the highest factor of influence.

Chapter 4

Environmental model

4-1 Introduction

In this chapter the environmental model is introduced. The probability of a leak in an oil tank is determined. The possible quantitative and qualitative environmental consequences of an oil leak is discussed. This leads to a risk assessment of the environmental damage in case of an oil leak. The risk assessment is compared to that of the risk of economic damage, which has been done in the previous chapter.

Environmental damage is defined as the damage caused when pollutants are released during a flood due to damage to a structure in which they are stored. With release of pollutants, significant effects can be found on nature, marine and agricultural areas. These could lead to health problems to both animal life as well as human life. Even with small amounts of pollutants, ecological systems can be disturbed for long periods of time.

A high importance is linked to ecological aspects, however, it is difficult to assess what values are directly linked to different aspects of ecological environments. Much of this appreciation lies in the connotation of ecology and of the durable image the country or business must pertain. There is a keen interest into being able to predict the amount of damage that is concerned with such an oil spill.

In most risk assessments so far this aspect has been analysed qualitatively instead of quantitative. This chapter gives a more quantitative assessment of environmental damage based on the case of the Botlek.

The environmental model aims to give insight into the actual costs that coincide with the release of pollutants in an industrial area. By looking at existing literature and making assumptions for an idealized situation for a single storage tank of crude oil a first estimate is made. The relative importance of the environmental damage is assessed by comparing it with the direct and indirect damages in the flood risk model.

4-2 Environmental consequences of tank failure

Several consequences are possible with the release of pollutants depending on several aspects. The consequences of these aspects can be divided into three overlapping categories.

- Flammability
- Pollution
- Toxicity

Each category has both tangible as intangible damages that are shown in figure 4-1. In case of flammable material, several scenarios can be considered with the consequence of a fire. First, ignition must be part of the possibilities, though this is realistic with the combination of water and electricity. Therefore, a situation where a fire can start is one to consider. The next step is to see if the released material is contained in a certain area or if the possibility of dispersion can lead to a floating fire. In all cases of fire a domino effect can occur, where the ignition of one area can lead to the ignition of a different area, be it vessels or parts of released pollutant.

Pollution is the release of potential hazardous material which contaminates the water, port area and shorelines. This pollution must be removed according to Dutch regulations. Part of this clean-up operation consist of surface oil and part of polluted sediment. The focus of this category lies on the costs relating to this clean-up operation and not of any health or marine conditions that are reduced by this pollution.

The category toxicity is the most intangible damage factor as the sensitivity of both ecological as human life to certain chemicals is uncertain. On top of that the effect of a reduction of plantlife or animal life on an ecological system is impossible to assess in depth. The quantification of this process is even more difficult. This category overlaps with that of pollution, however, this category has the focus on the value appreciation of ecological and marine life.

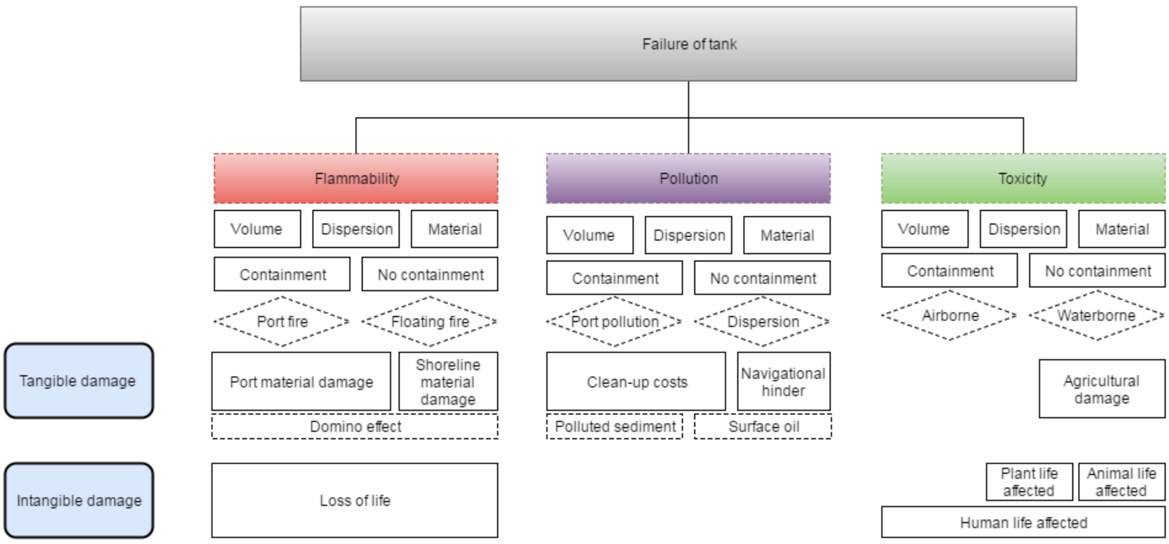


Figure 4-1: Possible consequences of a release of pollutants of a storage tank

As most of these consequences are difficult to assess quantitatively, this research focusses on the category pollution. The other two categories are discussed qualitatively.

4-3 Flammability

The flammability consequence is considered in this section. A qualitative analysis of this category has been made using a risk matrix in order to give insight into the risks relating to fire and if it is a risk that requires more research.

A risk matrix is a widespread used tool for risk evaluation. This type of tool is used to determine the magnitude of an event and the probabilities that such an event occurs. The risks are then mapped out in a figure and categorised in three categories, acceptable(green), transitional area(yellow), unacceptable(red).

The risk matrix is set up with different consequence categories. In case of a floating fire the safety of personnel and loss of life in case of spreading to habited area is considered. Furthermore, economic losses are considered, which can be substantial in case of a fire. The business interruption that is the result of a fire and the corresponding societal impact of such an event are also considered in the consequences. Judicial consequences are also considered, namely the accountability and insurance of such an event. Lastly, the image related consequences are assessed. These are the consequences that relate to recovery of a customer base, permits that can be granted after a safety assessment and damage to the security with which people feel living relatively nearby industry.

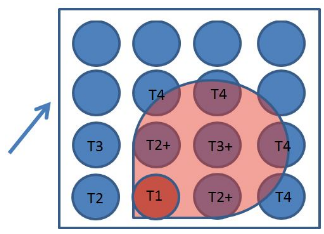
First a calibration risk matrix is set up to give a certain risk value to the likelihood and level of consequences. For example, a highly unlikely situation with catastrophic consequences is valued under the name A1. For lower consequences with higher probabilities E6 is considered. See figure 4-3 for this analysis.

These risk values are used in the actual risk matrix. Several scenarios are shown in figure 4-3. The acceptance of these risk values is based on the relative risk that is considered acceptable in the framework made by RHDHV[31], based on studies of the VNK project[30]. These levels are determined to be acceptable for a probability of 1/1000 per year with economic consequences of 1 billion Euro(and follows from a public viewpoint in case of levee failures of inner dike rings). This is obviously one viewpoint, many others are possible.

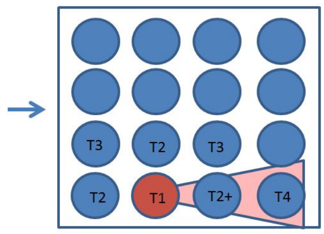
In order to use the calibration matrix several aspects are estimated in a non-detailed method. These are the probabilities of storm occurrence, tank failure and domino effects. The costs of fire damage to a tank are also estimated. The recovery time of the industry needs to be taken into account. Loss of life and injuries are considered, but are estimated unlikely. Further, some degree of insight is needed into the judicial and image related problems of such an event.

4-3-1 Probability of initiation of fire

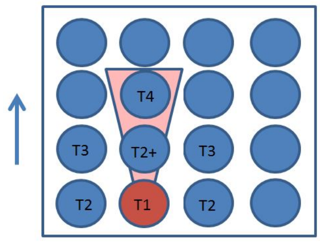
Two causes related to spreading of fire in storage tanks are considered. Firstly, the heat radiation is considered based on the geometry and substance of the tank. The probability of failure due to heat radiation is explained below. The second cause of domino spreading of fire are tanks that are engulfed by ignited oil that has leaked from a storage tank. The probability



(a) First scenario - flow direction is assumed to be north-east



(b) Second scenario - flow direction is assumed to be east



(c) Third scenario - flow direction is assumed to be north

of this is dependent on many variables, such as discharge of oil, burning rate, volume of the tank, wind velocity, flow velocity, exposure time and distribution of the oil. This aspect of spreading is considered, but qualitatively estimated.

In these figures a uniform distribution of tanks is used for the estimation of heat radiation. For the engulfment of fire three predominant flow and wind directions are taken: north-east flow and wind direction (figure 4-2a), flow and wind direction predominately north (figure 4-2b) and flow and wind direct predominately east (figure 4-2c). The distribution of tanks is a simplified view of what the Botlek layout is like.

The scenarios differ in the amount of likelihood and the consequences that accompany each scenario. The heat radiation is the same for each scenarios as it is based on static heat radiation from only the first tank, T1. It does not consider higher order domino effects. However, due to engulfment the likelihood and consequences are different for each scenario.

Spreading due to engulfment of fire is considered with the estimated exposure time. An atmospheric storage tank that is exposed to fire usually takes between 5 min to 15 min (depending on the extent and severity of fire) to get damaged(personal communication with Nima Khakzad). Exposure time depends largely on flow velocity. Therefore, if the flow velocity is high, the duration the unaffected tanks are exposed to burning fuel is low.

First, the probability of failure of a tank is determined. An unanchored tank is taken as in case of a domino effect the weakest link is dominant. A water level of NAP+5.5m is considered as an example, the equivalent of an inundation depth of 1m. Inundation levels of this nature lead to considerable probabilities of failure. For an inundation of 1m the failure probability corresponds with 0.15 for an unanchored tank[12]. The fragility curve of the failing of an unanchored tank is discussed in section 4-5-1. The probability of a storm event of NAP+5.5m occurring corresponds with an exceedance probability of 1/10,000 years. The total probability is 1.55e-5 per year as is seen in equation 4-1. The probability that this happens at least once in 100 years is shown in equation 4-5.

$$Total\ probability\ per\ year = 0.15 \cdot 1/10.000 = 1.55e-5\ per\ year \tag{4-1}$$

$$P(x > 0) = 1 - P_0 \tag{4-2}$$

$$P(x > 0) = 1 - e^{(-t\lambda)} \tag{4-3}$$

$$P(x > 0) = 1 - e^{(-100 \cdot 1.55e-5)} \tag{4-4}$$

$$P(x > 0) = 1.5e - 4 \ per \ lifetime \tag{4-5}$$

This probability can be taken into consideration as a base failure probability in assigning risk values to each scenario in the risk matrix. The domino effects relating to the ignition of other tanks are considered as well. Rough estimations of the probabilities are considered for the domino effect in the following manner. These are applied in the risk matrix seen in figure 4-3.

To analyse the probabilities of the fire spreading, the heat radiation received by the following tanks needs to be considered. The heat radiation depends on the distance between the tanks. A simplified layout of the area is made. This assumes that the 1,800 tanks are distributed evenly in a rectangle of 25 by 70 tanks. Over a surface area of 23 million square metres, using the uniform layout, the distance between tanks is 37m.

The damage probability of T2 is described using equations 4-6, 4-7 and 4-8[33]. Ttf is the time to failure of target tank in (s); Q is the amount of received heat radiation (kW/m^2); V is the volume of target tank (m^3); Y is the probit value; P(T2) is the damage probability of T2; $\phi()$ is the cumulative density function (CDF) of standard normal distribution.

The heat radiation between an ignited tank T1 and the tanks T2 and T3 is determined by the programme ALOHA. According to this, the probabilities of igniting a tank due to heat radiation are 0.684 and 0.247 for respectively T2 and T3.

$$ln(ttf) = -1.13 \cdot Q - 2.67e - 5 \cdot V + 9.9 \tag{4-6}$$

$$Y = 12.54 - 1.847 \cdot ln(ttf) \tag{4-7}$$

$$P(T2) = \phi(Y - 5) \tag{4-8}$$

These probabilities increase if the neighbouring tanks are in the direction of the ignited leaked oil from tank T1. Ignition of neighbouring tanks due to engulfment of flames is dependent on the duration of exposure to fire. In this assessment a look is taken at the flow velocities that increase or reduce the exposure time. These are different for each flow direction scenario.

In case of north-east direction the flow velocity is determined due to both the gradient in water level, between the Hartelkanaal and the Nieuwe Waterweg, and wind direction. Leading to relative fast flow conditions and therefore a relatively low increase in probability. For east direction the flow velocity is predominately wind-induced. This results in the lowest flow velocities and therefore the highest increase in probability. For north direction it is primarily driven by the water level gradient. This causes the flow conditions to be the fastest and therefore the increase in probability to be the lowest.

The resulting probabilities are shown in table 4-1. These probabilities, combined with the costs of failure of a tank, have been considered to come to an estimation of the risk in figure 4-3.

Table 4-1: Probability of failure due to fire related domino effects

		Flow direction		
	Source	North-East	East	North
T1	Tank failure and ignition	<1.5e-4	<1.5e-4	<1.5e-4
T2	Heat radiation	0.684	0.684	0.684
T2+	Heat radiation and fire engulfment	0.85	0.9	0.75
T3	Heat radiation	0.247	0.247	0.247
T3+	Heat radiation and fire engulfment	0.6	0.65	0.55
T4	Fire engulfment	0.4	0.5	0.3

4-3-2 Costs relating to flammability

A rough estimation of the costs relating to damage of the tanks is made. The consequences for these scenarios were assessed by taking both the material damage and the possible environmental damage. The damages were determined by assuming that the amount of oil tanks are spread evenly across the Botlek area. With this assumption the amount of area that each tank can affect individually is the area of the Botlek divided by the number of tanks. This comes down to 13,000 m^2 per tank. The maximum damage per m^2 for industry is 823 Euro according to Tebodin[8] and combining this with the expected costs of clean-up related activities of 400 Euro/m^2 leads to a total damage of 1,223 Euro/m^2. With this value the several scenarios have been analysed in relation to economic damages. The damage related to a single tank that is on fire is 15.9 million Euro per tank.

Also the recovery time of the industry is a highly influential factor in the risk matrix. The recovery time for the industry is highly related to the amount of area that is affected. In case of large areas of the Botlek being affected by fire it is assumed that the recovery times are extremely long based on the recovery curves in the idealized model.

4-3-3 Other important aspects relating to fire

In relation to loss of life and injuries, the casualties are assumed to be related to rescue workers and inhabitants. The size of the fire is dominant in this assessment. Also the number increases when a floating fire reaches habitable areas.

The judicial and image problems are difficult to estimate. The judicial problems for the companies in the Botlek are the accountability for damage that is caused by a fire. Insurance and accountability play a large role in the judicial consequence. Image related problems are that of a safe supplier, employer and providing safe vicinity.

4-3-4 Conclusion

From the risk matrix shown in figure 4-3 can be concluded that the scenarios concerning a floating fire can lead to unacceptable risks depending on flow conditions and distance between tanks. This analysis suggests that it is beneficial to do a full probabilistic assessment concerning a threat such as flammability. This is not performed in this research, but can be a worthwhile follow up research.

In addition, it needs to be considered that many companies already have standard shut-down procedures and necessary precautions to prevent such an event from occurring. These need to be considered before doing such an analysis as it can prove to be of significant impact in the actual risk assessment.

