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By
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Flood risk management in the unembanked areas: an optimal approach?

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Preface

This is my graduation thesis for the master Civil Engineering and Geoscience at the Delft University of Technology. It is my last step of becoming an engineer. This last step has been made under the supervision of the university and the company Vopak.

It has been an interesting endeavour to see how theory from my study and experience from the company's practice could be combined into a useful thesis.

Here I want to thank my supervisors. Bas Kolen, for being reachable and being positive. Matthijs Kok and Mathijs van Ledden for showing interest in the results and having experience-loaded questions. Betty Zaaijer and Tom Maclennan I think you did admirably in supporting my graduation process. A graduate student was new for you, and since graduating is always new for the student, I could not help you with that. When feedback or help was needed I could always ask for which I am very grateful.

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Summary

The flood risk management in the Netherlands aims at an optimal flood risk for society and therefore is flood risk management a balancing act. Neither too much nor too little risk is beneficial. For example, it will be very costly to reduce the flood risk below a very small threshold. In the embanked areas, the government builds embankments at an optimum between the cost of the embankments and the flood risk. This thesis is about the flood risk management in the unembanked areas where the flood risk is in principle an individual responsibility and it is not the legal obligation of the government. The increasing flood risk due to climate change is therefore covered differently compared to the Dutch embanked areas.

The government, although not legally responsible, aims to limit the amount of flood risk in the unembanked areas by stimulating actions to reduce the flood risk. Especially liquid bulk companies are expected to be vulnerable to flooding. Liquid bulk companies are obliged to assess their flood risk through a recent addition of the BRZO (Besluit Risico Zware Ongevallen). Furthermore, they are stimulated by the government through pilots to assess their flood risk. Pilots which assess the flood risk for specific unembanked areas, such as the Rotterdam harbor. This thesis builds on the assumption that stimulating companies to reduce their flood risk should support the goal to reach an optimal flood risk. The hypothesis is that the companies in unembanked areas are not fully aware of the flood risk and therefor stimulating flood risk assessments by individual companies leads to the lowest total cost (prevention costs + risk costs) which equals the optimal flood risk.

To research if the current practice of mandating individual flood risk assessments supports the goal of an optimal flood risk a case study is performed in this thesis. The flood risk in 2050 is assessed for the liquid bulk storage terminals of the company Vopak located in and near the Botlek area of Rotterdam harbor. The used flood risk assessment method in this case study enables a quantitative risk evaluation in which there is a distinction between four risk categories; fatalities, environmental, economic and reputation risk. The monetized values from each category are joined in the combined flood risk for a terminal. The scale at which the assessment is performed enables an evaluation of measures that change the risk for an individual object. This choice is made to incorporate small scale measures into the evaluation of the optimal flood risk.

The result from the case study is that the combined flood risk for the Vopak terminals in the Botlek area in 2050 is twenty eight thousand Euros annually. The risk results for 88% from downtime and 12% from direct damages and for less than 0.1% from monetized fatalities. The downtime originates from the repair time of externally damaged electrical utilities. The environmental risk is zero which follows from limited inundation levels at the Vopak terminals for which no failure of tanks or pipelines occurs. Spills from pump pits do not contribute significantly to the flood risk which is contrary to expectations at the company. Relatively speaking the flood risk in 2050 for Vopak is limited. The risk of fatalities is more than ten times below the national flood risk standard for embanked areas, the economic risk is around the future national embanked average, the flood risk is more than fifty times below the social disruption guidance values for the unembanked areas and there is no environmental risk in the Botlek. At the nearby Vopak terminal Europoort the environmental risk due to flooding is similar to other environmental risks on site. However, the expected annual flood risk in 2050 is not optimal for Vopak. Of the different considered options elevation of electrical stations will lead to an optimal risk; the cost of the measure is less than the risk prevented.

The case study performed for the terminal sites showed a difference between the optimal flood risk from Vopak's point of view and the optimal flood risk from the governments point of view. The difference arises from a different evaluation method and a different valuation of the net present value of the risk. For the

Vopak Botlek case the ALARP method used by Vopak leads to a higher (+70%) valuation of the flood risk. The discount factor for Vopak as a company leads to a lower valuation of the a risk reduction (-19%). For a terminal site of Vopak the approach used by the company leads to a lower level of flood risk compared to an evaluation from the governments point of view.

The findings in this thesis support the conclusion that for the Botlek area the current approach of the government, which is to stimulate/mandate individual risk assessments will lead to a higher level of flood risk than an authority implementing large scale flood risk reduction measures. The level of risk at Vopak is lower with the measure that is deemed cost-effective for the Botlek area. This measure, however, is not effective when it is evaluated from Vopak's point of view. Observations during the case study indicated that cooperation by Vopak for a large scale flood reduction measure is not likely. If this observation holds, the current unembanked flood risk practice does not pursue the principle of the national flood risk policy which aims at an optimal risk. If the implementation of a flood risk measure by an authority is an unwanted option the current approach does lead to an optimal risk for a single company.

1 Introduction

In this chapter starts with introduction of the background which culminates in the research objective. It finishes with a short description of the outline of the thesis

1.1 Background

1.1.1 Flood risk

Flood risk is one of the larger natural risks worldwide. Globally it causes €36 billion in damages annually (OECD, 2016). Zones that are prone to flooding are often zones of high economic importance; in the United States half of the economic wealth is located in these regions (National Oceanic and Atmospheric Administration, n.d.). In the Netherlands the importance is even larger with 59% of the country being prone to coastal or river flooding (BPL, 2016). Coastal flooding occurs from the sea and is driven by a high tidal situation, wind setup and a storm surge. River floods follow from a high discharge of the rivers due to melting of ice and/or high levels of precipitation upstream. Based on the numbers in Figure 1-1 it is calculated that 93% of the Dutch flood prone area lies in dike rings. Another 7% is located outside of the dike rings. These areas comprise of flood plains, nature areas and harbor areas. In the areas outside of the dike rings, areas that are unembanked or so called *buitendijks,* the government has no legal obligation to prevent flooding (Arcadis, 2011).

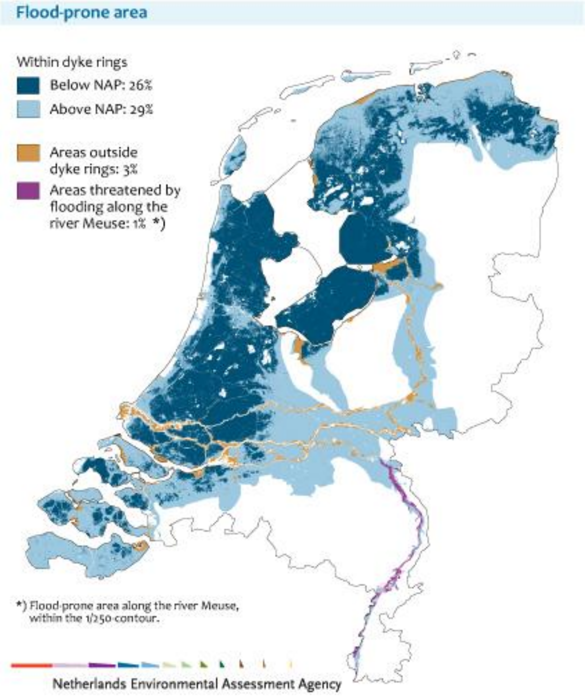

Figure 1-1 Flood prone areas in the Netherlands (BPL, 2016)

Without action the flood risk is increasing in the coming century due to climate change. The changing climate increases the probability and the size of the floods that occur. Both increase the flood risk.

1.1.2 Climate change in the Netherlands

For the Netherlands the Dutch metereological institute (KNMI) has considered multiple climate scenarios for the future and has stated boundaries that enclose the range in which it is likely that the climate will develop. Important aspects for the change in flooding conditions are the increase in intensity and amount of the precipitation, next to the increase in sea level. A change in storm climate or wind conditions changes a storm surge as well but this is not expected (KNMI, 2015). For coastal flooding the sea level rise is the predominant factor.

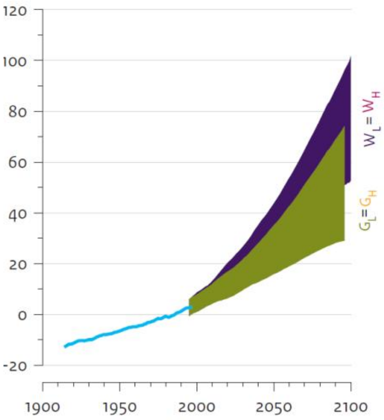

Figure 1-2 The future sea level for different scenarios (KNMI, 2015)

Figure 1-2 shows the increase in the sea level since 1900 and shows that it is expected to increase further in the coming century. While the speed of the sea level rise is uncertain and under discussion, the fact that there will be an increase in sea level, is not. The average expection of the sea level in 2050 is 35 centimeters higher than in 2000.