						Highly improbable	Improbable	Possible	Likely	Most likely	Almost sure
Effect	Safety	Economic damage	Business recover time	Judicial	Image	1.00E-09	1.00E-08	1.00E-07	1.00E-06	1.00E-05	1.00E-04
Catasprophic	>100 cases of serious injury	>100 billion Euro	>10 years	Accountability to companies for all damage	Unrecoverable damage to image	A1	A2	A3	A4	A5	A6
Severe	<50 cases of serious injury	>50 billion Euro	>5 years	Accountable for damage to infrastructure	Great deal of image related damage	B1	B2	B3	B4	B5	B6
Mediocre	<25 cases of serious injury	>10 billion Euro	>1 years	Only accountable for damage to own company	Recoverable damage to image	C1	C2	C3	C4	C5	C6
Small	<10 cases of serious injury	>1 billion Euro	<1 years	Partially insured	Natural recovery of image	D1	D2	D3	D4	D5	D6
Negligible	No cases of serious injury	>1 billion Euro	<1 years	Fully insured	Almost no damage to image	E1	E2	E3	E4	E5	E6

Flow direction	Estimated risk based on calibration risk matrix
North-East	B2
East	B3
North	C1

Figure 4-3: Risk matrix for floating fire scenario

4-4 Toxicity

The toxicity aspect of the environmental hazard is not analysed quantitatively as putting a value on human or ecological life is a subjective subject. As this model concerns a storage tank of crude oil the effects on human life are not considered. The dispersion of oil into the waste water treatment facilities could have an indirect effect on human life. However, this does not directly affect human life as the treatment facility is only briefly shut down.

Many variables determine the ecological effect of an oil spill. Some of these are, the possible dispersion, shoreline contamination, contaminated vegetation, bird and fish life that would be affected by an oil leak. As these variables are to widespread and sensitive for interpretation an analysis is not made in this research.

However, the effects of such ecological systems have high value accredited to them and could prove to be a very significant consequence. Therefore it needs to be considered in a proper risk assessment. It would be recommended to make use of extensive dispersion models and to inventory what kind of marine and vegetative life could be affected. In this analysis should be considered whether the environment would be able to recover naturally.

4-5 Pollution

This form of contamination is subdivided into two parts, clean-up costs and navigational hinder. The direct consequence of an oil leak is that a large amount of oil floats on the surface water. As this can lead to many possible ecological and societal problems it cannot remain there. The oil on the surface water needs to be cleaned. During this time navigation can not continue, as contamination of boats, harbours and equipment will be the indirect result.

Clean-up costs can also refer to the clean-up of sediment that has been polluted. Since oil is lighter than water and floats, the contaminated sediment does not lie on the river bottom. Therefore the sediment pollution consist of the sediment that is located on the river banks.

The model for environmental damage is set up in several steps. The failure mechanisms are discussed first, followed by geometry of the tank. Furthermore, the generation of random water levels, the linking to a probability of failure for the tank, the volume of pollutants released and the clean-up costs are discussed.

4-5-1 Failure mechanisms of a storage tank

For a storage tank in an industrial area the following failure mechanisms occur as a result of flooding. Each of the following failure mechanisms is described more extensively below and an elaboration is given on whether it is included in the model or not.

- Floatation of vessel
- Buckling of vessel
- Impact of debris

- Failure of closure valves due to electronics
- Failure of closure valves due to installations

Floatation is the process where the self-weight of the tank becomes lower than the buoyancy force of the water. This depends on the diameter of the tank and with increasing diameter the floatation phenomena becomes more probable. To prevent this from occurring many tanks are placed on a concrete slab and connected with anchors. This greatly reduces the chance of floatation. This failure mechanisms is one of the more straightforward failure mechanisms that can be considered. In addition it is also one of the most probable failure mechanisms to occur. Therefore this failure mechanism is considered in the model.

The process of buckling is when the outside pressure, both hydrostatic pressure and drag pressure, become larger than the critical pressure the tank can handle. The critical pressure depends on the geometry of the tank, inside pressure and the construction material. A variety of researches has been done on buckling of storage tanks. High pressures are required before such an event can occur, but it is a known failure mechanism. For this reason this is also considered in the model.

Due to the flow velocity in case of an inundation, floating debris can be a potential failure mechanisms leading to rupture. In the Botlek area inundations are very limited. This leads to low flow velocities. With low flow velocities the impact of debris remains limited and most likely is not of high importance in the failure assessment. In addition, a lot of assumptions are needed to model such an event, leading to high amount of uncertainties. It is not estimated to be of high influence and is therefore not taken into account for the failure mechanisms in this research.

Failure due to closure of valves is an aspect that can be important, but the processes that determine how this happen are confidential and is not handled in this assessment as the information is not available. The same applies to the influence of electronics on the failure mechanisms. Even though this might provide for an interesting research, it is not considered in this research.

4-5-2 Geometry of tank used in environmental model

The Botlek area has numerous variation of tank geometry ranging from 1 - 80 meters in diameter. There are 3,848 tanks in Botlek I,II and III. Based on work done by RHDHV(Van Ledden, personal communication) only tanks with a diameter of 10 meter and higher can have a significant environmental effect when there is release of pollutants. With this considered the number of dominant tanks that need to be considered is 1,800. The average diameter of these 1,800 tanks is 24 meters. This is higher than the diameter of 15m used in the fragility curves of Kameshwar[12].

The in-depth finite element analysis done for both floatation and buckling is more accurate than a simple limit state Monte Carlo analysis. This leads to the use of the fragility curve for the 10m diameter tank. This means underestimation concerning the actual risks in the Botlek. However, using the fragility curve based on the finite element analysis is expected to be more accurate even though the probability of failure is underestimated due to the lower diameter. The area is modelled as an elevated flat surface with a single storage tank similar to the model in chapter three. The storage tank that is used has fixed dimensions, which are 15 meters in diameter, a height of 10m and a wall thickness of 1cm according to the storage tank used in the doctoral research of Kameshwar[12].

4-5-3 Generating of random water levels

The first step is the generation of random water levels over a lifetime of 100 years. This is done in the same way as the economic model. To reiterate, the model generates a random water level each year of the lifetime according to the exceedance graph for the reference year of 2015. The result is a set of 100 random water levels over a lifetime for each run of the model.

These randomly generated water levels are then linked to a probability of failure with which the tank gain a leak due to floatation and buckling. In case of failure the amount of volume that is released needs to be determined to examine the extent of pollution. With the volume of oil and the probability of failure known, only the damage per litre of leaked oil is required to determine the risk profile. These steps are explained more extensively in the following sections.

4-5-4 Determining probability of failure for a storage tank

The second step is the linking of the generated water levels to a probability of failure. In case of inundation the inundation height is linked to a fragility curve. The fragility curve that made by Kameshwar[12] is used. The dimensions of the tank used in the model match that of his fragility curve. This is done to be compatible with the fragility curve. To determine the fragility curve for a storage tank the two failure mechanisms floatation and buckling are determined. In the research of Kameshwar an existing curve is made for both floatation and buckling.

Measures to reduce the probability of flot have been taken.. Anchoring is such a measure. This is the mechanisms of bolting the vessel onto the concrete slab. This reduces the probability of failure as the resistance to floatation becomes larger. Logically with larger tanks the relative effectiveness of anchoring becomes smaller. For an idealized situation it is important to make an assessment of what the general probability of tank failure is. The Botlek consists of 80% anchored tanks and 20% of un-anchored tanks(expert judgement, RHDHV).

For the two failure mechanisms the probability of failure for storage tanks is investigated by Kameshwar[12]. In figure 4-4 is seen that the inundation levels for both floatation, but especially buckling have to be high before there is any probability of failure. This is only for anchored storage tanks, for un-anchored storage tanks the threshold value for floatation is much lower. It can start to fail from inundation levels of 0.5m.

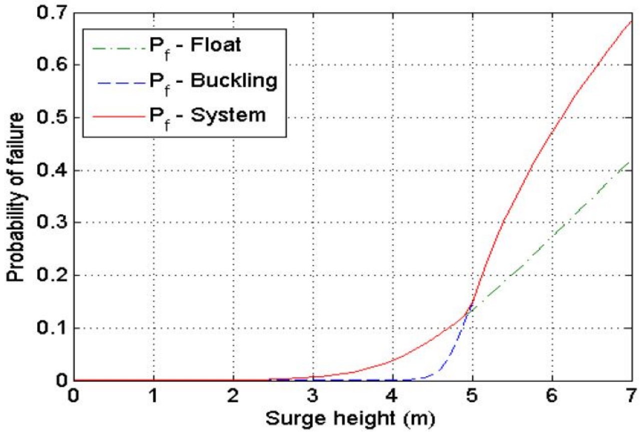
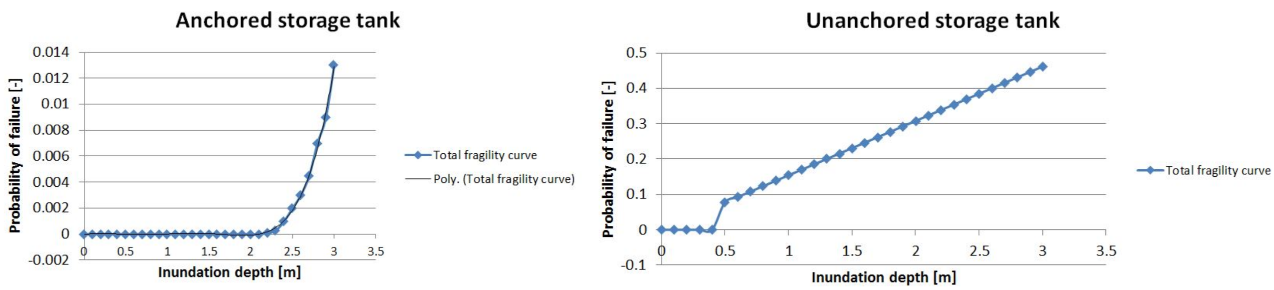


Figure 4-4: Probability of failure for buckling and floatation for an anchored tank

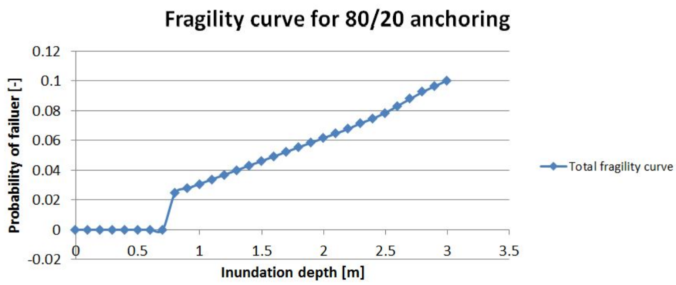
There are several scenarios that are possible. These are all explored and for each a fragility curve is determined. The scenarios are the following.

- Anchored
- Un-anchored
- 80% anchored and 20 % un-anchored



(a) Anchored storage tank **(b)** Un-anchored storage tank

Figure 4-5: Location of pilot area



(a) 80% of the storage tank anchored

Figure 4-6: Different fragility curves used

4-5-5 Estimating the released volume of oil in case of failure

The volume that is released is uncertain as it depends on not only the fill, but also the size of the breach and the conditions that allow release of pollutants. The fill is uncertain as it changes on daily basis. According to Kameshwar[12] the fill is uniformly distributed between 1.89m and 7.11m, based on the production availability.

A leak on the upper side of the tank causes lower volume released than a leak in the bottom. There is uncertainty about how much release takes place in case of a leak. Variables such as the location, size and geometry of the leak affect this. A uniform distribution for the volume of pollutants released is assumed. This distribution describes the amount of volume that is released in such a scenario. This uniform distribution is distributed between 0 and 100 percent of the tank capacity. The volume that is released in the model is therefore independent of the fill as it is unknown what this is at the moment of inundation.

4-5-6 Environmental damage related to pollution

With the estimated volume of oil that is spilled the expected damage needs to be calculated. This section shows the costs related to an oil leak of a storage tank. The total cost of an environmental leak can be categorised much like economic damage into direct and indirect damage. The direct damage in the case of oil leak is in the clean-up costs. The indirect damage can be found in the recovery operation of the released oil. This can shut down a harbour for a considerate amount of time with high costs. Also the recovery time in the case of operational material can lead to an additional cost source.

4-5-7 Damage related to oil spills on surface water

With an oil leak on the surface water a number of response strategies are available. These consist of the following five.

- Leave the oil alone and let it break down by natural means
- Contain oil with booms and collect it from the water with skimmer equipment
- Use dispersant's to break up the oil and enhance mixing with water
- Use biological agents to the spill to hasten biodegradation
- Burn the oil where it has spilled to remove it

As the location of the spill is in-port, in-situ burning is not a preferable method. Leaving the oil alone in the harbour is also not a viable option as it would hinder shipping and dramatically increase the recovery time.

Therefore the option to clean it up remains. However, if the case of the Botlek is considered, there is the Maeslantkering which will hold the oil. There is an option to also open the

Maeslantkering and to release all the oil offshore. There are many uncertainties in case of this solution. With it going directly offshore it could disperse easily and not cause too much trouble. The possibility is there that the oil affects the shoreline when the Maeslantkering is opened. This would be harmful and create much social disrupt and protest. Due to so many uncertainties that can occur in such a situation, this possibility is not considered and only the clean-up strategy is considered. The clean-up costs depend on a number of variables, listed below.

- Oil type
- Length of shoreline affected
- Type of shoreline affected
- Spill size volume
- Clean-up strategy

A single algorithm was created by the Worldwide analysis of marine oil spill clean-up cost factors[13]. This algorithm takes a variety of data of 300 oil spills in 40 nations to come to a per unit clean-up cost figure. For each variable a modifier is used to determine whether in the specific situation of the Botlek the modifier increases or reduces the costs. The total algorithm looks as follows.

$$C_{li} = r_i * l_i * C_n \tag{4-9}$$

$$C_{ui} = C_{li} * t_i * o_i * m_i * s_i \tag{4-10}$$

$$C_{ei} = C_{ui} * A_i \tag{4-11}$$

Cui = response cost per unit for scenario, i
Cli = cost per unit spilled for scenario, i
Cn = general cost per unit spilled in nation, n
Cei = estimated total response cost for scenario, i
ti = oil type modifier factor for scenario, i
oi = shoreline oiling modifier factor for scenario, i
mi = cleanup methodology modifier factor for scenario, i
si = spill size modifier factor for scenario, i
ri = regional location modifer factor for scenario, i
li = local location modifier for scenario, i
Ai = specified spill amount for scenario, i

The algorithm starts with a base value of the unit price, C_n in case of a leak. This price is a base unit price.

The first modifier is that of the regional location, r_i ,in this case the Netherlands. The costs vary per country. This is related to different costs in man-hours, different appreciation values on pollution and different acceptance levels. The general cost per unit spilled is taken for the Netherlands and is \$ 5.98 per liter of spilled marine oil in the year 2000. This has been discounted in the model to Euro anno 2016 with a rate of 1 dollar = 0.89 Euro and a 3 percent interest rate.

The second modifier is the local location modifier, l_i, whether the area is in-port, nearshore or offshore. An oil leak with the same volume offshore is a much smaller problem than that in a port as one can deduce. This leads to a location specific unit price for oil spill costs, C_{li}.