1.1.3 Dutch flood risk management

The national flood risk management in the Netherlands follows a risk based approach. In this approach and in this thesis risk is defined as the probability of an event multiplied with the consequence of the event. The flood risk management follows van Dantzig's theory (van Dantzig, 1956), where the total costs in a system have to be minimized to reach an optimal situation. This theory makes the management of risk a balancing act. Neither too much nor too little risk is beneficial. An example can be seen in Figure 1-3. The optimal amount of risk reduction is where the total costs function reaches its lowest point; the total costs increase for a higher and for a lower amount of risk reduction.

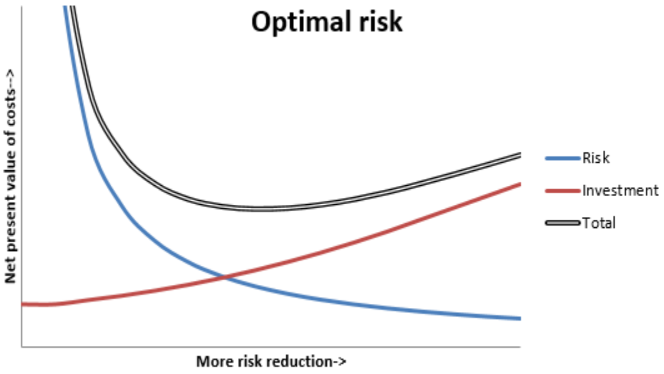

Figure 1-3 Optimal risk as used in Dutch flood risk management. The optimum is the point of the lowest total costs in the total cost function

Adjacent to the aim of an optimal risk there is also a change in recent years in the decision making on flood risk management. It is changing to a higher level in the hierarchy of needs of Maslow. The decision making aims to reach a solution that is more than just economically optimal on aspects of human life and economic risk. Therefore, more stakeholders are included in flood risk management (Voorendt, 2013). To assist this aim approaches are chosen in policies that respect individual choice on an optimal flood risk within certain boundaries. A common favoured approach is the approach of multi-layered safety.

The multi-layered safety approach for flood risk builds on three aspects to reduce the flood risk. Prevention, spatial planning and crisis management (Ministerie van Infrastructuur en Milieu , 2009). In Figure 1-4 is shown from bottom to top; a dike around an area as prevention, higher located grounds for housing as spatial planning and available information about escape routes as crisis management. In this example all three layers reduce the risk of fatalities due to a flooding event.

For the reduction of flood risk in the Dutch embanked situation, prevention of inundation in the form of improving the dikes is the best method in respect to the required investment (Hoss, 2010) (Expertise Netwerk Waterveiligheid, 2012). In these reports it is explained as a difficulty that different parties are responsible for the different layers. For a stance of shared responsibility this might be a positive effect.

Figure 1-4 Multilayer safety. From top to bottom: crisis management, spatial planning/water robust design, prevention

“The safety chain is as least as safe as it strongest link” is a statement by Jongejan (Jongejan, 2008). The considered safety chain by Jongejan consists of proaction, prevention, preparation, repression and recovery. The multi-layered safety approach for flooding is similar to the considered safety chain and therefor his remarks can be used for flooding as well.
(The strongest link is here considered as the layer that is contributing most to the reduction of a risk)

1.1.4 Unembanked areas

Actions to mitigate the increasing risk due to climate change for embanked areas are clear; following legislation the Dutch authorities are responsible for maintaining an optimal risk level. For unembanked areas the increasing risk is addressed differently.

As stated earlier the unembanked areas are flood prone areas without legal norms for flood risk prevention. The principle of unembanked areas is that the residents are responsible for their own safety (Ministerie van Infrastructuur en Milieu , 2009). This individual responsible has been reaffirmed in 2011 and 2014 (Ministerie van Infrastructuur en Milieu, 2011) (Ministerie van Infrastructuur en Milieu, 2014). Meanwhile in those years reports such as *Het Nationaal Waterplan* have indicated that specific areas that are unembanked require further attention to reduce the nationwide flood risk (Ministerie van Infrastructuur en Milieu , 2009) (Programmateam Rijnmond-Drechtsteden, 2014). The adaptive capacity of the companies in unembanked areas is low and it is considered beneficial for society to conduct research into flood risk reducing measures (Klostermann, Koperberg, Smale, & Slager, 2013).

Local authorities which are responsible for the unembanked areas struggle with the combination of optimal flood risk and the principle of individual responsibility (Moet & Eshuis, 2009) (Programmateam Rijnmond-Drechtsteden, 2014). In practice those authorities consider unembanked flood risk as a shared responsibility. To help address the difficulties and decrease the flood risk in these areas multiple projects are currently underway. Projects such as the pilots ‘Waterveiligheid Botlekgebied’, ‘Kop van Feijenoord/Noordereiland’ and ‘Merwevierhaven’.

The pilot ‘Waterveiligheid Botlekgebied’ looks into the flood risk of a part of the Rotterdam harbor (Bonte, van Dijk, van Ledden, & Visch, 2016). Within this pilot the companies that are present in the harbor are stimulated to consider their flood risk and implement measures to reach the optimal flood risk. The optimal risk is dependent on how benefit is considered. It is expected that there is a difference between the flood risk management by a company and the management by authorities on behalf of society. While the flood risk may originate from a company, the principle of the polluter pays (read: the flood-affected company pays) is a principle that not always leads to the most cost-effective measures for society as a whole or to an optimal risk (Jongejan, 2008).


Figure 1-5 Harbor of Rotterdam (HbR)

1.1.5 Rotterdam harbor

An example of an unembanked area is the port of Rotterdam as shown in Figure 1.5. The port of Rotterdam is the largest harbor and industrial complex of Europe and is located in the Netherlands. It covers 105 square kilometres and stretches over 40 kilometres. In the port area a lot of industrial activity takes place. The port and the industrial activity in the port area provides 3.7% of the gross domestic product of the Netherlands and 145.000 jobs (van den Bosch & Volberda, 2011).

As the largest European harbor it is an important hub for Europe and it is important for the Dutch economy. It is expected that major damage to the Rotterdam harbor will cause national and international disruption (Nationaal Coördinator Terrorismebestrijding en Veiligheid, 2015).

When the harbor area was developed the surface was elevated as a flood risk reducing measure. It was elevated to an optimal level with respect to the costs of elevation and benefit of the risk reduction. However, the harbor has grown in steps over the last century, as shown in Figure 1-6. Over time different surface elevation levels were used to reach an optimal flood risk. Other measures than elevating the surface level were not implemented. A question is if the flood risk is still at an optimal level.

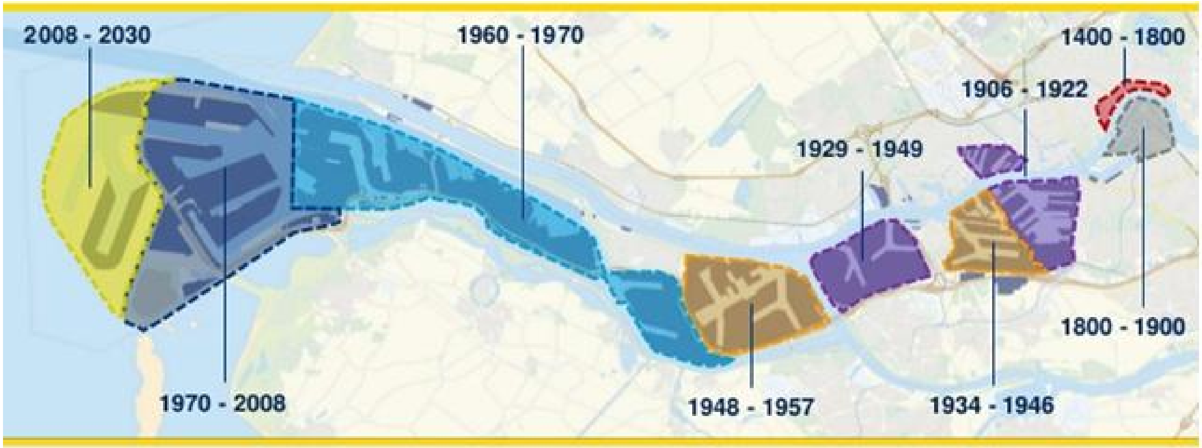

Figure 1-6 Development of the Rotterdam harbor (HbR)

The port authority (HbR) manages the harbor. It is a non-listed public limited company owned by the Rotterdam municipality (70%) and the Dutch government (30%). Its core tasks are the development, construction, management and operation of the port and industrial area in Rotterdam. Its income consists of rental income and port dues and it does not build flood risk reducing measures other than when elevating the surface level when developing the harbor[1].

To provide a safe port in the future the port authority started in 2015 the earlier named pilot 'Waterveiligheid Botlek', in combination with the Rotterdam municipality, the Ministry of Infrastructure&Environment and the Department of Public Works. The pilot is a project to identify the probability and the consequence of a flooding of the Botlek area of the harbor. The pilot area is the area of Figure 1-6 that is developed between 1948 -1957 and part of the neighbouring areas.