In the next step the modifiers of oil type, t_i, and clean-up methodology, m_i, are introduced. The type of oil can vary how easily it disperses and how difficult it might be to clean-up. The clean-up method can lead to increase or reduction of costs due to difficulty, timely and manual intensive methods.

Also the modifier spill size, s_i, is introduced. This modifier suggests that the unit price gets lower as the spill size increases. As this might be difficult to understand on first hand it is very logical. The same amount of equipment, material and workers is often used for a small oil spill as for a large oil spill. These are fixed costs that lead to relatively high costs for small oil spills while for larger spills the costs do not become that much larger. The modifier s_i is used to implement this effect in the algorithm.

Another important modifier that is used is the shoreline oiling modifier, o_i. This modifier describes the increasing costs that are involved in case of increasing lengths of shoreline that is contaminated. The shoreline clean-up is the most labour-intensive and time consuming of the clean-up operation.

With all these modifiers a unit price, in Euro/litre, is determined for the oil spill. To get the total clean-up costs this per litre price is multiplied with the total spill amount. This spill amount is obtained in the previous section by means of a uniform distribution.

The value for each modifier can be found in table 4-2.

Table 4-2: Values for different variables in the cleanup method

Cost Factor	Modifier	Cost Factor	Modifier
Oil Type		**Location Type**	
No. 2 fuel (diesel)	0.18	Nearshore	1.46
Light crude	0.32	In-Port	1.28
No. 4 fuel	1.82	Offshore	0.46
No. 5 fuel	1.82	**Primary Cleanup Method**	
Crude	0.55	Dispersants	0.46
Heavy crude	0.65	In-Situ Burning	0.25
No. 6 fuel	0.71	Mechanical	0.92
		Manual	1.89
Spill Size		Natural Cleansing	0.1
< 34 tonnes	2	**Shoreline Oiling**	
34-340 tonnes	0.65	0-1 km	0.47
340-1,700 tonnes	0.27	2-5 km	0.54
1,700-3,400 tonnes	0.15	8-15 km	0.54
3,400-34,000 tonnes	0.05	20-90 km	0.61
>34,000 tonnes	0.01	100 km	1.06
		500 km	1.53

To get to the right modifier several assumptions have been made.

- The oil type that is assumed is crude oil. This is in line with the type of industry in the Botlek.
- The clean-up strategy is uncertain therefore a distribution is used that randomly selects the variable for this. This is with exception of in-situ burning, which is not possible inside a harbour and residential area.
- The length of the shoreline that is affected is also dependent on a number of variables such as flow direction, flow velocity, dispersion qualities of the material, containment by structures and weather conditions. Determining what happens under what conditions is a research on its own and therefore a different approach is taken. Backtracking from different shoreline coefficients used for getting the cleaning coefficient there are five scenarios that can be determined. Based on expert judgement the probabilities for each scenario are determined and a distribution for the shoreline coefficient is made. The scenarios are determined and described with a certain probability of occurrence based on the report of RHDHV[9].

Table 4-3: Shoreline oiling scenarios

Scenarios	Shoreline affected	Location type
Scenario 1	>500km	Nearshore
Scenario 2	>100km	Nearshore
Scenario 3	20-90km	Nearshore
Scenario 4	8-15km	In-port
Scenario 5	2-5km	In-port
Scenario 6	0-1km	In-port

From all of these scenarios the expected value is determined in Euro/m^2 and discounted to Euro/m^2 in 2016.

The type of shoreline used are: in-port, nearshore and offshore. As the Maeslantkering shuts of the access to the sea this situation is not considered. When the shoreline that is affected exceeds 20km it is considered nearshore and when it is smaller than 20 km it is in-port.

Table 4-4: Different distributions of environmental variables

Type of variable	**Distribution type**	**Range**
Density water(kg/m^3)	Uniform	1021.9 - 1027
Density oil(kg/m^3)	Uniform	404 - 596
Density steel(kg/m^3)	Uniform	7891 - 7987
Fill(m)	Uniform	1.89 - 7.11
Volume(m^3)	Uniform	0 - 100
Clean-up method (-)	Uniform	0.46 - 1.89
Length of shoreline affected(m)	Uniform	0 - 500

4-5-8 Damage related to interruption of port operations

Possibly the damage of the environmental clean-up may not be very high. However, the action is obligatory and something that needs to be considered is the clean-up time is takes. Even if the costs of such an endeavour are marginal the costs of shutting down a harbour for an extended period of time could prove significant.

For this reason the clean-up time and recovery time of the harbour in case of an oil leak needs to be addressed. For the material damage a recovery curve is used following a convex curve. This is in case of inundation and the failure of equipment and the recovery of that failure.

For oil leaks, the recovery time depends on the clean-up of the oil in the water as this shuts down the entire harbour activities. It is assumed that the recovery time of the equipment in case of an oil leak does not exceed the standard recovery time of material damage in case of the corresponding inundation damage. Thus only the clean-up time of the oil in the surface water is considered as this shuts down the entire harbour after the Maeslantkering. The relating costs are modelled as the gross national product(GNP) of that area per day times the number of days that clean-up is required.

The gross product of the harbour is estimated to be 3.3% of the GNP of the Netherlands[25]. With interdependency among companies the estimated loss of the Botlek is 30% of the GP of the harbour per day(based on private communication with J. de Nooijer) that the Maeslantkering is closed. The GNP is estimated to be 738.4 billion Euro. Therefore the total loss per day of the Botlek is 20.4 million Euro per day.

The assumption is made that skimming equipment is used for the clean-up strategy in the case that it is contained by the Maeslantkering. Therefore, for the duration of the clean-up, the time is used that skimmers would need. The maximum volume that is considered is 1,800 m^3. For a skimmer the removal capacity depends on the amount of pump capacity, the storage capacity of the vessel and the time it takes for the vessel to arrive.

For the pump capacity a capacity is generally between 4.5 and 5.9$\frac{m^3}{h}$ [26]. This is per available vessel. An assumption is made that between 1-4 vessels are able to operate simultaneously and are available.

4-5-9 Computational procedure

To compare the environmental risks with the direct and indirect damage risks a similar procedure is used to produce a risk profile. First, hundred years of random water levels are generated in the same way as in the flood risk model. These have been generated with the exceedance frequency graph of HKV/VU[3]. With each water level event, the probability of failure is determined by means of the fragility curve of Kameshwar[12]. This links a probability of failure of a single storage tank to that water level event and thus that year in the lifetime.

There are a number of uncertainties in the model, the volume that is released, the shoreline that is affected and the cleaning method that is used. Every time the model runs, thus for each lifetime, a random generator is used to generate the value for these uncertainties based on their corresponding distribution. The distributions for each of this have been determined by expert judgement. The values for these uncertainties are implemented in the algorithm that calculates the amount of damage per litre calculated by equation 4-9.

The damage that is calculated is the damage that is generated for a single independent storage tank that has failed. To convert this to a similar unit as in the flood risk model it is converted to Euro/m^2. This is performed by taking the number of tanks that are dominant in such a situation, which is 1,800 (based on data of RHDHV [9]). The total damage for the area is then the number of tanks times the damage per tank. Divided by the area the unit Euro/m^2 is attained. This damage is discounted for the year that it takes place in the lifetime to the year 2016.

With some of the variables changing each lifetime it is essential to run the model several times to get each possible outcome in order to calculate the actual expected risk. This is done with the same number of simulations as in the flood risk model, 2,000,000 times. The expected value is determined with the received distribution of outcomes.

4-6 Results

The results of the model are shown in this section. First, the results of the model that analyses the clean-up costs of the oil that is released on the surface water are discussed.

Lastly, the costs of recovery time are shown and a total expected value for environmental costs is concluded.

4-6-1 Resulting costs for oil pollution in the surface water

The results of the surface water clean-up operation are surprising. The expected risk in NPV calculated over period of a lifetime is much lower than the expected risk in NPV of the economic risk. This is due to the combination of the low probability of a storm event and the low probability of failure of a tank. Especially the anchored tank fragility curve leads to an extremely low chance of a release of pollutant to occur. However, potential high damages in case of an event could lead to a risk that needs to be taken into account.

The clean-up costs that are calculated vary due to the uncertainties of some parameters. The uncertainties have been implemented in the model and are used to calculate clean-up related costs with the algorithm developed by Worlwide analysis of marine oil spills[13]. The resulting costs per litre are distributed between 0 and 35 Euro/litre with an expected value of 10.1 Euro/litre.

With the volume that is released being uncertain and the costs per volume being uncertain the clean-up costs can vary as well. The costs are converted to the Euro/m^2 unit. The resulting clean-up related costs per m^2 range from 0 - 6,000 Euro/m^2 depending on the variables taken from the uncertainty distributions. The expected value is found from all these different combination is roughly 400 Euro/m^2

These expected costs are linked to the probability of occurring of an extreme water event and the probability of failure of the tank under inundation. The resulting expected risk over a lifetime converted to net present value is shown in table 4-5.

Table 4-5: Resulting risk NPV over lifetime of surface water clean-up for anchored, unanchored and 80 percent anchored tanks

	Expected surface clean-up costs over lifetime [Euro/m^2]
Anchored	2.14E-04
Unanchored	0.011
Anchored with containment	2.14E-04
Unachored with containment	2.25E-03
80/20 with containment	2.25E-04
80/20 without containment	2.22E-04

These values are very low as can be seen, but the probabilities are also very low. The inundation depth needed for an anchored tank to start failing is NAP+6.75m which corresponds with a probability lower than 1/30,000. This low probability leads to these low risks.

To test the validity of the model a simplified check is necessary. This check is done manually and determines the probability of failure and the corresponding clean-up costs. It is found in Appendix D. It shows that in case of an unanchored storage tank, the risks that are a result of the model are in the order of magnitude of the hand calculation.

4-6-2 Resulting costs for interruption of port operations

The results of the analysis of recovery time on the risks of an environmental hazard are discussed in this paragraph. The assumption is made that the response time for the right equipment is distributed somewhere between 1 and 3 days after an event. Then combining this with the time it is required to pump up the oil with skimmer equipment leads to an estimated clean-up time. Also the amount of vessels that are used in the clean-up operation and the availability of these vessels is considered. These values are for leakage from a single storage tank, but expected is that the interruption for several tanks is close to this value due to conglomeration of oil and extra vessels that are used. The clean-up time is shown in table 4-6.

Table 4-6: Duration of port interruption due to clean-up activities

Clean up time [days]	**Response time [days]**		
Amount of vessels	1	2	3
1	15	16	17
2	8	9	10
3	5	7	8
4	5	6	7

This clean-up time is multiplied with the total loss per day of 20.4 million Euro per day. The results are shown in table 4-7.

Table 4-7: Costs of port interruption due to clean-up activities

Clean up costs [x10^6 Euro]	**Response time [days]**		
Amount of vessels	1	2	3
1	315	335	355
2	168	188	208
3	118	139	159
4	94	114	135

As there are several different options and many uncertainties the clean-up recovery costs are taken as a uniform distribution between the smallest and largest cost scenario (134 - 314 million). With this implemented in the model the expected clean up recovery cost during a lifetime of 100 years is 7.8e-06 Euro per lifetime. This is due to the extreme low probability of an event. This in combination with a significant damage source still leads to marginal risks.

4-6-3 Total resulting risks for pollution

The total environmental risks are shown in table 4-8. Both the risks per square meter as the total risks for the area are shown. The risks are those calculated over a period of 100 years. These are only the risks concerning the costs of clean-up related activities for oil on surface water and the costs related to interruption of operations of the harbour during the clean-up activities.

Table 4-8: Total expected environmental risks over a lifetime of 100 years

	Surface clean-up risks [Euro/m^2]	Port interruption risks [Euro/m^2]	Total risks of environmental leak [Euro/m^2]	Total risks for Botlek [Euro]
Anchored	2.14E-04	7.79E-06	2.22E-04	5.11E+03
Unanchored	0.011	1.52E-06	0.011	2.53E+04
Anchored with containment	2.14E-04	7.79E-06	2.22E-04	5.11E+03
Unachored with containment	3.96E-04	4.21E-06	4.00E-04	9.21E+03
80/20 with containment	6.28E-05	2.66E-05	9.10E-05	2.09E+03
80/20 without containment	6.28E-05	2.66E-05	9.10E-05	2.09E+03

4-7 Comparison to reference cases of past oil spills

In Appendix E some reference cases of past oil spills are discussed. The released volume, costs, shutting down of port operations and type of shoreline affected have been considered. Only the costs related to clean-up and related fines are considered. This resulted into table 4-9 where a comparison can be made between the analysis done in this chapter and actual cases.

Table 4-9: Costs and volumes related to reference cases of past oil spills

Oil spill name	**Location**	**Volume released [x 10^6 litre]**	**Estimated damage [Euro anno 2015]**	**Damage/litre [x 10^6 Euro/litre]**	**Closing of port operations [days]**
Exxon Valdez	Nearshore	41.6	4,664	112.03	-
Port Arthur	In-port	1.7	1,159	681.93	4
Ashland oil spill	Nearshore	3.8	45.5	12.03	7
Xingang Port oil spill	In-port	69.9	2,318	33.16	14
Kalamazoo river	In-land	3.30	1,194	361.83	4
Deepwater horizon	Offshore	794	16,229	20.44	-
Sea empress	Nearshore	93.0	117.4	1.26	-
Average amounts				**€174.67**	**7.25**

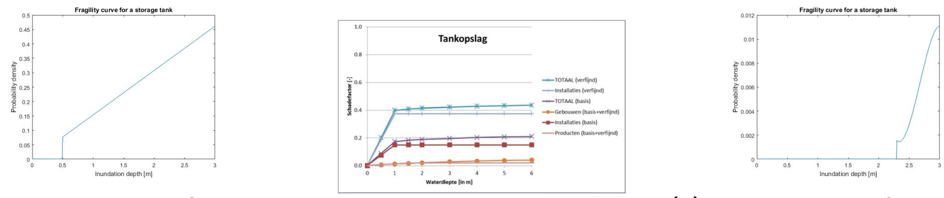
From this analysis comes forth that the costs related to clean-up activities are very high and also vary depending on the situation. The model results were between 0 and 36 Euro/litre. When compared to the cases looked at in the reference projects this is at the low margin. The reference projects show costs that range from 1.26 Euro/litre to 682 Euro/litre. However, there is limited data of a similar in-port situation where a storage tank fails. The Ashland oil spill is the only storage tank that failed where actual damages are estimated. This specific situation is very close in the found damage per litre of 12.03 Euro/litre and the expected value of 10.1 Euro/litre. Relying on this single case is unreliable. In comparison to the other cases the expected damage is on the low side. This is unexpected as it does concern an in-port event, which would lead to relative higher per unit damage than a typical offshore event like most of the reference cases. The reason for this could be that the quantities of each of these reference cases are much larger and the amount of shoreline affected is much larger. This however would only account for an increase of roughly 50%, due to the modifiers, of the estimated costs and not an observed difference of factor ten.

From this analysis it becomes clear that the expected clean-up costs are still very uncertain and could be as large as a factor of ten times higher than the expected economic costs. However, this has only limited influence on the related risk, which is still low.

4-8 Comparison of environmental model to economic model

From the environmental analysis became clear that there is a large difference in expected risk between the environmental model and the economic flood risk model. This is not due to the difference in damage that occurs in case of a damage event. It is due to the lack of probabilities that is taken into account with the damage curves. The damage is a direct function of the water depth without probabilities describing how likely damage is.

The environmental damage model makes use of a fragility curve. This curve puts a probability in between the inundation depth and the related damage. Two situations are compared, an unanchored tank in the environmental model with an expected risk of 0.011 Euro/m^2 where the environmental model is used. This is compared to the reference calculation of the idealized flood risk model, which used the damage curves, with an expected risk of 5.1 Euro/m^2. The expected damages are also similar as the expected clean-up costs are roughly 400 Euro/m^2 and the maximum damage in the Tebodin is 823 Euro/m^2.



(a) Fragility curve for unanchored situation

(b) Damage function [3]

(c) Fragility curve for anchored situation

Figure 4-7: Comparison of the damage function to the fragility curve

Looking at figure 4-7a and 4-7c in comparison to figure 4-7b one thing can be concluded. The unanchored fragility curve is much closer to the damage function than the anchored fragility curve.

This can explain that the expected risk for the unanchored situation is much closer to the flood risk model than the anchored situation. The expected risks of the unanchored situation is a factor of 45 lower than the reference model. However the anchored situation has a factor of 25,000 due to the lower fragility curve.

This could mean that the damage curves used by Tebodin are overestimating the damage. The probabilistic method in this case could mean that the initiation of damage happens much slower than for the damage curves.

It could also mean that damage can occur before failure. On top of this the damage curves consists of much more than just tanks, they also consist of installations and products. Installations make up the largest part of the damage related to storage tank industry.

4-9 Conclusion

The environmental model shows the effect of the clean-up costs in case of an oil leak. The consequences of an oil leak can be quite large. The maximum costs for a clean-up scenario are 32.4 billion Euro over a lifetime if all tanks are full and they all independently fail. The recovery time costs are a maximum of 581 million Euro. The total maximum costs in such a scenario relating to environmental hazards is 33 billion Euro.

These costs are very high and yet the expected risk over a lifetime is marginal. The expected risk converted to NPV is not higher than 2.53 million Euro calculated over a period of a lifetime for the total area. This is already assuming that none of the tanks are anchored and are without containment dikes, which in reality are present in the tanks. The low expected risk is because of the extremely low probability of occurring. The cumulative effect of the low probability of a high water event, combined with the low probability of tank failure in case of inundation causes the probabilities to be very low. Additionally, the probability of failure reduces as the tank is full and the consequences are reduced if the tank is close to empty. This increases the risk reduction already created by the low probability of failure.

Concluded can be that the quantitative risks of an environmental hazard are marginal. Uncertainties are high in reference to expected damage, but failure probabilities in the case of a storage tank are very limited.

This does question whether the difference in damage modelling is the reason for the large difference in expected risk. The difference originates because of the low probability of failure of a tank in the environmental model compared to the relatively quick initiation of damage in the damage curves. However, damage is not the same as failure and there are many components of industry that are affected other than the tanks itself. This leads to a much different methodology than the fragility curves.

Other than economic risks the qualitative aspects of environmental damage must not be overlooked. Flammability can lead to possible significant risks and is worthy of looking into further. The damages related to this are difficult to assess as possible regulations and bans are difficult to predict. On top of that the ecological damage related to an environmental event is very difficult to quantify. There have been cases, such as the Deepwater Horizon oil spill where the oil company loses there license to extract oil in certain countries.

Chapter 5

Flood risk reduction measures

5-1 Introduction

In this chapter the most promising flood risk reduction measures are discussed. A brief explanation is made about what the flood risk reducing measures entail. Furthermore, each measure is modelled in a way so that it can be incorporated into the existing risk model. With the measures implemented into the model, the risk reduction is calculated for each measure and compared to the costs of the measure. A comparison between the analysed measures herein is made.

5-2 Type of protective measures considered

There are several protective measures that could be promising and are discussed here. Each measure is discussed qualitatively and are also analysed in a quantitative method. A short list is given below.

- Containment dike as a water retaining structure
- Constructing a ring dike around the entire area
- Floodproofing vital components

5-3 Containment dike as water retention

Containment dikes are dikes that are designed to hold all the fill fluid in case of a breach of the tank. These tanks are designed in such a way that the entire volume of the tank can be contained in the containment area. These containment dikes are mandatory to have in the case of oil storage facilities and hazardous material[27].

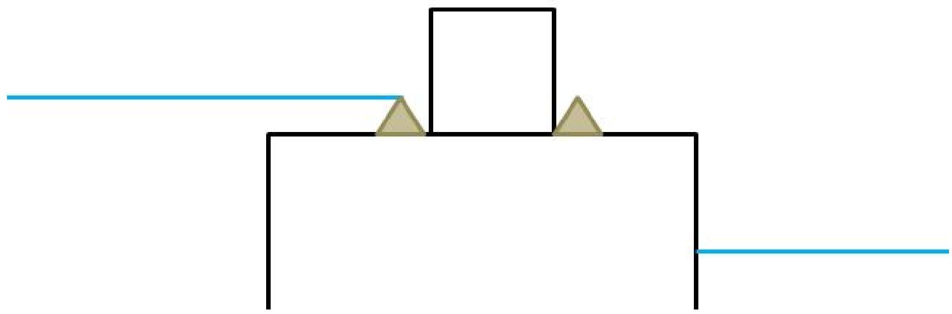


Figure 5-1: Illustration of Containment dike

These containment dikes are tested on the stability to contain oil on the inside. They have however not been tested on stability against inundation of water on the outside. This test is performed in this section.

The geometry of a containment dike varies as the volume it needs to be able to contain also varies. Known is that the minimum slope of the dike needs to be 1:1, but there are no height or width restrictions. The height is estimated based on both visual inspection, data from the AHN[32] and the fact that it needs to contain the entire volume of oil. In the AHN database the containment dike in the Botlek have a height varying between 1m and 3m. This leads to an estimated average height of 2m. A crest width is assumed of 10cm. As material is unknown it has been tested to both clay and sand, but the assumption is made that a clay lens is always present. The stability test is therefore for a containment dike of dimensions 2 meter in height and 4.1 meters in width with a crest width of 0.1m.

To investigate if the containment dike can also contribute to protection against failure due to inundation several failure mechanisms are considered. The failure mechanisms that are calculated are those that are most likely to be the dominant failure mechanisms. These are, macro stability, shearing and overtopping inner slope erosion. Piping is assumed not to be a problem due to the presence of a clay subsoil and a clay lens in the dike.

The soil properties are unknown. Therefore the dike is tested for both a sand and a clay body. The properties are listed in table B-1.

Table 5-1: Soil properties for both sand and clay

	Sand	Clay
Density [kN/m3]	19	14
Cohesion[kN/m2]	0	9
Angle of friction[degrees]	50	20

5-3-1 Macro stability

Slope stability is a well-known failure mechanism. Failure occurs when a slope starts to slide in case of a flood or heavy rainfall. The soil is subdivided in an active and a passive zone, where the active zone causes the driving moment and the passive zone causes the resistant moment. Many slip circles are possible and finally the path of least resistance is the normative slip circle.

With the help of D-Geo the dike has been tested by means of the Bishop method and has been proved to be stable with a safety factor of 1.35 for clay and 1.1 for sand. For the results see Appendix B

For this failure mechanism it is therefore assumed that the containment dike holds until an inundation depth of 2 meter in which it fully overflows. The probability of failure is therefore a binary plot which goes from 0 to 1 at the crest level.

5-3-2 Shearing

Shearing is the failure mechanism that occurs in case of horizontal instability. This occurs when the horizontal water pressure exceeds the shear strength at the bottom of the dike. This process is illustrated in figure 5-2.

The shear strength is dependent on the soil properties of the dike and the phreatic line in the dike body as these influence the effective stresses in the body.

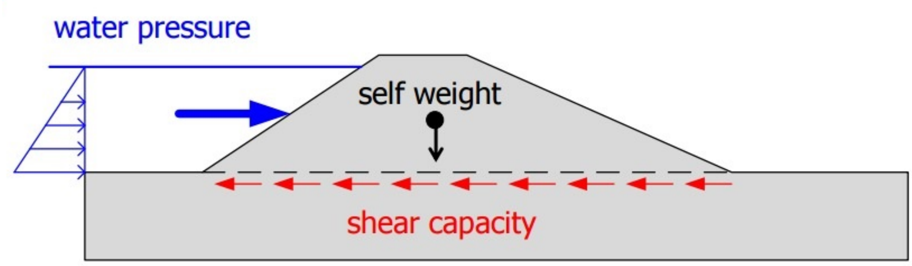


Figure 5-2: Shearing mechanism

The calculation for this is performed in Appendix B-2. The result is that the structure is stable for this failure mechanism for both a sand and clay body.

5-3-3 Overtopping

Overtopping is the failure mechanism when water caused by waves and wind overtops a dike and causes damage to the inner slope of a dike leading to instability. For overtopping there are clear guidelines for the maximum overtopping amounts. In this case with the poor slope conditions it is assumed that maximum overtopping is allowed at 0.01 l/s/m.

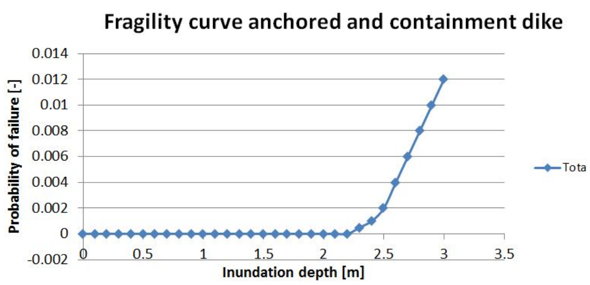
For the fragility curve this means that in case of a containment dike the probability of failure is zero as long as the inundation depth does not reach 1.24m. The full calculation can be found in Appendix B.

5-3-4 Resulting fragility curves

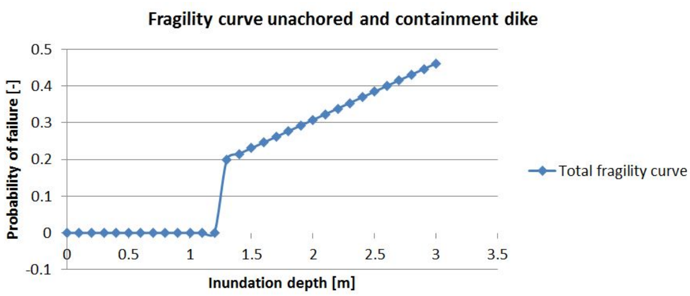
With the stability established and the limiting water depth of 1.24m determined the fragility curve must be made. This is done for three situations.

- Anchored tank and containment dike
- Unachored tank and containment dike
- 80% of the tanks anchored and 20 % un-anchored with containment dikes

With the new limiting water depth a threshold value must be implemented in the fragility curve. This has been incorporated in the model with taking the ground level of 4.5m + NAP and adding the required 1.24m of the containment dike. Before the water level of 4.5+1.24=5.74m +NAP is reached there is no damage. However, now when this threshold value is exceeded there instantaneously is damage according to an inundation depth of 1.24m. This has been incorporated in the model and the following fragility curves are the result.

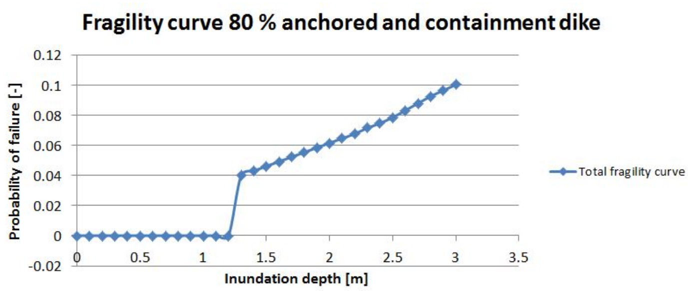


(a) Anchored storage tank with containment dikes



(b) Un-anchored storage tank with containment dikes

Figure 5-3: Location of pilot area



(a) 80% of the storage tank anchored with containment dikes

In case of an anchored tank the containment dike does not lead to a different fragility curve. For the un-anchored storage tank the initiation point with which the probability of failure occurs is shifted to a higher inundation depth. The same occurs with the 80% anchored situation.

5-3-5 Resulting risk reductions

The total risk reduction in the situation for a containment tank can be divided into the economic and environmental damage that is prevented. In both of these categories there is direct damage due to broken equipment and clean-up operations and indirect damage due to business interruption and clean-up time.

The resulting risk reduction is shown for both the environmental and economic damages. Due to the low risk of the environmental damage, this aspect does not lead to a high risk reduction. In table 5-2 the resulting reduction in the expected outcome is seen for each combination of uncertainties for the economic damages.

The current method of modelling causes the entire area to be protected while in reality only the tanks are protected. The tanks only take up roughly 50% of the expected direct damage. As the indirect damage is a function of the indirect damage it is assumed that the indirect damage behaves accordingly. Therefore the total risk reduction of both direct and indirect will be reduced to 50% to take the limited protection of only the tanks into account.

Table 5-2: Material risks in case of a containment dike

	No protection		Containment dike protecting 50 percent	
	Expectedvalue [Euro/m^2]	Relative influence [-]	Expectedvalue [Euro/m^2]	Relative influence[-]
Deterministic calculation	5.1	1	2.7	1
Uncertainty in water level	18.1	3.56	9.6	3.54
Uncertainty in turning point	5.1	1	2.7	1
Convex recovery curve	5.1	1	2.7	1
Concave recovery curve	5.08	0.99	2.7	1
Lineair recovery curve	5.08	0.99	2.69	0.99
Uncertainty in direct damage factor h0	4.97	0.98	2.64	0.98
Uncertainty in direct damage factor hmax	5.5	1.08	2.92	1.08
Uncertainty in direct damage factor fmax	5.09	1	2.7	1
Uncertainty in direct damage all uncertainties	5.37	1.05	2.84	1.05
Uncertanty in interest rate	5.36	1.05	2.85	1.05
All uncertainties	20.2	3.97	10.7	3.94

Table 5-2 shows that the risks are lower for the containment dike scenario in comparison to that of no protection. The influence of the knowledge uncertainties does not change significantly.

For the environmental damage the following is found in relation to the protection of a containment dike. The values from table 4-8 lead to a marginal difference in risk with relation to a containment dike as is seen in table 5-3.

Table 5-3: Environmental risks with and without containment dikes

	Without containment dike	With containment dike
Anchored	2.14E-04	2.14E-04
Unachored	0.011	2.25E-03
80 percent anchored	2.25E-04	2.22E-04

Table 5-4: Risk reduction of 50 percent of the total economic damage

	No uncertainties	All uncertainties
Risk per square meter reduction [Euro/m^2]	2.7	10.7
Total risk reduction [x 10^6 Euro]	62.3	245.4

With this result the risk reduction of a situation with containment dikes compared to a situation without a containment dike is clear. Only economical damage is reduced, where as the environmental damage is not affected.

5-3-6 Costs benefit analysis of containment dikes

To make an informed decision about whether the risk reduction is higher than the possible costs of such a containment dike the costs are assessed. This is done by assuming a soil based containment dike. The costs for constructing such a structure are mostly in the costs of material and its excavation, transport and placement.

The length of the containment dike is considered with a tank diameter of 34 meter. The costs are taken from [28]. The costs of soil are estimated at 15 Euro per m^3 and the transport, placement and slope levelling being 4 Euro per m^3. On top of this the following charges are taken.

further detailing:	30%
engineering:	4%
indirect costs:	15%
legal charges:	2%
unforeseen:	10%

The volume is estimated for a tank diameter of 19 meter, a height of 2 meter and width of 4.1 meter with corresponding slope of 1:1. It is assumed that each of the 1800 tanks has a containment dike.