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[1] There is one exception; the port authority is responsible for maintaining the 'Tuimeldijk'.

1.1.6 Risk regulation for industrial companies (BRZO)

Part of the industrial activity in the port of Rotterdam originates from the presence of BRZO companies. Dutch company locations that store or use products that are hazardous to the environment or the public health are subjected to the BRZO (Besluit Risico Zware Ongevallen). This is the Dutch implementation of the European SEVOSO Directive. The Seveso Directive aims at prevention, preparedness and response to accidents involving dangerous substances in industry in the European Union. The SEVESO directive has been instigated to lower the number of industrial incidents and create a higher level of safety throughout the EU. It is named after the Italian town SEVESO where a catastrophic incident took place in 1976.

The SEVESO directive applies to more than 10.000 establishments in the European Union. An example of a SEVESO establishment is shown in Figure 1-7. In the Netherlands the regulation covers more than 400 establishments through the BRZO. There are two levels of being subjected to the SEVESO Directive/BRZO. For both levels companies are required to conduct safety management. A company that surpasses the high threshold has to also maintain a more extensive safety report which includes a quantitative risk assessment. The most recent amendments were done in 2012, which added the obligation to take natural disasters into account. Major-accident scenarios that include the effect of natural hazards have to be considered. For the companies which surpass the upper threshold value this means including flood events in their safety reports. The implementation of the SEVESO III directive went in effect with the BRZO 2015.

The PGS6 (Publicatiereeks Gevaarlijke Stoffen 6) is a guideline how to implement BRZO. The PGS6 draft version 2016 states that for a flooding scenario a company has to use a probability up to 1/1.000 or 1/10.000 a year (PGS-projectbureau, 2016). It also states sources that can be used to assess the risk of flooding (at the moment all these sources are only useful for inner dike areas).

In the port of Rotterdam are 67 out of a total of 264 companies in the Netherlands that require a safety report due to the BRZO (Bureau BRZO+, 2016). One of the BRZO companies in the Rotterdam harbor is the company Vopak which is an independent tank storage company that is specialised in the storage of liquid bulk. The liquid bulk type of BRZO company is estimated to be critical in the aspect of flood risk in the harbor. This follows from vulnerable components at liquid bulk sites and the presence of hazardous goods (Lansen & Jonkman, 2010). Vopak is also part of the pilot to identify the flood risk in the harbor (More details about the company Vopak follow in the case study).

BRZO companies are stimulated to consider the flood risk in unembanked areas through the new legislation and through the pilots. While this can result in a reduction of the flood risk there is an important question from the Dutch flood risk perspective; does it also result in an optimal level of risk, for the society and/or the company?

Figure 1-7 BRZO establishment (Vopak archive)

1.2 Research objective

This thesis builds on the statement that stimulating companies to reduce their flood risk should support the goal to reach an optimal flood risk. The hypothesis is that the companies in unembanked areas are not fully aware of the flood risk and therefor stimulating flood risk assessments by individual companies leads to a lower total cost (prevention costs + risk costs) which equals the optimal flood risk.

To discover if it does, a flood risk assessment for a single BRZO company in the unembanked area of the Rotterdam harbor is performed.

The objective of this thesis is *a flood risk assessment for Vopak installations in the Rotterdam area (Botlek, TTR, Chemiehaven, Laurenshaven and Europoort) due to direct flood damages and downtime due to flood related causes from a company's point of view*.

During and with this flood risk assessment the following questions are answered:

1. *What is the flood risk at Vopak terminals in 2050?*
2. *What are possible measures to influence the flood risk at Vopak terminals?*
3. *What are the benefits of the possible measures compared to their costs for Vopak terminals?*
4. *What is the relative value of the flood risk at Vopak terminals?*
5. *What are options for an authority to influence Vopak to reduce its flood risk?*
6. *Does stimulation of flood risk measures lead to the lowest total cost in the Botlek area?*

The choice of looking into a BRZO (Besluit Risico Zware Ongevallen) company is initially made following the high level of awareness of general risks at BRZO companies compared to other companies (Mollee, 2016). Secondly this choice is made since they have a legal obligation to account for flood risk since the update to the BRZO with the BRZO2015.

The harbor of Rotterdam is chosen due to the presence of 67 BRZO establishments that require a safety report which now has to include flood risk and the widely felt impact of a flood at this location. And the scope of a single company is chosen since the private decision to invest in flood risk reduction measures is made at this level.

The company Vopak in specific is useful since it has multiple establishments in the Rotterdam area and it operates liquid bulk storage terminals. Liquid bulk companies were indicated to be vulnerable to flooding (Lansen & Jonkman, 2010).

1.3 Thesis outline

This section concludes chapter one which introduced the subject and the research objective.

The thesis continues with chapter two in which three subjects are covered. First the relevant flood risk policies are introduced. Secondly the risk approach of Vopak as an BRZO company is evaluated on the aspect of flooding. And as third part of the second chapter it is considered what kind of method is required to assess the flood risk at a liquid bulk company with a multilayered safety approach.

The knowledge gained in chapter two provides the basis for chapter three. In this chapter the method for assessing the flood risk is formulated. It is presented what framework will be used for the case study and which information is used or how it is acquired.

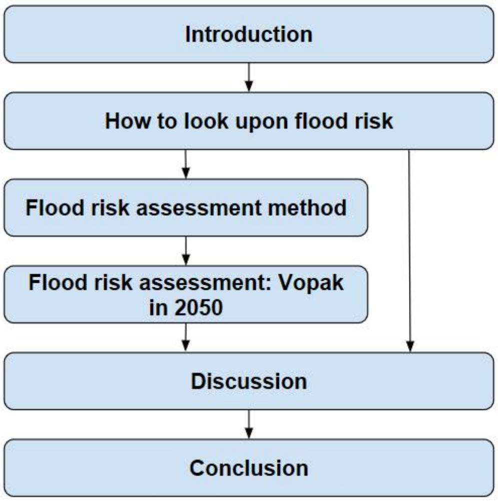

Figure 1-8 Outline of the thesis

Chapter four is the risk assessment for the different Vopak terminals. The flood risk assessment method of chapter three is applied which results in the flood risk values and flood risk measures. In this chapter answers to the first three research questions are presented.

Chapter five discusses the results of the flood risk assessment. With this discussion it provides the answers to the research questions four to six.

The conclusion states the answers to the research question. Additionally, it gives two types of recommendations. Recommendations for Vopak and recommendations for further research.

2 How to look upon flood risk

This chapter describes first the flood risk policies used by authorities. Secondly it describes how a BRZO company looks at general risks and how this changes with regard to the specific risk of inundation. As third part of this chapter it is considered what is required for a specific multi-layered flood risk assessment.

2.1 Flood risk policies

In this section the Dutch flood risk policies are described which are geographically relevant following the scope of this risk assessment. The national standard for flood risk levels is only legally binding and implemented for the embanked areas (see 1.1.3). This thesis considers the principle behind the standard also leading for unembanked areas, despite it not being legally binding. The policy for unembanked areas is not implemented at a national level but at a provincial level. The policy described is from the province of Zuid-Holland. Also policies at a lower scale of organization are described; the policy of two large municipalities close by and the responsible party for the Rotterdam harbor.

2.1.1 National embanked flood risk policies

Current Dutch national standard

The current flood risk standard for embanked areas is based on withstanding a water level of a certain probability. The embankments are built to resist that water level. The probability of the water level is based on an economic optimization of the total costs. The costs are a combination of the monetized risk of human life and economic risk added with the costs of reducing the risk. The standards were defined by the first Delta Committee in the fifties.

New Dutch national standard

The flood risk standards currently used are considered outdated. Since the standard was defined the number of people and the economic value inside the dike rings has changed and the knowledge about the strength of the embankments has increased. Therefor a new standard will be implemented in the coming years (Ministerie van Infrastructuur en Milieu, 2014).

The new flood risk standard considers the inundation probability of a dike ring. The used level of probability of inundation is based on three aims. The standard is stated in six classes ranging from 1:300 to 1:100,000 a year. The three aims are (Ministerie van Infrastructuur en Milieu, 2014):

1. To provide an equal level of protection for everyone living in the embanked areas. At every location a person should have a chance of less than 10^{-5} a year of dying due to a flood.
2. To provide more protection where there is a chance of a high amount of fatalities and/or large amount of economic damage.
3. To provide more protection where an impairment of vital infrastructure leads to nationwide disruption.

The old and the new standard are both based on the Dutch principle of cost optimization with the costs coming from the value of the risk and the implementation of risk reducing measures. In this thesis the new standard is meant when there is referred to the national standard. The new standards are expected to be implemented in legislation in 2017.

2.1.2 Flood risk policies for the unembanked areas

As described earlier, the regional authorities play a key role in designing and implementing flood risk policies for the unembanked areas. Considering the location of the case study of this thesis (Rotterdam Harbor), this includes the Province of Zuid-Holland, Rotterdam municipality, Dordrecht municipality and Rotterdam port authority.

Province of Zuid-Holland

The interest of the province is to maintain the safety level and improve the development of unembanked areas. The principle is that building in unembanked areas is allowed if flood risk is considered in the design of the construction. Especially buildings that are vulnerable or fulfil vital functions need to be robustly build to prevent social disruption (Moet & Eshuis, 2009).

The goal the province has with its policy is that municipalities have insight in the flood risk associated with developing unembanked areas and have the option to evaluate measures, and can approve or reject the construction plans (Provincie Zuid-Holland, 2013). It has developed the application 'Risico applicatie Buitendijks' to help assess flood risk in unembanked areas. This application follows a risk-based standard for fatalities and social disruption. (Huizinga, Nederpel, de Groot, & Batterink, 2011)

Rotterdam municipality

The policy of the Rotterdam municipality with respect to new developments in unembanked areas was before 2012 based on a surface elevation level in the building code. This was an approach that lowered the attractiveness of the area for urban development (Siepman & Blom, 2012). It was concluded that while a shared responsibility was expected following the water act, a more hierarchical approach was used by the authorities which resulted in an suboptimal risk due to strict guidelines on which measures had to be implemented. Consequently, private parties were dissatisfied with the standards by the authority which increased the development costs (Van Veelen, 2013).

The municipality introduced in 2012 a new policy called the 'Water Act 2'. In the 'Water Act 2 Rotterdam' it is stated that the policy of Rotterdam is based on communication and agreement between private parties and the municipality. It uses high water procedures and an evaluation guideline on urban development. This aims to improve the development of various alternative solutions that are more cost effective, such as adaptive building (Gemeente Rotterdam, 2013). It explicitly aims to use multi-layered safety in its flood risk management, a concept discussed in more detail in chapter 1.

Dordrecht municipality

In the city of Dordrecht, the historical inner city lies unembanked and two new city quarters are build unembanked. For these quarters flood adaptive measures were incorporated for in the development plans to receive a building permit (Siepman & Blom, 2012). For the inner city provisions are made for temporary flood prevention measures. Some citizens made their house fronts water-resistant but this has been an individual choice.

Rotterdam port authority

In the port of Rotterdam, the key principle was that elevation of the surface level when a harbor area is developed provides an adequate safety level. The optimal elevation level is chosen with a cost-benefit analysis. No measures are taken to reduce the risk further with other measures than elevating the surface level. This policy is currently under evaluation. This evaluation is underway since reports such as *Het Nationaal Waterplan* have indicated that specific areas that are unembanked require further attention to reduce the nationwide flood risk (Ministerie van Infrastructuur en Milieu , 2009) (Programmateam Rijnmond-Drechtsteden, 2014).

Common denominator of the current unembanked policies

All of the policies for unembanked area only prescribe standards or evaluations on new developments and large changes in these unembanked areas. The policies do not state requirements for areas that are already developed. In developed unembanked areas, only communication and (emergency) measures by authorities themselves are implemented when deemed necessary. The policies all follow the advised approach by the 'Notitie Waterveiligheid' (Deltaprogramma Nieuwbouw en Herstructurering, 2011).

2.2 Flood risk assessment at a BRZO company

Companies that store liquid bulk have a legal obligation to assess and evaluate risks, following the BZRO. This section describes how Vopak as a liquid bulk company assesses it general risks and how this changes with regard to the specific risk of flooding. In every paragraph it is first stated how Vopak approaches a general risk after which it is considered why this will change for flood risk. For every part it is stated which approach will be used to define the method for the case study.

2.2.1 Risk categories

The company Vopak uses four risk categories (Vopak Terminal Europoort B.V., 27 Juni 2016) (Vopak Terminal Chemiehaven B.V., 31 May 2016):

- Safety
  Injuries or fatalities to a person or multiply persons
- Environmental
  A spill of an environmental hazardous product.
- Economic
  The costs of reparation and the costs of being not to fulfil promised services
- Business
  Being not able to service customers for a certain amount of time, having media coverage about the incident and other.

The flood risk policies described in previous section 2.1 are used to consider if risk categories used in these policies will improve the assessment when those are used to assess the flood risk. If so there additions and/or changes to Vopak's categories.

Two of the stated flood risk policies use specific risk categories. The national standard uses the category safety in the form of individual risk on fatalities and group risk on fatalities. The category Economic in the national standard includes the environmental costs, the costs of national disruption and economic costs next to the monetized value of fatalities. The unembanked risk application unembanked (RAB) of the province Zuid-Holland takes two risk categories into account; fatalities and social disruption (Huizinga, Nederpel, de Groot, & Batterink, 2011).

Vopak follows the BRZO and considers the environmental damage individually while the national flood risk standard takes the environmental damage into account in the economic costs. Using this category separately is assumed to improve the risk assessment and therefore this will be used in the method of this thesis.

The category social disruption from the policy of the province is similar to the business risk category; both consider downtime. Therefore the social disruption category is not added independently.

It is concluded that the four risk categories are useful for a flood risk assessment and do not require change compared to a risk assessment Vopak would perform for a non-flood related risk. For clarity the naming of the risk categories in this thesis is altered compared to Vopak's risk evaluation and Vopak's risk matrix. How these relate is shown in Table 2-1.

Table 2-1 Naming of the risk categories

Name of the risk category in this thesis	Name of the risk category in Vopak's risk matrix
Fatalities	Safety (People)
Environmental	Environmental (Soil, air)
Economic	Economic (Lost damages)
Reputation	Business (Reputation, customers)

2.2.2 Risk evaluation type

There are three common used risk evaluation types at BRZO companies. This section describes the options and the chosen method for this thesis.

Besides these evaluation options, a company can also consider to simply adhere to hard limits set by regulating authorities. Yet this option is not further explored in this thesis since it is not in line with the intent of the BRZO regulation[2] or does it create an economically optimal situation for the company.

Evaluation options

Economic optimization

The first type is an economic optimization between the implementation costs and the benefits of risk reducing measures. Negative effects of a risk reducing measure are included in the evaluation, such as hindrance for daily operations. It requires that every cost and every benefit to be expressed in the same unit, which is nearly always money. This is the approach used in the flood risk optimization in the national flood risk standard.

Best Available Technique

The second type takes into account the best available techniques. It is the so called BAT (Best Available Technique) or BAP (Best Available Practice). The BAT/BAP considers the best available technique or technology to reduce the risk (Environmental Protection Agency, 2016). While in principle it does not take costs into account, in practical appliance the costs are considered (Sorrel, 2001). Sometimes it is also used to refer to common practice in the industry The advantage of this risk evaluation type is incorporating ongoing technological improvements. Instead of referring to a static technology reference, it requires companies to use the most up-to-date technology readily available.

As Low As Reasonably Practicable

The third type considered is ALARP (As Low As Reasonably Practicable). Applying ALARP involves weighing the risk against the trouble, time and money that is required to reduce the risk. Following the doctoral thesis of Basta ALARP would in principle enable action until there is a gross disproportion between the benefits and the costs. However, it is noticed that the interpretation of ALARP is different in practice (Basta, 2009).

The application of ALARP it is often used in combination with a cost-benefit analysis. In such combination guidance values are used to specify when reaching a ratio between the costs and the benefits that is considered a gross disproportion (Ershdal & Aven, 2008). In industrial safety ALARP is sometimes used directly to indicate that the benefits have to outweigh the costs (Rushton & Reston, 2006). For a simple economic case this method holds (Vrouwenvelder, Lind, & Faber, 2015). When looking into what gross disproportion is with regard to the risk of life, a good practice is stated in an ALARP evaluation by Bowles (Bowles, 2002).

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[2] Besluit Risico Zware Ongevallen art. 7.lid1 sub d

The ALARP method enables using a different value for gross disproportion for the different risk categories. This gross disproportion can be stated in a CB-ratio (Cost Benefit ratio).

The definition of reasonable practical set out by the Court of Appeal (in its judgment in Edwards v. National Coal Board, [1949] 1 All ER 743) is: "'Reasonably practicable' is a narrower term than 'physically possible' … a computation must be made by the owner in which the quantum of risk is placed on one scale and the sacrifice involved in the measures necessary for averting the risk (whether in money, time or trouble) is placed in the other, and that, if it be shown that there is a gross disproportion between them – the risk being insignificant in relation to the sacrifice – the defendants discharge the onus on them."

The evaluation method used for the flood risk assessment

Vopak assesses its risk with the ALARP method (Royal Vopak, 2013). This is in line with the BRZO practice for the fatalities and the environmental category; the preferred risk in those categories is not the pure economic optimal. The benefit in the form of risk reduction for the company are required to be a certain ratio lower than the benefits before the measures are seen as to costly from a legal perspective.

The BAT practice is not used; evaluating without a costs limit is not in line with an practical approach or the approach of the new national standard. If the practical approach to BAT is followed it changes in the ALARP method.