Table 5-5: Total costs of a containment dike

	Volume per containment dike [m^3]	Number of containment dikes [-]	Total volume of soil[m^3]	Total costs [x 10^6 Euro]
Containment dike of 2m	454	1800	816,000	26.5

The total costs of the containment dikes are far lower than the prevented damage in case of the risks that are lowered therefore it is a worthwhile investment. The fact that these containment dikes are present is therefore beneficial to the risk profile of the Botlek.

These dikes are already in place, therefore the costs of constructing a whole new containment dike are overestimated. The soil conditions are uncertain for the existing containment dikes. In order for them to truly be able to retain water some floodproofing needs to be made. The costs of improving the existing containment dikes and floodproofing them are much lower than those of constructing them entirely. As the soil conditions are unknown, the exact operations and expenses that are needed are not available. Therefore the assumption is made that with 25 percent of the investment costs the current dikes can be made floodproof.

Table 5-6: Total costs of a containment dike

	Circumference of containment dike [m]	Volume per containment dike [m^3]	Number of containment dikes [-]	Total volume of soil [x10^3 m^3]	Total costs [x 10^6 Euro]
Containment dike of 2m	106.76	453.73	1800	817	6.2

To put the three options of do nothing, floodproofing the dike or rebuild the dike so that it can retain water in perspective, a cost benefit comparison is made. In figure 5-5 a graph is shown that clearly shows that the floodproofing the current containment dike has the lowest total costs.

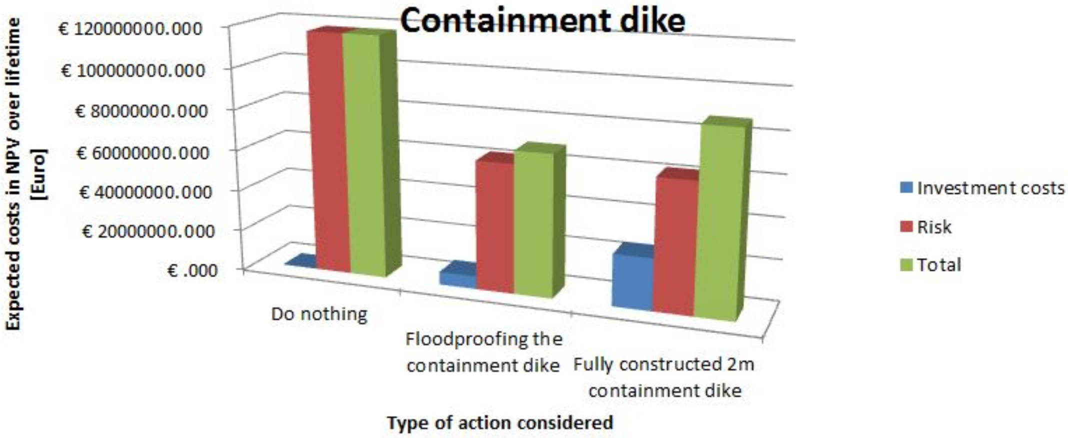


Figure 5-5: Cost benefit comparison for containment dike possibilities

5-4 Constructing a ring dike

Another possible option is the construction of a ring dike. In the Botlek area, this would be raise and extending the existing Tuimelkade. The current elevation of this dike is NAP +5.20m, but this dike does not completely protect the Botlek from the Hartelkanaal and is also not designed to resist stability tests. For this simplified model, however, it is assumed that a ring dike protects the area completely from the channel.

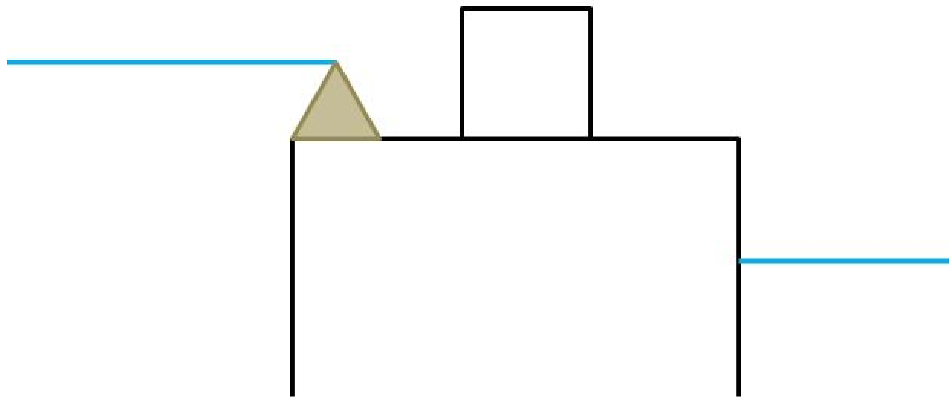


Figure 5-6: Illustration of a ring dike

In the Botlek the Tuimelkade which acts as a ring dike already has a level of NAP+5.20m. For this reason this is used as the starting point of a raised ring dike. Therefore, a reference level run is made that takes a ring dike as a completely protecting dike at NAP +5.20m. This is compared with raising the ring dike in steps of 0.25m.

- Raising to the level of the Tuimelkade, NAP+5.2m
- Raising of 0.95m to a level of NAP+5.45m
- Raising of 1.2m to a level of NAP+5.7m
- Raising of 1.45m to a level of NAP+5.95m
- Raising of 1.7m to a level of NAP+6.2m
- Raising of 1.95m to a level of NAP+6.45m
- Raising of 1.95m to a level of NAP+6.7m

The current Tuimelkade consists of a clay body with a grass revetment on top[1]. It has not been tested on stability or whether it can withstand overtopping. The soil properties of the subsoil are also unknown. These are assumed to be clay, but if they are sand the stability for the structure could prove to be lower. It is assumed that the ring dike has the same properties as the Tuimelkade.

The slope for the design of the ring dike will be constructed at 1:3 with a crest width of 3m as these are geometries that are generally stable. The slopes will be protected with a revetment to withstand overtopping and wave attack.

5-4-1 Failure mechanisms and fragility curve

The structure is tested for horizontal shearing, slope stability and overtopping. Piping is not considered as the subsoil and dikebody are presumed to be a clay structure. The calculations are found in Appendix C. The resulting fragility curves have been determined. An example fragility curve is shown in figure 5-7.

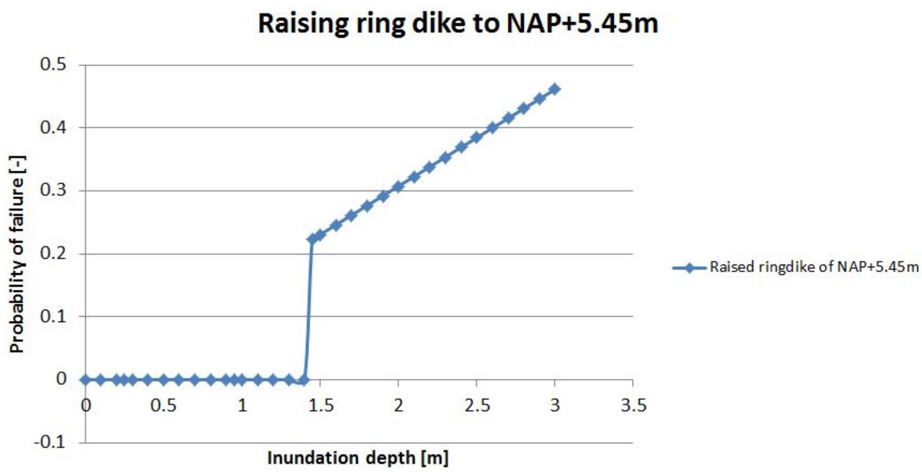


Figure 5-7: Unanchored storage tank with containment dikes

5-4-2 Reduction of risk

The reduction of risk is determined by the economic and environmental damage. The environmental risk is very low. Hence the reduction of the risk in this category is trivial. It is therefore not considered herein.

The effect of the raising of the ring dike has been implemented assuming that the water is fully retained before the maximum retaining height is reached. When the water level is higher than the maximum retaining height, the hinterland with the tanks instantly inundates to the outside water level.

Table 5-7: Risk reduction in case of a raised ring dike

	NAP+5.20m	NAP+5.45m	NAP+5.7m	NAP+5.95m
	Expected NPV over lifetime [Euro/m^2]	Expected NPV over lifetime [Euro/m^2]	Expected NPV over lifetime [Euro/m^2]	Expected NPV over lifetime [Euro/m^2]
Deterministic calculation	1.8	0.81	0.36	0.17
Uncertainty in water level	6.3	2.7	1.15	0.56
Uncertainty in turning point	1.8	0.8	0.36	0.17
Convex recovery curve	1.8	0.8	0.36	0.17
Concave recovery curve	1.8	0.8	0.36	0.17
Lineair recovery curve	1.8	0.8	0.35	0.16
Uncertainty in direct damage factor h0	1.8	0.81	0.36	0.17
Uncertainty in direct damage factor hmax	1.7	0.8	0.37	0.17
Uncertainty in direct damage factor fmax	1.8	0.81	0.36	0.17
Uncertainty in direct damage all uncertainties	1.7	0.8	0.37	0.17
Uncertanty in interest rate	1.9	0.85	0.4	0.18
All uncertainties	6.3	2.8	1.24	0.6

As expected the risk reduces significantly with the raising of the ring dike. The total reduction per raising scenario is listed in table 5-8.

Table 5-8: Risk reduction for raising the ring dike

	No uncertainties		All uncertainties	
	[Euro/m^2]	[x10^6 Euro]	[Euro/m^2]	[x10^6 Euro]
NAP+5.2m	3.3	76	13.9	320
NAP+5.45m	4.3	98	17.5	401
NAP+5.7m	4.7	108	19.0	436
NAP+5.95m	4.9	113	19.6	451
NAP+6.2m	5.0	115	20.0	460
NAP+6.45m	5.1	114	20.1	461
NAP+6.7m	5.1	114	20.2	463

5-4-3 Cost benefit analysis ring dike

The risks reductions that are associated are put against the costs of raising the ring dike. The costs are put against the risk reduction and a cost benefit analysis is made. First the costs are determined, followed by the cost benefit analysis.

Table 5-9: Costs of raising the ring dike

	Total volume [x10^3 m^3]	Total costs [x10^6 Euro]
Raising to NAP +5.20m	22.8	5.2
Raising to NAP +5.45m	29.3	6.4
Raising to NAP +5.70m	51.1	7.1
Raising to NAP +5.95m	76.4	9.3
Raising to NAP +6.2m	90.9	11.4
Raising to NAP +6.45m	106.3	13.2
Raising to NAP +6.70m	118.9	14.2

The costs for the ring dike take cost of soil of 15 Euro per m^3 and the transport, placement and slope levelling of 4 Euro per m^3 into account. On top of that, a revetment needs to be put in place. This is assumed to be to the extent of 50 Euro/m^2. The costs of the ring dike are relatively low and might be underestimated by this simple cost calculation. However compared to the risk reduction of the ring dike the costs are marginal even if they are slightly underestimated.

A cost benefit analysis has been made to assess what dimensions are most lucrative for the investment of the ring dike. In figure 5-8 the most profitable investment is a ring dike raised to a level of **NAP+6.2m**. What needs to be considered is that this is the ideal height for a ring dike in the idealized model. It does not represent the Botlek specifically.

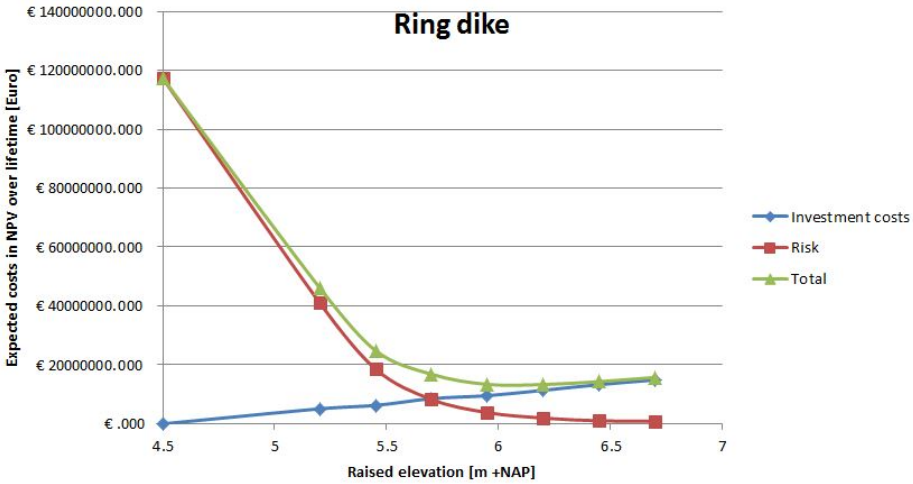


Figure 5-8: Cost benefit analysis for raising the Tuimelkade

With this in mind, raising the ring dike is a smart investment. However, there are some limitations. As this is a harbour area, with constant shipping and related activities, building a ring dike in front of the waterline is not beneficial for accessibility. Leaving the quays open would diminish the effectiveness of the retaining structure. Therefore in case this option is considered accessibility must be taken into account.

5-5 Floodproofing vital components and elevating the industry

Flood proofing is the reduction of damage in case of inundation. It does not prevent inundation, but does prevent vital components to be damaged. Certain areas have more priority to flood proofing than others. Such areas are linked to the quick recovery of the operating systems. This can be found in electricity facilities, nitrogen facilities and infrastructure in the Botlek. An added benefit of floodproofing is that also damage due to inundation in case of extreme precipitation is reduced.

At first glance this is very expensive. However, industry has a write off process where components are replaced. When this scheduled replacement strategy is considered, it could be feasible that with a small extra investment, of say 1 to 10 percent of the replacement costs. The components could be placed at a higher elevation or modified in such a way that they are made flood proof. A rough example of such a process in handled in this section. The assumption is made that over the course of 100 years all components of industry will have been made flood proof gradually.

Assuming that the maximum direct damage value for a storage tank is 0.41 times 823 = 337 Euro/square meter the replacement costs for the entire facility are expected to be 50 percent of the maximum damage. This is based on the fact that purely material replacement is considered and not products. Also the flood proofing might not be needed or be possible for all installations. For this reason the factor of 0.5 is estimated to be reasonable. For the total Botlek area this would come down to 3.9 billion Euro.

5-5-1 Risk reduction

The risk reduction in the case of floodproofing is estimated based on the foreseeable lifetime of 100 years. This reduction is calculated by implementing the floodproofing in the same model. Starting for the first year the maximum damage is reduced annually by 1 percent. After 100 years the industry is fully flood proof.

Table 5-10: Total risk over lifetime for a gradual flood proofing

	Expected risk in NPV over a lifetime of 100 years [Euro/m2]
Reference calculation	3.6
Uncertainty in water level	12.9
Uncertainty in turning point	3.6
Convex recovery curve	3.6
Concave recovery curve	3.6
Lineair recovery curve	3.6
Uncertainty in direct damage factor h0	3.5
Uncertainty in direct damage factor hmax	3.9
Uncertainty in direct damage factor fmax	3.6
Uncertainty in direct damage all uncertainties	3.8
Uncertanty in interest rate	3.7
All uncertainties	14.0

This reduction in risk is substantial as can be seen in table 5-10 and table 5-11. However the investment costs are also substantial. The added benefit is that after 100 years assuming the industry is still at that location, there is a fully floodproof facility. This added risk reduction is not taken into account.