In this thesis the ALARP method will be used with CB-ratio for the different risk categories. When multiple risk categories have their risk reduced by a single risk reducing measure the risk categories will be considered individually; no summation of the risk will take place after the CB-ratios have been applied. This is chosen as it is in line with the principle of the ALARP method (URS, 2003).

Influence of a natural risk on risk evaluation

The perception of a risk influences the acceptance of a risk and therefor the ALARP evaluation. Perception is for example influenced by the level of voluntariness of a risk and by its origin (Milieu- en Natuurplanbureau, 2003). More voluntariness makes a risk generally more acceptable: The risk of skydiving is more accepted since you can chose to do it. The risk of a company is involuntarily for the people living in the surrounding areas. The origin of the risk influences the perception as well; nature induced risk are accepted different than manmade risks (Ale, 2006). This partly results in the fact that in the Netherlands the average probability to die from a flood is larger than from an accident at an industrial site (Ale, 2006). In Figure 2-1

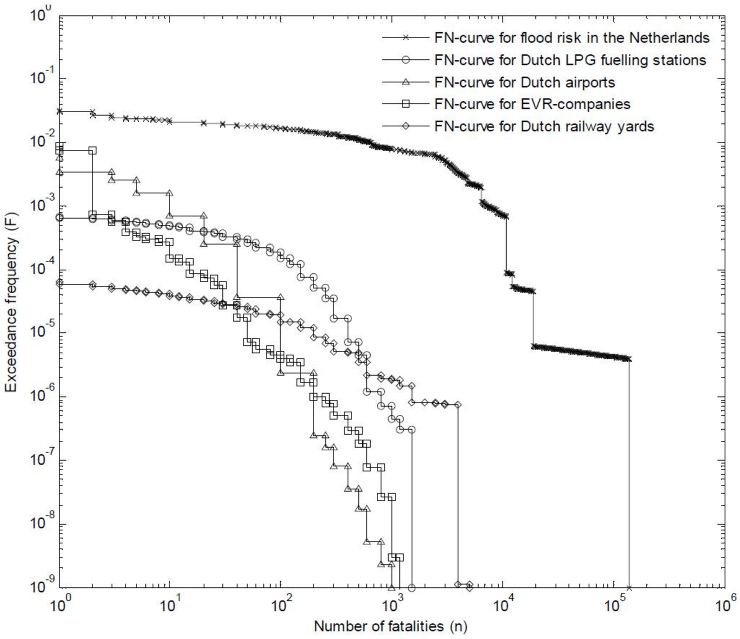

Figure 2-1 FN curves of manmade versus the nature made risk (Jongejan, 2008)

it is shown how several manmade risks on fatalities compare to the natural risk of flooding. The current average probability of flood events that result in a number of fatalities is higher than of several industrial risks.

The Dutch national flood risk standards and the norms in the BRZO are equal in the aspect of risk of fatalities (Ministerie van Infrastructuur en Milieu, 2014) (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, 2004). The origin of the risk does not make a difference for the legal perception on loss of life. Although it influences the definition of the acceptable risk value when it is set by expert discussion (WHO, 2016). Both considerations are used in this thesis when defining guidance values for the what is gross disproportion.

2.2.3 The additional costs of risk reducing measures

The decisions on the investment in the flood risk measures are based on the benefits and the costs of a measure for a company. The benefits can be expressed in a net present value of the annual risk reduction. For the costs of the measures here are various considerations given that influence the costs additional to the implementation costs.

First the enforcement of regulation increases the costs. For example, if the government would mandate certain flood level standards for all companies in unembanked areas this would result in a cost for these companies and additionally, regulation costs for the government. For achieving an optimal risk, the combination of both costs has to be less than the risk prevented. Otherwise no action is the best strategy (Jongejan, 2008). This is similar for a situation within the company; if a risk department of a company mandates action for the engineering department.

Mandated standards can create inflexibility on how to address the risk. An optimal risk level depends on the possible measures implemented. If strict implementation standards are enforced this might lead to implementation of measures that reduce the risk inefficiently and lead to a suboptimal risk (Jongejan, 2008).

Negative effects of measures such as hindrance for the daily operation of an establishment are difficult to monetize. Also not all effects are known beforehand and therefor some of those will be not assessed. Expected unknown or not monetized negative side effects lead to an amount that the benefits have to outperform their costs before a measure is implemented.

2.2.4 The cost of cooperation

To achieve the optimal risk a risk reduction measure is sometimes required at the location of another company. In practice such options are rarely executed by Vopak. This suggest that such option has to outperform an option that can be executed at a company's own location. The difficulty of working together results from a characteristic of risk reduction. Risk reduction, and especially flood risk reduction, is often a public good.

Flood risk reductions in the form of embankments have two characteristics that classify it as a public good: non-excludability and non-rivalry. Every company residing behind such measure gets a reduced risk whether the company has contributed to the measure or not and reducing one companies risk does not increase the risk of another.

The optimal situation for a single company is that someone else pays for the flood protection and one can 'free-ride'. Free-riding means having the benefits of such protection without bearing the costs, visually depicted in Figure 2.2. This is a problem of public goods. The possibility of freeriding reduces the chance of private implementation of large scale flood measures. This problem results in a partial market failure since an optimal risk is not reached. Flood risk reduction is more efficient at a larger scale, if everyone company cooperates. This is the reason why large scale flood measures are often implemented by authorities who have tools, such as taxes, to prevent freeriding.

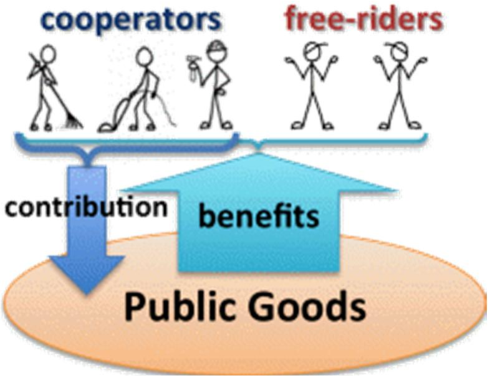

Figure 2-2 Free riders and public goods (Amy Glenn)

Within the method of the BRZO it is not stated how off site risk reduction should be addressed. It is left to the company to find the best location for risk reduction. The indication from everyday practice (Chemiehaven, 2016) (Europoort, 2016) that onsite measures are preferred is qualitatively considered in the risk assessment.

2.2.5 Aversion of large consequences

Regarding risk acceptance, it is commonly chosen to accept a higher annual risk when the consequence of an occurrence is small compared to an occurrence with a larger consequence. This is very much the case with people, the risk of dying in an airplane crash is lower than the risk of dying in a car accident (National Center for Health Statistics, 2013). The consequence of an airplane crash is large compared to several smaller consequences which sum up to an equal risk.

A reason for a company to avoid large consequences is to prevent single instance that cause crippling effects for the company. An incident with a large economic impact on the company can cause a company to go bankrupt. However, when spending too much money on unprofitably risk reduction it will as well cause reason for closure of a company.

Considering the will of BRZO companies to have zero incidents and no negative press it might be actually be more important to have an avoidance of small and middle sized incidents. The middle size would indicate incidents that are just large enough to create press attention. This would be implemented by having a group factor of less than one.

Vopak use an aversion for large consequences in its risk evaluation. It differs compared the flood risk approach of the national standard on how the aversion is applied and how much aversion there is. The national flood risk standard uses a group factor to assign a higher weight to large consequences when assessing fatalities due to flooding. The group factor used there is two which means that if there are ten times more fatalities, the accepted probability is a hundred (10^2) times smaller.

In this thesis it is chosen to formalize the risk aversion as is present at the company by assigning higher CB-ratios if a certain threshold is surpassed. If and what kind of aversion of certain consequence sizes is optimal is not considered further.

2.2.6 Uncertainty in information

In a flood risk assessment, such as will be performed in this thesis, data and assumptions will have to be used. Uncertainty in those can influence the outcome. The definition of uncertainty in this thesis follows the definition as stated by Zimmerman (Zimmerman, 2000). The choice on how to address the uncertainty according to Zimmerman follows from "the cause of uncertainty, the quantity and quality of information available, the type of information processing required by the respective uncertainty calculus and the language required by the final observer." Following part of Zimmerman's view on addressing the uncertainty, most of the uncertainty is addressed qualitatively in the discussion. This done used since the quantity of information is limited and the language required by the observer is not focused on quantitative uncertainty.

Within the appliance of the regulations of the BRZO uncertainties are addressed by assuming conservative values. An example: if the content of a tank is known to be fuel oil or naphtha the substance is assumed that leads to the higher risk. conservative value is for In the flood risk policies mean values are commonly used with uncertainty bounds. In this thesis when assumptions are made they follow the idea of the BRZO regulations. The influence of this is considered in the discussion.

2.3 Flood risk assessment of a liquid bulk company

In this section it is considered what is required for a flood risk assessment at a liquid bulk company that enables evaluation of measures within the framework of multi-layered safety. Therefore, it is first stated what is required for such assessment. This is followed by describing different risk assessments that are used for unembanked areas in the same region of the Netherlands as the Rotterdam Harbor. It is described what can be used from this examples and their limitations. The third paragraph of this section covers two studies into inundation damage to tanks at liquid bulk companies.

2.3.1 The requirements

Based on the research question, the Dutch preference to multi-layered safety and the approach of Vopak, the following is at least required from an risk assessment method.
Quantitative results possible: With a QRA (Quantitative Risk Assessment)[3] the impact of different options to reduce the flood risk can be assessed to reach an economic optimum (OECD, 2016) For each of the four risk categories a quantification method is required.
Multi-layered: It has to be possible to compare measures from different layers of safety as is the current practice in Dutch flood risk. To support a multi-layered approach, the assessment has to be at a small grid size so risk reducing at the size of individual objects can be considered.

2.3.2 Flood risk assessments in unembanked areas

For the pilot 'Waterveiligheid Botlek' damage functions for unembanked areas are used and the area usage (Bonte, Dijk, Ledden, & Visch, 2016). This is an approach that is useful for assessing the economic risk and the risk of fatalities on a large scale. The assessment in this thesis is made for a specific company and aims to assess also measures which aim it is to protect individual objects which lead to a risk reduction. This makes a largescale risk assessment of limited use. For this thesis the pilot is useful to qualitatively indicate the risk that need to be assessed.

For the vulnerability of port infrastructure in unembanked areas a study that made use of expert judgement was performed in 2010 (Lansen & Jonkman, 2010). In the study the probability of damage if inundated was estimated, this was done for different objects based on three options; small (1%), a middle (10%) and a high probability (100%). There was no specific relation to damage and inundation level and the study was done for a scale of a whole port. The study of Lansen & Jonkman is useful for a qualitative indication of the damage but is of limited use for the quantitative part of this thesis since no relation between the inundation level and the damage is made nor are there damage values.

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[3] For BRZO companies the QRA is used in safety reports for solely the external risks due to chemical accidents.

In the same study by Lansen & Jonkman a worst case without flood, but then with a flood was considered to assess the environmental damage. This approach follows a possible approach by the SEVESO guideline on how to assess flood risk (Lansen & Jonkman, 2010). The approach is more general than can be used for this thesis; it is relative to a non-flood situation while an absolute comparison is required for a quantitative evaluation of the risk.

In a study into multi-layered safety there were damage functions used which are specific on the types of risk reduction used and several area usages (Wolthuis, 2011). The principle can be used to evaluate different types of risk reduction measures. A limitation is that the study by Wolthuis focussed on housing areas.

In the ‘Risicomethode Buitendijks’ fatalities and societal disruption is considered for different object classes. When possible inundation level is included in the assessments (Huizinga, Nederpel, de Groot, & Batterink, 2011). In the study a local inundation level is used which is a useful approach for a specific, small scale method. The approach of this study is also used for the comparison with the social disruption. The limitation is that this study does not state when a company is partially considered as a utility for other industries; external effects are not accounted for.

2.3.3 Flood risk assessments for tank storage of liquid bulk

For the flood risk assessment for tank storage there are two studies used as reference.

In the first study by (Kameshwar & Padgett, 2015) the failure probability in respect to inundation level is calculated for different values of the internal liquid height and density which range from 0-9 m and 500-1000 kg/m3 respectively. This is done for unanchored tanks and for anchored tanks. The result in shown in Figure 2-3 and Figure 2-4 respectively. The surge height inside the tank pit is considered. The tank radius is 15 meter and wall thickness is assumed at 10 mm. A uniform distribution of the operative filling levels of the tank is assumed

The second study by (Landucci, Antonioni, Tugnoli, & Cozzani, 2012) used a similar approach and also assumed a linear distribution of the operative filling levels. Floodwater velocity is also considered in this study. The floodwater velocity increases the probability of damage. The study is conducted for river flooding where flow velocities are more significant compared to coastal flooding.

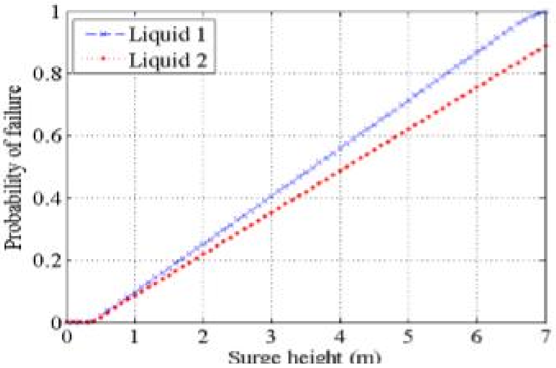

Figure 2-3 Floating of unanchored tanks for two liquid densities. Liquid 1: 740kg/m^2, liquid 2: 850kg/m^2

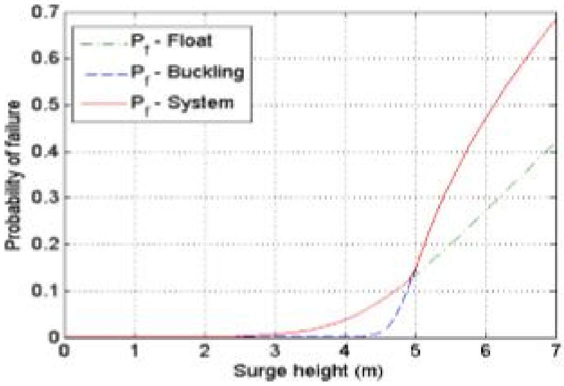

Figure 2-4 probability of failure of tank due to a surge height (inundation level) for anchored tanks

The insights and practices from this study will be followed to define specific failure probabilities for the tanks and pipelines considered. The insights used are; uniform distribution of the filling level is the best assumption, floating and possible buckling are leading failure mechanisms, anchored or unanchored has an influence and if inundation occurs with a significant flow velocity this will be a driving damage factor.

3 Flood risk assessment method

In this chapter the flood risk assessment method for the case study of a liquid bulk storage terminal is formulated which is based on the considerations in chapter 2. It start with a summary of the method in section 3.1 which briefly introduces the idea, the risk calculation and the evaluation. Section 3.2 presents the used framework and an overview of the different processes within the flood risk assessment method. The main matter of the method is formulated in section 3.3 where the processes are detailed. The summary is placed in front of the chapter to provide better understanding how the different parts build the risk assessment.

3.1 Summary of the method

The flood risk assessment method enables a quantitative risk evaluation which uses the four risk categories from paragraph 2.2.1; fatalities, environmental, economic and reputation risk. The scale at which the assessment is performed enables an evaluation of flood risk measures that change the conditions for an individual object.

The risk calculation for each risk category is performed with equation 1. This equation summarizes the risk over different inundation events and over different individual objects. In this equation there is an object-specific consequence and probability of failure given the inundation event. Section 3.3 elaborates on which events, which objects, which probability and what consequence are used in the assessment.

Equation 1 $$E_k = \sum_{j=1}^{m} q_j \sum_{i=1}^{n} \left(p_{k,ij} \cdot C_{k,ij} \right)$$

$E_k = Risk\ of\ risk\ category\ k\ [see\ paragraph\ 3.3.7]$
$q_j = Probability\ of\ inundation\ event\ j\ [\#/year]$
$p_{k,ij} = Probability\ of\ failure\ object\ i\ when\ inundation\ event\ j\ for\ risk\ category\ k\ [\%]$
$C_{k,ij} = Consequence\ of\ failure\ object\ i\ with\ inundation\ event\ j\ for\ risk\ category\ k\ [see\ paragraph\ 3.3.7]$
$m = number\ of\ inundation\ events\ [\#]$
$n = number\ of\ objects\ considered\ for\ risk\ category\ k\ [\#]$

With Equation 2 the flood risk of each risk category is expressed in Euros a year .

Equation 2 $$R_k = M_k \cdot E_k$$

$R_k = Monetized\ risk\ of\ risk\ category\ k\ [€/\text{year}]$
$M_k = Monetizing\ value\ for\ risk\ category\ k$

Copy of Table 3-3 The risk categories and their respective units

Fatalities (k=1)	Environmental (k=2)	Economic (k=3)	Reputation (k=4)
Fatalities on site	Spills	Reparation costs, general clean up and cost of downtime	Downtime
$C_1\ [fatalities]$ $E_1\ [fatalities/year]$ $R_1\ [€/year]$	$C_2\ [litres]$ $E_2\ [litres/year]$ $R_2\ [€/year]$	C_3 [€] E_3 [€/year] $R_3 = E_3$ [€/year]	C_4 [weeks] $E_4\ [weeks/year]$ $R_4\ [€/year]$

The combined flood risk value is calculated from the flood risk value of the different categories. The calculation is performed with the ALARP method as used by the company and with the CBA method as used in the national flood risk approach.