Table 5-11: Reduction of risk for flood proofing

	No uncertainties		All uncertainties	
	Reduction of risk per square meter [Euro/m2]	Reduction of risk for total area [x10^6 Euro]	Reduction of risk per square meter [Euro/m2]	Reduction of risk for total area [x10^6 Euro]
Flood proofing	1.50	34	6.26	144

5-5-2 Cost benefit analysis of floodproofing

The costs are determined as a fixed percentage, between 1 and 10 percent of the replacement costs. With the replacement costs at 3.5 billion Euro the corresponding additional flood proofing costs would be from 35 million to 345 million Euro.

Assuming that each year the same relative investment is made, namely 1/100 of the replacement costs, the total additional replacement costs can be calculated back to the NPV. With this, the total costs in NPV can be calculated for gradually making the site flood proof.

Table 5-12: The net present value of flood proofing of the entire plant facility

Flood proofing	NPV in 2016 [x10^6 Euro]
1 percent of replacement costs	12
5 percent of replacement costs	61
10 percent of replacement costs	122

These costs are significantly higher than costs for other measures and lower risk reductions than for other risk reduction measures. Floodproofing will, however, also give protection against extreme precipitation and inundation related to climate change scenarios. The quality of this protective measures is higher than the quality of other measures, but comes with a high price card. On top of this, there could be difficulties on the operation end of business due to elevated access points and unforeseeable difficulties.

Interesting to see is for what level of investment costs floodproofing would be a profitable measure. Therefore an analysis is made to investigate for what percentage of replacement costs the floodproofing measure is still cost efficient. In this the percentage of the replacement costs is set against risk and the investment costs. Naturally the most benefit is gained with the lowest investment costs. In figure 5-9 the maximum profitable replacement costs are shown by the intersection of the critical line. The maximum is found to be 3 percent of the replacement cost.

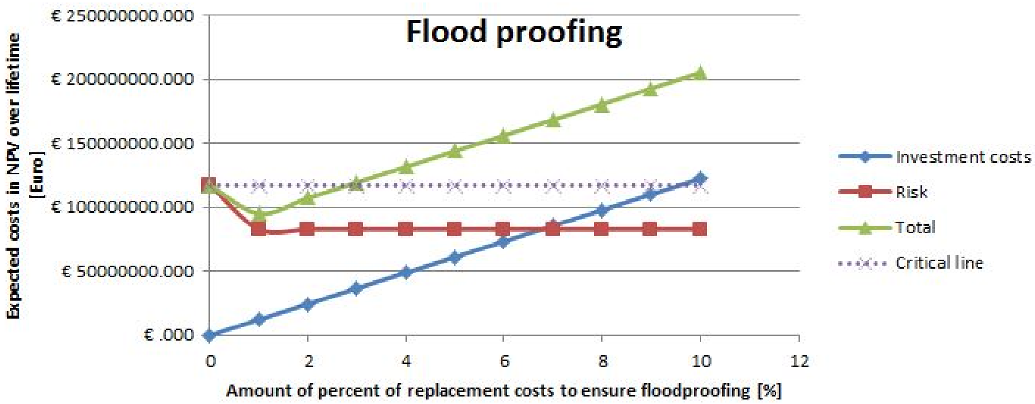


Figure 5-9: Cost benefit analysis for floodproofing the area

5-6 Conclusion

From this analysis of the different type of protective measures there is one predominant conclusion. For the containment dike and ring dike the risk reduction are higher than the investment costs. Therefore it is assumed to be a better choice to employ one of these measures than to do nothing. For floodproofing it is only beneficial if investment costs are lower or equal to 3 percent of the replacement costs

Between the different quantitative measures the cheapest option would be that of the raising the ring dike. The most expensive would be that of flood proofing if the costs prove higher than 1 percent of the replacement costs.

The costs for the containment dikes are relatively high, however, these are already in place. If the subsoil is found clay, they are sufficient in protecting a large part of industry.

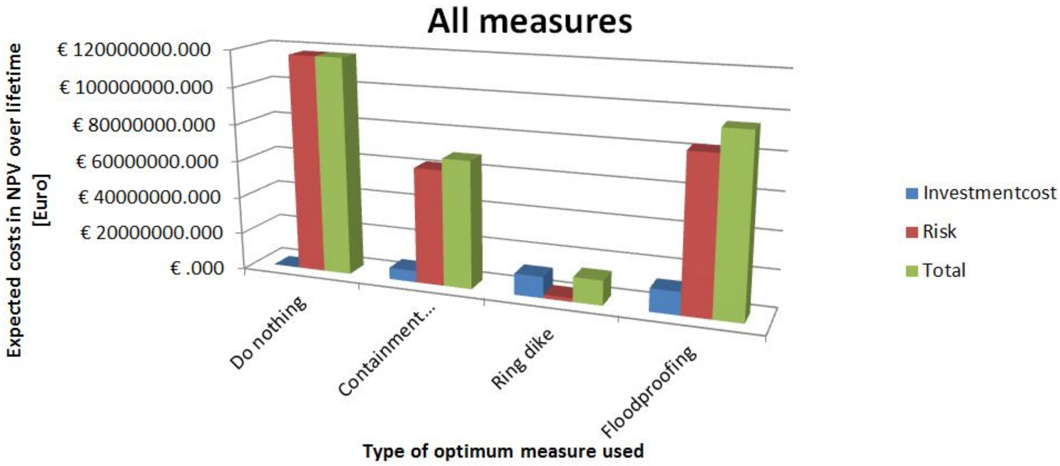


Figure 5-10: Cost benefit analysis comparison for all optimum measures

In figure 5-10 a comparison is made between the most cost efficient set-ups of each measure. With this in mind the ring dike currently is the most cheapest and efficient way to reduce risk substantially. Flood proofing would however be an interesting addition to prevent precipitation induced damage.

What needs to be considered is that the current risk estimation is based on an idealized approach and does not match the geographical characteristics of the Botlek. The average elevation taken in the model is lower than that of the Botlek. Therefore the risk in the risk profile and thus in the risk reduction are overestimated. However looking at the relatively small investment costs even for a lower risk reduction placing a ringdike or a containment dike are considered a valid strategy.

Chapter 6

Conclusions and recommendations

The goal of this thesis was to understand how a flood risk profile behaves for an outer-dike industry. Key aspects that have been addressed are: how the knowledge uncertainties in estimators influence this flood risk profile, what impact environmental damage has and what adaptive measures could be efficient. In this chapter, the conclusions from the research are summarized and the interdependency is discussed. The main conclusions is given first, followed by the conclusions of each of the subquestions. Finally, several recommendations are discussed.

6-1 Main conclusion

The use of an idealized model was implemented to quickly and directly gain insight into the effect of several knowledge uncertainties, environmental impact and flood reduction measures. It became clear that the idealized model led to a higher expected flood risk than a more detailed model for the case study area (Botlek, Rotterdam). However, the order of magnitude of the idealized model was similar to that of the detailed model.

The idealized economic flood risk model demonstrated that the expected flood risks increased significantly by incorporating knowledge uncertainties in damage estimators and water level predictors. The knowledge uncertainty in water level predictors is predominant in the various sources of knowledge uncertainties. In case of sea level rise the expected flood risks and influence of the corresponding knowledge uncertainties increases as well. It is also noticeable that the low inundations with relatively high probabilities play a much larger role than high inundations with low probabilities in the flood risk assessment.

If no knowledge uncertainties are considered the flood risk is comparable with the flood risks that are present in an inner-dike area. In this case it could be considered that they are deemed acceptable. However, in case of knowledge uncertainties or sea level rise they are an order of magnitude, four times, larger than inner-dike situations without knowledge uncertainties.

The flood risks concerning environmental damage are limited. This is due to very low probabilities of tank failure. The influence is low enough that they don't play a dominant role in the flood risk profile. However, only clean-up related costs are considered. Ecological effects and flood risks related to a possible fire prove significant enough from the qualitative assessment to investigate further.

Due to the increasing flood risks a flood reduction measure is advisable from a cost benefit perspective. The most beneficial measure is the construction of a ring dike as this protects the entire area from water intrusion through the channel. Floodproofing is more expensive than the other flood risk reduction measures and is possibly not beneficial, but it also protects against extreme precipitation. However, it is still unclear to what extent floodproofing protects the industry and a lot of knowledge uncertainty is present in the actual costs.

6-2 How do knowledge uncertainties in flood indicators and damage estimators influence the estimation of flood damage?

The first observation of the results was that the flood risks are much lower without knowledge uncertainties than with knowledge uncertainties. Including the knowledge uncertainties, the expected flood risk over a lifetime of 100 years increased by almost a factor 4.

This increase is mainly dependent on the knowledge uncertainty in the prediction of water levels. When solely this knowledge uncertainty is implemented, the expected flood risks increase by a factor 3.5 over a lifetime of 100 years. What also became clear from implementing the knowledge uncertainty in water level predictor is the influence of higher and lower frequency storm events. The influence of the higher frequency storm events, which consist of very low inundation depths are predominant in the expected flood risk of the model.

Implementing the knowledge uncertainty in damage estimators was split into two aspects, direct and indirect damage. The influence of the knowledge uncertainty in direct damage estimators was modelled and led to an increase in expected flood risk in the order of 5 percent. This analysis shows that the knowledge uncertainty in the inundation depth where maximum damage is attained contributes primarily to the increase in expected flood risk.

For the indirect damage uncertainty assessment two methods were used. The indirect damage factor, where with an uncertainty band of 0.5 to 2 times the indirect damage an increase of 12 percent in expected flood risk over 100 years was found. The second method was the use of recovery curves. In this, recovery times were considered for different inundation depths. Extrapolated recovery curves were made and the corresponding expected flood risk was calculated. When these curves were used in the model two aspects became clear. Indirect damage reduces to almost 0 and the implementation of knowledge uncertainty no longer has relevant influence on the expected flood risk. The choice of whether a convex, linear or concave recovery model must be used proved to be of little influence as the recovery times for the low inundation depths were so small.

The last knowledge uncertainty implemented was the interest rate. Uncertainty implemented here led to an increase of the expected flood risk of 5 percent over 100 years.

Sea level rise scenarios were implemented in the model leading to an increase in expected flood risk. In addition the influence of the knowledge uncertainties got higher, however the knowledge uncertainty in water level predictor is still the most predominant influence. For lower elevated harbours the influence of the knowledge uncertainties in water level prediction, indirect and direct damage increased. The amount of indirect damage using the recovery curves increased slightly, but still the direct damage was predominate in the expected flood risk.

The economical flood risks were compared to an inner-dike expected flood risk. When taking the simplification and idealizations in the outer-dike flood risk assessment into account the results are in the same order of magnitude. When sea level rise or the effect of the knowledge uncertainties are considered the expected flood risks for an outer-dike area increase significantly to much larger flood risk levels. However, the same applies to when knowledge uncertainties are considered for inner-dike situations.

6-3 In what way can environmental damage caused by a chemical leak be modelled and how does it compare to the existing flood risk profile?

To answer the next subquestion, an analysis was made on environmental risk. From the analysis came forth that the focus in this research is to analyse pollution quantitatively and flammability and toxicity qualitatively.

The total expected risk for environmental damage is very low, a factor of at least 450 lower than the economic and material flood risks. The environmental damages in case of a leak are in the same order of magnitude as economic and material damages. The probability of tank failure, however, is very low leading to very limited expected risks.

The damage curves, which have been based on expert judgement, are compared to the probabilistic assessment of tank failure. The result is that the probabilistic assessment leads to much lower expected risks. This can be related to the probabilistic assessment, but also to the fact that in the damage curves more components of industry are considered in the damage assessment. In the probabilistic model only tank failure is considered. Also difference between damage and tank failure can be accredited to the reduction in risk.

The damage to ecological systems and possible fire related damage could prove to be significant. The fire risks are the highest in case of an eastern flow direction and are estimated to be questionable to unacceptable for all scenarios. Ecological damage due to toxicity is difficult to assess and is advisable to look into more.

6-4 What protective strategies are possible and which are most effective according to the decision model?

Several flood risk reduction measures are possible, three have been selected for this research: the placement of a ring dike, the constructing or improving of containment dikes in order to retain water and finally the use of flood proofing to investigate what a long term benefit could be.

The flood risk reduction as result of such a containment dike is considerable. Floodproofing the current containment dike is the most economical option. In this risk reduction it is assumed that the containment dike protects 50 percent of the industry components.

The ring dike does protect the entire industry as it fully shuts of the Botlek of the Hartelkanaal. A considerable investment must be made to create a ring dike that is able to retain the water, but the flood risk reduction is certainly worth the investment. The ring dike is most beneficial when elevated to NAP+6.2m.

The final option that is considered is the use of floodproofing. This leads to lower flood risk reductions due to the gradual protection An optimum of 1 percent of the replacement costs causes the largest flood risk reduction. When the investment costs for floodproofing are higher than 3 percent of the replacement costs it is no longer a cost efficient measure.

6-5 Recommendation

Improving the accuracy of the water level predictors is most effective when looking at the influence of the knowledge uncertainties in the flood risk model. The higher frequency events proved more influential than lower frequency events. This is beneficial for increasing the accuracy as low probability events that are not available are of diminished influence. As increase in data cannot be influenced directly, the increase in accuracy must be attained elsewhere. A research into how much knowledge uncertainty is currently present in the translation from sea water level to in-port water level needs to be done. Furthermore, the accuracy in method of modelling must be increased.

Investigate the effects of possible domino effects in case of a fire during a flood. This situation of a floating fire is expected to have very small probabilities, but also very high consequences. A model will need to be constructed that shows dispersion in case of an oil spill, the duration for which the oil remains at each consecutive tank and the heat radiation that each tank suffers. To make a full probabilistic analysis also higher order domino effects must be considered and multiple point of origin.

The possible ecological damage that could be the result of an oil spill could be interesting to assess with a dispersion model and an ecological analysis of what marine life could be seriously affected. The dispersion model will need to show what areas are affected and what level of concentration needs to be considered. In the ecological analysis an inventory of available marine life and type of vegetation must be made. With the concentrations and contamination type known an estimation can be made to what degree the ecological life is affected. With estimations in recovery time the damage can be expressed.

A study based on the damage curves in relation to a probabilistic assessment is recommended to increase insight into damage assessment. Although the influence of knowledge uncertainty in damage estimators was shown to be limited, the difference between the probabilistic assessment(environmental) and the damage function(economic) was shown to be large. An investigation into when damage actually occurs and linking probabilities to this can reduce the expected flood risks significantly.

Appendix A

Results of the economic model

The results of the economic model are shown in this appendix. First the distribution of the damage is shown, both including zero values and one without zero values. After this the expected risks resulting of all calculations of the economic model are shown. Followed by this are the expected risks for each of the flood risk reducing measures.

A-1 Distribution of damage

In this section the results are shown of the matlab configuration of the idealised flood risk model for a single tank. The results shown are for an anchored tank and are used to illustrate the distribution of damage in case of a run during a lifetime. The left figure illustrates the amount of runs that damage takes place, the large majority is that there is no damage and therefore is 0. The right figure illustrates the distribution of damage in each case that damage is present.

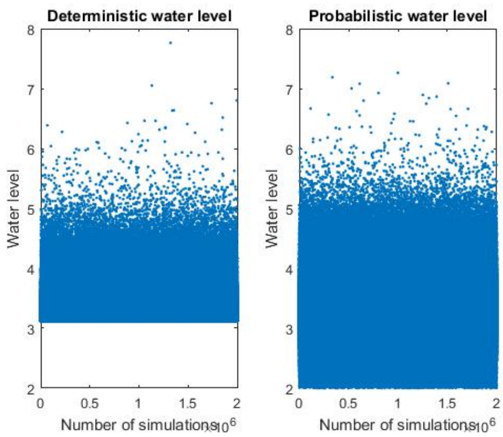


Figure A-1: Generated water levels

Table A-1: Total results of indirect damage factor

	Expected value of NPV over lifetime [Euro/m^2]	Relative influence on outcome [-]	Coefficient of variation [-]
Reference calculation	10,1	1	-
Uncertainty in water level	36.214	3.587	0,12
Uncertainty in indirect damage	11.32	1.12	0,43
Uncertainty in direct damage factor h0	9.84	0.97	0,58
Uncertainty in direct damage factor hmax	10.91	1.08	0,29
Uncertainty in direct damage factor fmax	10.1	1	0,13
Uncertainty in direct damage all uncertainties	10.631	1.05	0,13
Uncertanty in interest rate	10,61	1,05	0,29
Combination of all uncertainties	45.65	4.51	-

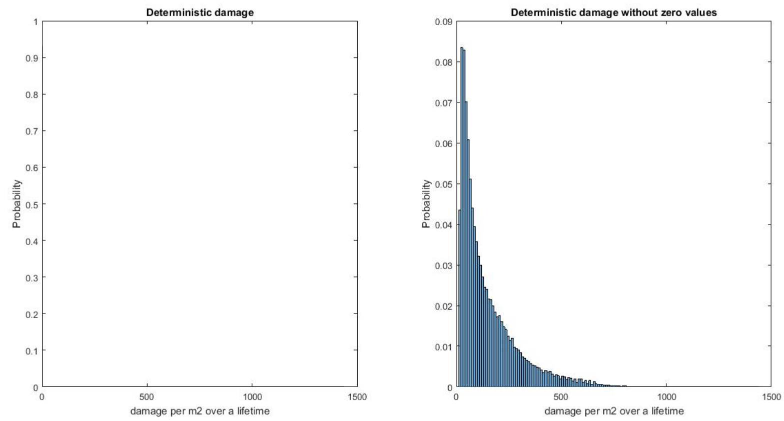


Figure A-2: Reference calculation

A-2 Model results

In this section the results of the model are shown for the basic model and each flood risk reducing measure measure.

A-2-1 Unprotected situation

For the unprotected situation the total expected risks relating to the indirect damage model and recovery curve model are shown. Both the direct and indirect risks are also shown for each of the models.

Table A-2: Total results of the recovery curve analysis

Variable	Expected value of NPV over lifetime [Euro/m^2]	Relative increase i.r.t. reference calculation [-]
Reference calculation with convex trendline	5.1	1
Uncertainty in water level prediction	18.1	3.6
Uncertainty in convex trendline	5.1	1
Convex trendline	5.1	1
Concave trendline	5.1	1
Linear trendline	5.1	1
Uncertainty in direct damage factor, h_0	5.0	0.97
Uncertainty in direct damage factor, h_{max}	5.5	1.08
Uncertainty in direct damage factor, f_{max}	5.1	1
Uncertainty in direct damage all uncertainties	5.37	1.05
Uncertanty in interest rate, r	5.36	1.05
All uncertainties	20.2	4.0

Table A-3: Total direct damage for the indirect damage model

	Direct damage	
	Expectedvalue	Factor
Reference calculation	5.05	1
Uncertainty in water level	18.11	3.59
Uncertainty in indirect damage	5.07	1.004
Convex recovery curve	5.05	1
Concave recovery curve	5.05	1
Lineair recovery curve	5.05	1
Uncertainty in direct damage factor h0	4.90	0.97
Uncertainty in direct damage factor hmax	5.47	1.084
Uncertainty in direct damage factor fmax	5.05	1
Uncertainty in direct damage all uncertainties	5.29	1.05
Uncertanty in interest rate	5.31	1.05
All uncertainties	20.12	3.99

Table A-4: Indirect damage based on indirect alpha factor method

	Smodel indirect damage alpha factor	
	Expectedvalue	Factor
Reference calculation	5.36	1
Uncertainty in water level	20.6	3.56
Uncertainty in indirect damage	5.78	1.07
Convex recovery curve	5.36	1
Concave recovery curve	5.36	1
Lineair recovery curve	5.36	1
Uncertainty in direct damage factor h0	5.18	0.97
Uncertainty in direct damage factor hmax	5.89	1.08
Uncertainty in direct damage factor fmax	5.36	1
Uncertainty in direct damage all uncertainties	5.68	1.05
Uncertanty in interest rate	5.67	1.05
All uncertainties	21.36	3.99

Table A-5: Direct damage of the recovery curve analysis

Variable	Expected value of NPV over lifetime [Euro/m^2]	Relative increase i.r.t. reference calculation [-]
Reference calculation with convex trendline	5.1	1
Uncertainty in water level prediction	18.1	3.6
Uncertainty in convex trendline	5.1	1
Convex trendline	5.1	1
Concave trendline	5.1	1
Linear trendline	5.1	1
Uncertainty in direct damage factor, h_0	5.0	0.97
Uncertainty in direct damage factor, h_{max}	5.5	1.08
Uncertainty in direct damage factor, f_{max}	5.1	1
Uncertainty in direct damage all uncertainties	5.37	1.05
Uncertanty in interest rate, r	5.3587	1.052
All uncertainties	20.2	4.0

Table A-6: Indirect damage according to recovery curve method

	Indirect damage recovery curve	
	Expectedvalue	Factor
Reference calculation	0.015	1
Uncertainty in water level	1.66E-05	0.001
Uncertainty in indirect damage	0.019	1.22
Convex recovery curve	0.015	1
Concave recovery curve	0.016	1.06
Lineair recovery curve	0.0006	0.04
Uncertainty in direct damage factor h0	0.015	0.99
Uncertainty in direct damage factor hmax	0.015	0.99
Uncertainty in direct damage factor fmax	0.015	1
Uncertainty in direct damage all uncertainties	0.015	0.99
Uncertanty in interest rate	0.02	1.31
All uncertainties	1.06E-05	0.0007

Table A-7: Results of the ring dike model

	Reference level	Raising of 0.25m	Raising of 0.5m	Raising of 0.75m	Raising of 1m
	Expectedvalue	Expectedvalue	Expectedvalue	Expectedvalue	Expectedvalue
Reference calculation	1.79	0.81	0.36	0.17	0.085
Uncertainty in water level	6.26	2.7	1.15	4.3	1.75
Uncertainty in indirect damage	1.77	0.8	0.36	0.17	0.08
Convex recovery curve	1.77	0.79	0.36	0.17	0.08
Concave recovery curve	1.76	0.79	0.36	0.17	0.08
Lineair recovery curve	1.76	0.79	0.35	0.16	0.08
Uncertainty in direct damage factor h0	1.83	0.81	0.36	0.17	0.08
Uncertainty in direct damage factor hmax	1.67	0.79	0.37	0.17	0.085
Uncertainty in direct damage factor fmax	1.79	0.81	0.36	0.17	0.08
Uncertainty in direct damage all uncertainties	1.7	0.79	0.37	0.17	0.08
Uncertanty in interest rate	1.89	0.85	0.38	0.18	0.09
All uncertainties	6.3	2.8	1.24	4.3	1.9

Table A-8: Results of the containment dike model

	Containment dike 2m	
	Expectedvalue	Factor
Reference calculation	0.32	1
Uncertainty in water level	1.02	3.22
Uncertainty in indirect damage	0.32	1
Convex recovery curve	0.31	0.99
Concave recovery curve	0.31	0.98
Lineair recovery curve	0.31	0.98
Uncertainty in direct damage factor h0	0.32	1
Uncertainty in direct damage factor hmax	0.32	1
Uncertainty in direct damage factor fmax	0.32	1
Uncertainty in direct damage all uncertainties	0.32	1
Uncertanty in interest rate	0.34	1.06
All uncertainties	1.09	3.5

Table A-9: Results of the floodproof model

Floodproofing	Floodproofing	
	Expectedvalue	Factor
Reference calculation	3.6	1
Uncertainty in water level	12.86	3.6
Uncertainty in indirect damage	3.6	1
Convex recovery curve	3.6	1
Concave recovery curve	3.6	1
Lineair recovery curve	3.6	1
Uncertainty in direct damage factor h0	3.5	0.97
Uncertainty in direct damage factor hmax	3.91	1.09
Uncertainty in direct damage factor fmax	3.6	1
Uncertainty in direct damage all uncertainties	3.8	1.05
Uncertanty in interest rate	3.71	1.03
All uncertainties	13.97	3.88

Appendix B

Stability assessment containment dike

In this chapter the stability of a containment dike is analysed. First, the slope stability of macro stability is analysed, after this both shearing and overtopping is handled.

B-1 Slope stability

The stability assessment has been performed using the Bishop method to determine the slope stability of the containment dike. As no data is available about the soil properties for the containment dikes the calculation has been performed for both a sand and a clay dike.

The geometry is the estimated geometry of that in a containment dike. This results in a steep slope of 1:1. The height is estimated to be 1 meter in height with a crest width that is very limited.

The soil properties that were used are shown in B-1.

Table B-1: Soil properties of the containment dike

	Sand	Clay
Density [kN/m3]	19	14
Cohesion[kN/m2]	0	9
Angle of friction[degrees]	50	20

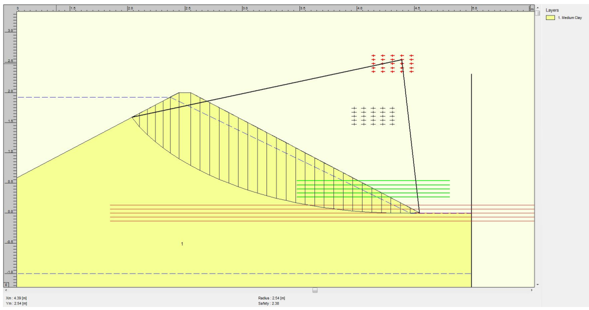


Figure B-1: Critical line for a sand dike

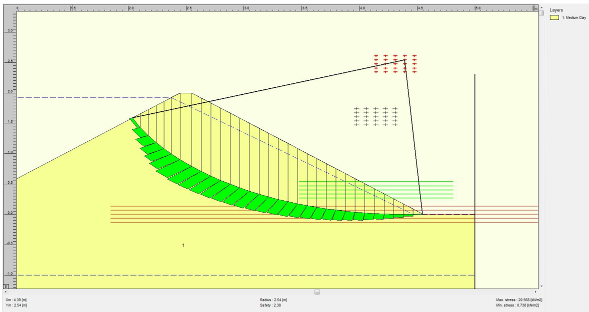


Figure B-2: Effective stresses for a sand dike

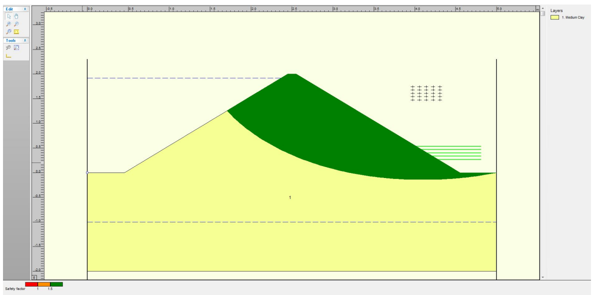


Figure B-3: Safety factor for a sand dike

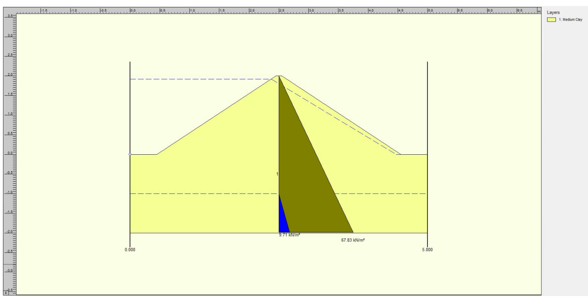


Figure B-4: Shear stress for a sand dike

B-2 Shearing

A generalised calculation has been done for shearing with the soil properties that are listed above in table B-1. The limit state equation and the factor of safety are given below.

$$
\begin{aligned}
Z &= p_{hydrostatic} < \tau \\
p_{hydrostatic} &= 0.5 * \rho_w * g * h_w^2 \\
\tau &= \sigma' * tan(\phi') + c' \\
FoS &= \frac{\tau}{p_{hydrostatic}}
\end{aligned} \tag{B-1}
$$

p = pore water pressure [kPa]
τ = shear strength [kPa]
σ' = normal vertical effective stress [kPa]

Table B-2: The factor of safety that is calculated for the shearing failure mechanism

	FoS
Sand	0.8
Clay	6.4

For a sand dike the stability is not ensured. With a factor of safety of 6.387 the shearing stability is guaranteed. Therefore it is assumed that the probability of failure for a 2 meter high clay containment dike for shearing stability is 0.

B-3 Overtopping

Maximum allowable overtopping for a low quality slope is 0.01 l/s/m[23]. The Van der Meer and Janssen(1995) formula describes overtopping for surging and plunging waves. In the scenario of the idealised set up surging waves are assumed. Wave height is assumed to have a maximum value of 0.73 times the waterdepth based on Battjes and Stive(1985)[24]. This is only for a horizontal bed and shallow water depths, which in this case are present.

$$\frac{q}{\sqrt{gH^3}} = \frac{0.06}{\sqrt{tan(\alpha)}}\gamma_b \xi_{op} exp(-4.7\frac{R_c}{H_s}\frac{1}{\xi_{op}\gamma_b\gamma_f\gamma_\beta\gamma_v})$$

The variables for this equation have been taken out of the Bed, bank and shoreline protection manual[23]. For the slope it is assumed that there is a grass slope without a wall. The berm has such a limited width that this is also set to 1. Further than that conservative values have been used which are shown below.

$tan(\alpha) = 1.69$
$\gamma_b = 1$

$\gamma_f = 0.95$
$\gamma_\beta = 0.9$
$\gamma_v = 1$
$\xi_{op} = 2$

After iteration the resulting crest freeboard the dike must have is $R_c = 0.76m$. This results in a maximum inundation depth of 1.24m. Therefore the overtopping mechanism is dominant.

Appendix C

Stability assessment Ring dike

In this chapter the stability assessment of the ring dike is made. First, the slope stability or macro stability is considered, afterwards the shearing calculation is made and finally the overtopping calculation is performed.