Measures to change the flood risk value are evaluated on their costs and benefits. The benefits results from an annual risk reduction following an change in a parameter of Equation 1. When the net present value of an annual risk reduction is higher than the cost of a measure the measures is deemed favourable.

3.2 Process overview

The framework of the risk assessment is as shown in Figure 3-1. The 'C.' stands for the case study chapter number with the number representing the corresponding section in the case study.
Table 3-1 (on the next page) displays for each process the preceding processes, the required input, the process name and the output of the process. An in-depth explanation of the processes will be provided in the paragraphs of section 3.3.

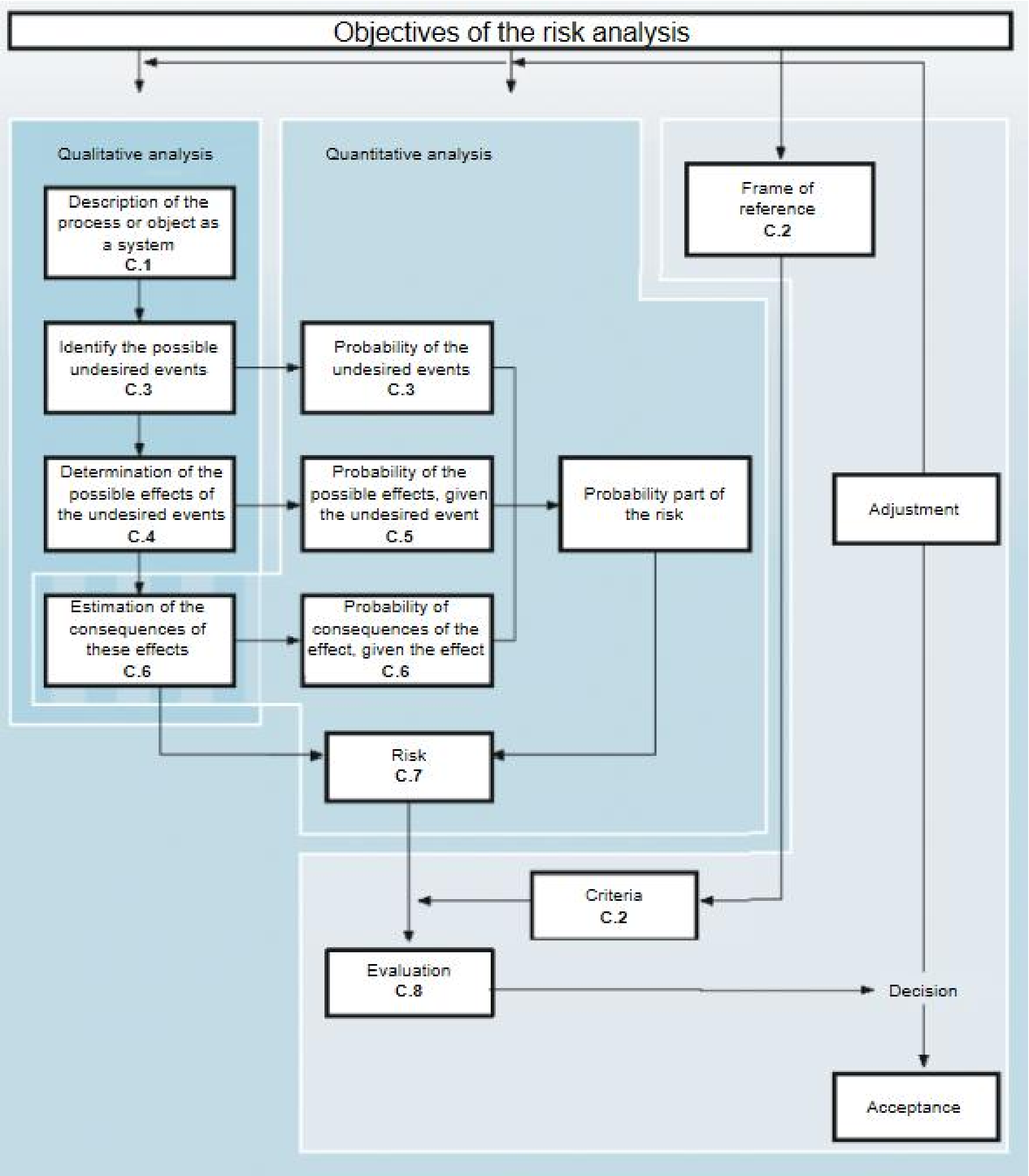

Figure 3-1 The framework of the risk assessment as performed in the case study

Table 3-1 Processes of the risk assessment

Preceding process(es)	Input	Process	Output
	Safety report of the terminal Company's website Site visits	C.1 System description	System overview of terminal Description of company
C.1	Description of company Risk matrix company Time horizon Discount rate	C.2 Frame of reference & evaluation criteria	Risk zones Guidance CB-ratios Net present value of annual gain
	Inundation data	C.3 Probability of events	Probability of events
C.1	System overview of terminal	C.4 Possible effects	Object list
C.4	Object list	C.5 Probability of effects	Probability of effect given event
C.4, C.5	Object list Probability of effect	C.6 Consequence	Consequence of effect
C3, C.4, C.5, C.6	Object list Probability of events Probability of effect given event Consequence of effect	C.7 Risk calculation	Annual risk values
C.2 C.7	Annual risk value Net present value of annual gain Risk zones Optimal CB-ratios	C.8 Evaluation & Decision	List of possible measures Favourable measures

3.3 The processes in detail

3.3.1 C.1 Description of the object as a system

Preceding process	Input	Process	Output
	Safety reports of the terminals Site visits Company's website	C.1 System description	Description of company System overview of terminal

The first process of the risk assessment is the system description. This process has as output a description of the company and its operating process. It additionally gives the schematization of the terminal as a system.

A description of the object as a system is based on the following sources:

- Company's website
- Safety report of the terminals (Vopak Terminal Botlek B.V., 26 May 2016) (Vopak Terminal Chemiehaven B.V., 31 May 2016) (Vopak Terminal Europoort B.V., 27 Juni 2016)
- Site and area visits, of which two in the form of multiday job shadowing of the operating crew. (Chemiehaven, 2016) (Europoort, 2016) (Neuhof, 2016, see Appendix B).

3.3.2 C.2 Frame of reference &the evaluation criteria

Preceding process	Input	Process	Output
C.1	Description of company Risk matrix company Time horizon Discount rate Growth rate	C.2 Frame of reference & evaluation criteria	Net present value factor Risk zones Guidance CB-ratios

The second process of the risk assessment is about the company's frame of reference. In section 2.2 a start was made; it elaborated on the evaluation of flood risk compared to other risks. This paragraph describes the frame of reference and the evaluation criteria which later will be used to evaluate the flood risk.

This process produces as output a visual description of the risk zones for the different risk categories, the corresponding guidance CB-ratios(Cost Benefit ratio) and a factor to calculate a net present value from an annual gain.

The following paragraphs elaborate on general assumption following the location and the date and on how the output from this paragraph will be produced.

Location and date

Currency: The sites are located in the Netherlands and the company is Dutch. Therefore monetary values are expressed in euros and the average conversion rates of 2016 are used when this is required; a British pound is €1.25 and an American Dollar is €0.91 (X-Rates, 2016).

Inflation: The risk assessment is performed in 2016 and accordingly prizes are adjusted for inflation to the price level of 2016. This is done with the inflation goal of the European Central Bank of 2% (European Central Bank, 2017).

Net present value factor

The discount rate, the time horizon and the growth rate are used to value an expected annual gain at a onetime gain. This value is used to compare such a yearly gain, following a risk reduction, to a onetime implementation expense of a risk reduction measure. It is calculated with Equation 3

Equation 3
$$N = R_r \cdot \sum_{i=1}^{T} \frac{1}{\left(1 + (r - r_g)\right)^i}$$

$N = \text{Net present value of an annual risk reduction} [€]$
$T = \text{Time horizon} [year]$
$R_r = \text{Annual risk reduction} [€/\text{year}]$
$r = \text{discount rate} [\%/year]$
$r_g = \text{risk growth rate} [\%/year]$

Time horizon: The time horizon is based on the lifespan of equipment; a time horizon of 35 years is used[4]. This is chosen since replacing an object requires a renewed investment in measure that reduces the risk of the object. Measures that have a longer useful period are evaluated with the same time horizon without taking maintenance into account to compensate.

Growth: The annual flood risk increase is known for the area and it is used in the calculation of the NPV. A annual growth for the company is not assumed unless there is a clear indication of growth; a standstill is assumed for the company.

Discount rate: The discount rate is defined by adding the risk premium for the company to the risk free reference rate in the form of long-term government bond (Scheuren, 2011). It is chosen to use a company specific discount rate instead of the one used by the government.