C-1 Stability

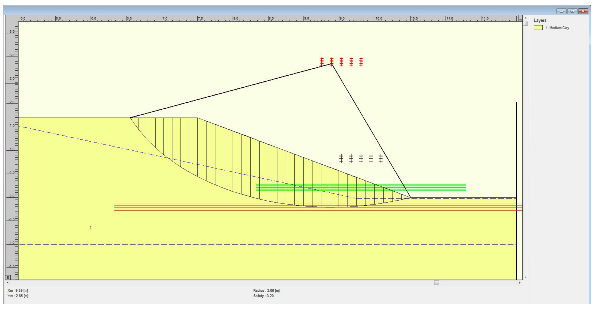


Figure C-1: Critical line for a sand dike

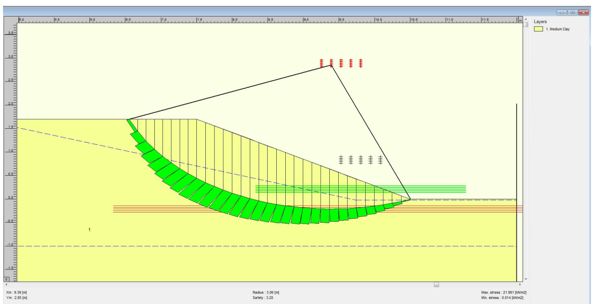


Figure C-2: Effective stresses for a sand dike

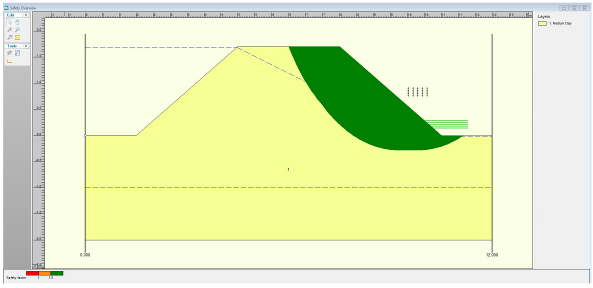


Figure C-3: Safety factor for a sand dike

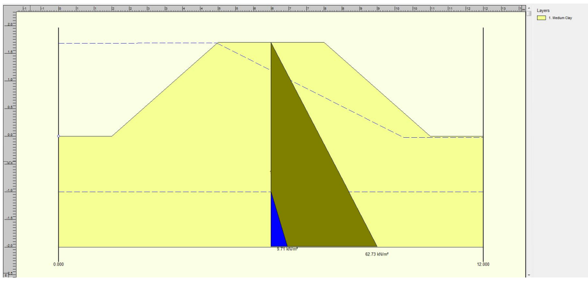


Figure C-4: Shear stress for a sand dike

C-2 Shearing

Again a generalised calculation has been done with the soil properties that are listed above in table B-1. The limit state equation and the factor of safety are given below.

$$\begin{aligned} Z &= p_{hydrostatic} < \tau \\ p_{hydrostatic} &= 0.5 * \rho_w * g * h_w^2 \\ \tau &= \sigma' * tan(\phi') + c' \\ FoS &= \frac{\tau}{p_{hydrostatic}} \end{aligned} \tag{C-1}$$

p = pore water pressure [kPa]
τ = shear strength [kPa]
σ' = normal vertical effective stress [kPa]

Table C-1: Factors of safety for the shearing failure mechanism in case of raising the ring dike

Amout raised	0.25m	0.5m	0.75m
Sand	1.6	1.3	1.04
Clay	2.7	1.8	1.3

With a factor of safety higher than zero the shearing stability is guaranteed. As is seen the FoS is higher than zero for all cases. A clay soil can be expected in the Botlek. Therefore it is assumed that the probability of failure for shearing stability is 0.

C-3 Overtopping

For overtopping the same variables and inputs have been taken as for the containment dike. The Van der Meer and Janssen(1995) formula is used for overtopping and the wave height is assumed to have a maximum value of 0.73 times the waterdepth for shallow water depths based on Batjes and Stive(1985)[24].

$$\frac{q}{\sqrt{gH^3}} = \frac{0.06}{\sqrt{tan(\alpha)}}\gamma_b\xi_{op}exp(-4.7\frac{R_c}{H_s}\frac{1}{\xi_{op}\gamma_b\gamma_f\gamma_\beta\gamma_v})$$

After iteration the resulting crest freeboard the dike must have is different for each raising of the ring dike. The corresponding maximum retaining height is also calculated with this in mind. These are shown in table C-2.

Table C-2: Critical water level in the Hartelkanaal for overtopping of the ring dike

Raising of Tuimelkade	0.25m	0.5m	0.75m
Freeboard [m]	0.27	0.38	0.5
Maximum water depth [m +NAP]	5.88	6.02	6.15

These maximum retaining heights are used to create new fragility curves. These are shown in figure 5-3. As is seen the initiation point where failure probability occurs goes to higher inundation depths the higher the ring dike is raised.

Appendix D

Validation calculations

D-1 Validation of economic model

In this section the validation of the economic model is done. First the probability of a storm is determined. For this reference calculation an inundation level of 0.5 meter is taken. This corresponds with a probability of exceedance of 1/3000 per year. This corresponds to a probability over lifetime of:

$$P_{x>0} = 1 - P_0 \tag{D-1}$$

$$P_{x>0} = 1 - e^{-p\lambda} \tag{D-2}$$

$$P_{x>0} = 1 - e^{-100 \cdot 1/3000} \tag{D-3}$$

$$P_{x>0} = 0.033 \; per \; lifetime \tag{D-4}$$

The damage factor that corresponds with an inundation depth of 0.5m is 0.2. The corresponding maximum damage for storage tanks is 823 Euro/m^2. A simple math expression can be made to see if it corresponds to the model.

$$Risk \; storage \; tank = f_{damage} \cdot S_{damage} \cdot P = 0.2 \cdot 823 \cdot 0.033 = 5.43 Euro/m^2 \tag{D-5}$$

This is also discounted to the net present value for the year the damage occurs. This surmounts to a factor of 1 to 1/20 depending on the year in which a high water event is present. With this calculation it is shown that the numbers calculated in the hand calculation are slightly lower than in the model, but are in the same order of magnitude.

D-2 Validation of environmental model

The probability of failure is determined for an inundation level of 1 meter(see section 4-3). This probability of failure is determined to be $P_f = 1.5e - 4 \; per \; lifetime$.

The expected cleaning costs per litre are roughly 6 Euro/litre depending on the modifiers. With a tank of diameter of 15 meter and 10 meter in height the following calculation can be made.

$$V_{oil,singletank} = 0.25 \cdot \pi \cdot 15^2 \cdot 10 = 1766m^3 \tag{D-6}$$

$$S_{singletank} = 1766e3 \cdot 10.1 = 17.84 \; million \; Euro \tag{D-7}$$

$$S_{singletank,persquaremeter} = S_{singletank} \cdot \frac{n_{tanks}}{A_{area}} = 17.84e6 \cdot \frac{1800}{23e6} \; Euro/m^2 = 1397 \; Euro/m^2 \tag{D-8}$$

$$Risk = 1397 \cdot 1.5e - 4 = 0.21 Euro/m^2 \tag{D-9}$$

This is also discounted to the net present value for the year the damage occurs. This surmounts to a factor of 1 to 1/20 depending on the year in which a high water event is present. This can account for the decrease to 0.011 Euro/m^2. As is seen this hand calculation delivers values that are higher than the ones out of the environmental model, but they are in the same order of magnitude. This validates that the model is correctly calculating the risks of a clean-up of surface oil.

For an anchored tank the probability of failure are roughly 15-50 times smaller than the probability of failure for an unanchored tank. This can be seen as the expected risk is also roughly 50 times smaller for the anchored tank.

Appendix E

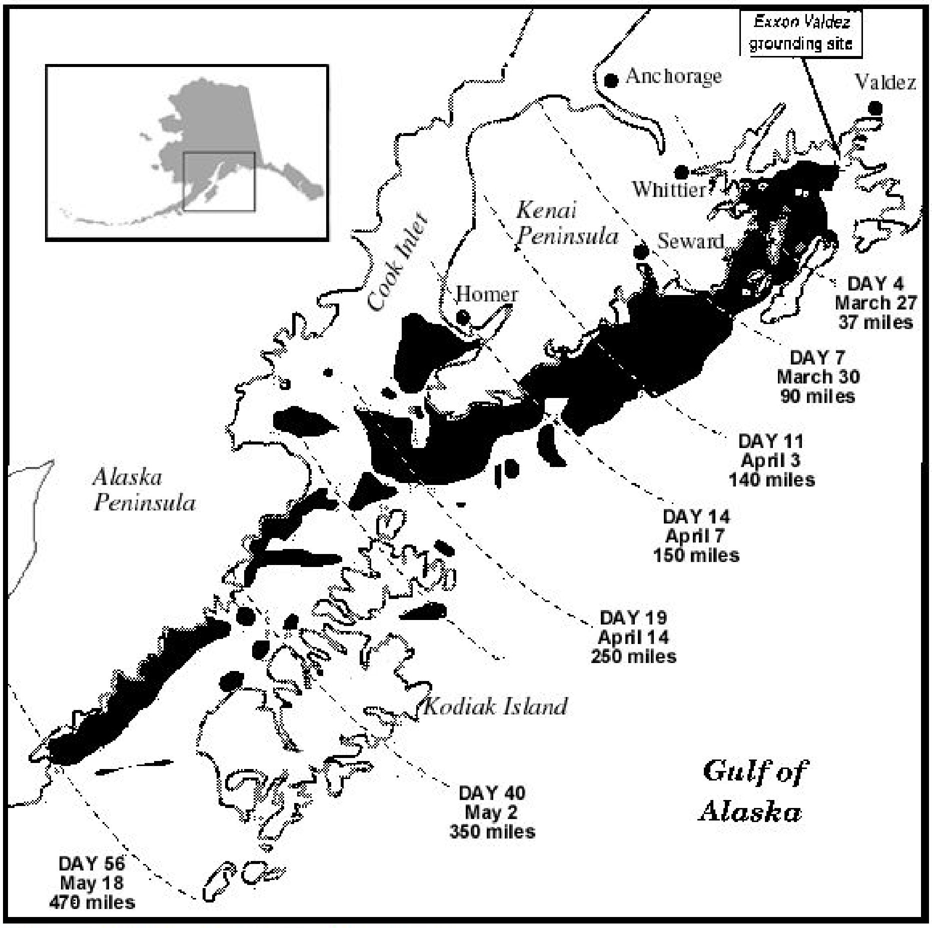
Reference oil leaks

In this chapter some reference oil spills are discussed. By assessing these a validation can be performed on whether the created environmental model leads to accurate values. It also gives some insight into the amount of volumes that are released in an event and in some reference cases the amount of dispersion is available. This reference project will look into released volumes, related costs as a result of clean-up operations and if available the amount of time a harbour or industry is halted as a result of clean-up operations.

E-1 Exxon Valdez

The Exxon Valdez was a large oil tanker that departed from the Trans Alaska Pipeline terminal. The ships pilot, William Murphy, an expert ship pilot was hired to manoeuvre the ship through the Valdez Narrows. After passing the Valdez Narrows the ship captain left controls over to the ship captain, Joe Hazelwood. The ship encountered icebergs in the shipping lanes and went out of the shipping lanes to avoid them. After a miscommunication where the ship did not re-enter the shipping lanes the ship ran aground on Bligh Reef where it lost significant amount of oil causing a major catastrophe.

The ship lost approximately 42 million litres of oil which spread over 2000 kilometres of shoreline. It took approximately 4 summers to clean all the oil up and costs an approximate 2.1 billion Euro to clean.



Source: 1993 State On-Scene Coordinator's Report

Figure E-1: Illustration of the dispersion of the oil of the Exxon Valdez

E-2 Port Arthur

The Port Arthur oil spill was the result of a collision between two vessels. The spill was located at the Sabine-Neches Waterway at Port Arthur, Texas. The oil was contained by both a closed perimeter around the spill as well as a lucky coincidence that it was located in the still part of the channel. This resulted in small flow conditions and therefore minimal spread. The entire Port Arthur shipping channel was closed and at first it could not be predicted how long it would take to re-open.

This oil spill contained 1.7 million litres of oil, but the spread was very limited due to the flow conditions and containment practices. Due to this proper containment there was no wildlife directly affected. The costs related to this spill were 1.16 billion Euro.

E-3 Ashland oil spill

The Ashland oil company inc. had re-purposed an old four million gallon(15 million litre) storage tank. This tank, holding diesel fuel, failed and collapsed. Much of the contents drained into the storm sewer leading to the Monongahela river. This led to significant drinking water shortages for the coming week. The diesel was contained with deflection booms and was collected by suction barges.

The material damages of this instance were estimated at 10-15 million Euro and the clean-up related damage were estimated at 20.5 million Euro. There was a lot of wildlife affected by this oil leak, around 2000-4000 water birds were killed in the incident.

E-4 Xingang port oil spill

A pipeline that burst in the Dalian's Xingang port resulted into a major oil spill, estimations range from 10-70 million litres of crude oil. The blast caused fire to spread to a nearby oil storage facility. As a precaution to prevent more fire, large quantities were leaked into sea. It is estimated that the environmental consequences and the effect of tourism and fishery is of lasting effect. The primary recovery activities lasted 14 days, but much of the clean-up operations was continued after that.

The actual damages of this spill are unknown as the Chinese government does not recognize the size of the oil spill, but are estimated to be higher than 2 billion Euro. The shoreline that is affected is estimated to be higher than 90 kilometre.

E-5 Kalamazoo River oil spill, Michigan

A pipeline containing diluted bitumen ruptured into the Talmadge Creek. It was one of the largest inland leaks. The response time was very slow as they originally thought the alarm was the result of a bubble in the pipeline. For this reason they also increased pressure, increasing the amount of oil spilled. It was one of the first cases where diluted bitumen had to be cleaned and this resulted into high costs.

The oil was spilled into a large area of over 170.000 square metres. The amount of oil spilled was estimated to be 3.3 million litres. The relating costs were estimated to be around 1 billion Euro.

E-6 The Deepwater Horizon oil spill

The Deepwater Horizon is estimated to be the largest oil spill in history. After an explosion and the sinking of the Deepwater Horizon oil rig a sea-flow gusher flowed for 87 straight days. The amount of oil spilled is estimated to be 794 million litres. There were several fatalities that occurred with the explosion and sinking of the rig. A massive response was initiated to protect the shoreline. Use was made out of many skimmer boats and other clean-up equipment. However due to the size of the spill the effect on marine and wildlife habitat was very large. With fish life dying at much higher rate than before the oil spill. The cost related to fines and other payments reached a record high of over 60 billion Euro. The clean-up related costs that are additional to this number were estimated at 14 billion Euro.

E-7 Sea empress

The sea empress oil spill was an oil spill that occurred when an oil tanker got grounded near Pembroke, UK. The ship was pushed off course and the collision with the rocks caused the hull to be punctured. The rescue operations only aggravated the leak after it was released and again collided with the rocks.

The volume released is estimated to be roughly 93 million litres. The clean-up operation related costs were estimated at over 117 million Euro.

E-8 Average costs

Table E-1: Costs for several oil spills

Oil spill name	Location	Volume released [x 10^6 litre]	Estimated damage [Euro anno 2015]	Damage/litre [x 10^6 Euro/litre]	Closing of port operations [days]
Exxon Valdez	Nearshore	41.6	4,664	112.03	-
Port Arthur	In-port	1.7	1,159	681.93	4
Ashland oil spill	Nearshore	3.8	45.5	12.03	7
Xingang Port oil spill	In-port	69.9	2,318	33.16	14
Kalamazoo river	In-land	3.30	1,194	361.83	4
Deepwater horizon	Offshore	794	16,229	20.44	-
Sea empress	Nearshore	93.0	117.4	1.26	-
Average amounts				**€174.67**	**7.25**

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