The timespan over which the risk-free rate is determined strongly influences the level of this reference rate, as shown in Table 3-2. Currently the value of the government interest rate is less than the long-term average. Considering the timescale of flood measures, the average value of the last ten years is assumed; 2.99% (Nederland 30-Jaar Obligatierendement, 2016).

Table 3-2 Reference interest rate

Timespan	Government interest rate (‘Risk-free rate’)
1993-2016	4.54%
2006-2016	2.99%
2015-2016	0.91%

Evaluation criteria: Risk zones and guidance CB-ratios

Optimum: For the company the risk is defined as “at or beyond its optimum” if there are no measures possible that have a CB-ratio lower or equal to the guidance value. The guidance value that is specific for the risk category and the risk zone the risk is originally located in.

The risk zones: The risk zones are defined by the risk matrix of Vopak; it is based on the consequence size and probability. For each risk category and each zone there is a guidance value for the CB-ratio.

Cost-Benefit ratio: The CB-ratios in this thesis for fatalities and environmental follow from the a authority on the aspect of ALARP; UK’s health and safety agency. For the economic category the ratios are based on executed flood risk reduction measures present at the company. This is done with a cost-benefit analysis

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[4] This is 20-50 years for electrical equipment. For the company Vopak electrical stations are built with a 30-year lifespan.

of the risk reduction measure that was implemented and a more expensive measure that was not. The additional costs as stated in 2.2.4 are assumed to result in the economic CB-ratio as is present at the company. For the CB-ratio of the reputation category an assumption is made; it is assumed to be double the CB-ratio of the economic category.
Legal limits are integrated in the CB-ratios with the use of the zones of the risk matrix. This is implemented by adjusting the CB-ratio when a risk is initially located in a certain risk zone of the matrix. This includes changing the ratio to zero or to infinite.

3.3.3 C.3 Identify the possible undesired events and their probability

Preceding process	Input	process	Output
	Inundation data	C.3 Probability of events	Probability of events Qualitative overview of the inundation

The undesired events in this flood risk assessment are several inundation events that relate to water level events with a certain exceedance probability.

The inundations events taken into account result from water level exceedance probabilities from 1/10 to 1/10,000 a year in 2050. The method is also applicable for other ranges of exceedance probabilities but for this thesis the upper value of 1/10,000 a year is used. The upper value is based on the risk matrix of the company Vopak. The other end of the exceedance probability range is based on the highest exceedance probability of an inundation. It is for simplicity assumed that an exceedance probability of 1/10 a year is at least such, in practice this probability can be smaller. The interval in between those limits is preferred to be a tenfold (1-10-100), or less if more data is available. An interval of a tenfold or less will lead to a limited difference in inundation levels which will enable small impact measures; sill for examples

Several parameters of the inundation event are of influence on the amount of damage company's receive (Kreibich, et al., 2009) (Smith, 2012). The parameters are:

- the inundation level
- the inundation duration
- the flow velocity
- the swiftness of the increase of the inundation
- the salinity of the water

For floods, apart from tsunamis, the inundation level is the most important parameter. Flow velocity has in general not a major influence on the damages for companies (Kreibich, et al., 2009). Following these reports the inundation level is the only considered parameter of influence.

Using the data provided by the government, water board or local authorities provides a basis for meeting possible legal standards. It is likely that a company uses the same data as neighbouring companies which is especially useful when (mutual) dependency is present.

Object level

The object level is the elevation of the object relative to the surface; as is shown in Figure 3-2. The inundation level is also relative to the surface level. For assessing the damage to the object the inundation relative to the floor level of the object is used. The surface inundation level minus the object level results in this value. The object levels are determined by visual observations on site.

Figure 3-2 Elevated electrical station (personal photo)

3.3.4 C.4 Possible effects of undesired events

Previous process	Input	process	Output
C.1	System overview	C.4	Object list Event tree

The effect of an inundation event on the objects of the terminal is checked. This check is performed by a comparison between the system overview and with three studies into the effects of inundation on a liquid bulk terminal. The system overview is adjusted if the system did not include an object that is indicated to be possible damaged.

The studies used are the following qualitative risk assessments on liquid bulk terminal terminals;

1) Vopak terminal Laurenshaven (Vopak's own qualitative flood risk evaluation) (Royal Vopak, 2016)
2) Pilot 'Waterveiligheid Botlek' (Bonte, Dijk, Ledden, & Visch, 2016)
3) Vopak terminal Neuhof (Vopak's own flood risk evaluation) (Vopak Terminal Hamburg, 2014)

This process provides an object list as output. On this list are (groups of) objects that are of influence to one or more risk categories. On the list it is stated which objects have an influence on which category. The objects of influence arefor every category also visually depicted in an event tree.

3.3.5 C.5 Probability of the effects given an undesired event

Preceding process	Input	process	Output
C.4	Object list	C.5 Probability of effects	Probability of effect given event

This process provides the probability of failure of the (groups of) objects from the object list.
When the inundation level at the object surpasses the object level the probability of an effect given an inundation event is 100% for the categories fatalities, economic and reputation.

The calculation of the probability of consequences that influence the environmental risk category follow the principles of the studies described in paragraph 2.3.3 for tank storage at liquid bulk terminals. Every tank pit is considered individually. The strength of tank dikes calculated with an simply approach for overtopping, sliding and conductivity.

Additionally the failure probability of a single tank in a tank pit is calculated.

3.3.6 C.6 Estimation of the consequence of the effects

Preceding process	Input	Process	Output
C.4, C.5	Object list Probability of effect	C.6 Consequence	Consequence of effect

The objects from the object list with a failure probability for one or more events have their consequences defined. The failure probability is zero if the object is not inundated for the considered events or its calculated failure function results in non-failure independent of the inundation depth. If one of those values has a probability of zero, the contribution of the object to the flood risk is zero, no matter the size of the consequence and therefore it is not required to define the consequence size. This process has as output the consequence of failure of the (groups of) objects from the object list expressed in a value that is specific for the risk category they influence.

Fatalities
The consequence of the risk category fatalities is defined with the use of the mortality fraction. The mortality fraction is a combination of different factors that influence the probability of a person dying when the area is inundated. This is a simple approach compared to the approach to the other risk categories. The simple approach is chosen following an expectation that the risk of fatalities is limited in magnitude (<10%) compared to the other risk categories. The method is adjusted when this expectation is not met.

The assessment uses as mortality fraction the value from the pilot ‘Waterveiligheid Botlek’. For defining the consequence of fatalities a number of people is assumed to be present at the terminal when inundation occurs. This assumption is made based on the number of operators present during a storm situation (which is correlated with an inundation event). During a storm situation there is no change in the number of operators present on a terminal site.

Environmental
For the environmental risk category, the consequence is calculated based on the content of the tank and the inundation level. The tank dimensions are used and the same assumptions as were used for the failure function are used for the calculation of the content of the tank. Every tank pit is considered individually.

Economic

For the economic consequence three options are used. When available, damage functions of the damage percentage relative to the inundation level are used. The basis is the Standard Method (Kok, Huizinga, Vrouwenvelder, & Barendregt, 2004) in which the percentage of maximum damage is in thesis used as a damage percentage of the replacement value. The replacement value is acquired based on estimates from the company's risk assessment and checked in a feedback session with the engineering department from the company. For objects that do not have a damage functions available a value of damage per square meter inundated is used. If the first two options are both not applicable the value of the damage is set per object inundated. For both options inundation is based on non-zero inundation levels and values are used from Vopak Hamburg Neuhof.

Economic damage per object is calculated with one of the following options in order of preference:

- Option A: Relates the damage as percentage of the RV to the inundation level at a specific point
- Option B: Damage per square meter inundated.
- Option C: Damage per object inundated.

Reputation

The reputation is expressed in downtime of the terminal. Therefor the recovery and repair time are the leading factor for this category. The repair time is acquired by consulting the relevant companies. For the electrical grid information is acquired from Stedin and TenneT. For the repair time of the nitrogen supply information is acquired from Air Products, the nitrogen supplier of Vopak. For repair times on Vopak itself a session is organized with members of the engineering department with a background in (electrical) maintenance and automation. For the repair time of electrical systems on the Vopak site the information of Stedin and TenneT is considered leading over information from Vopak.

The recovery time is based on how soon Vopak will be up and running when external utilities fail. It is estimated by of Vopak. In a disaster situation the temporary fixes are more difficult or not an option at all, due to scarcity of equipment and/or manpower (Appendix D). Therefor the probability of a successful temporary fix is assumed at 50% by the author. With this estimate the downtime will calculated from 50% of the recovery time and 50% of the repair time.

While the mean values for the inundation levels are used for the parallel systems a different approach is used for the serial systems. For a parallel system the local uncertainty in inundation level creates a limited variance in the consequence for the system.
When taking the mean value in a serial system, this results in an underestimation of the consequence for the system, as shown in Figure 3-3. This follows from the fact that an individual failure of a part of the system results in failure of the whole system. Therefor a Monte Carlo simulation will be used for the reputation consequence.

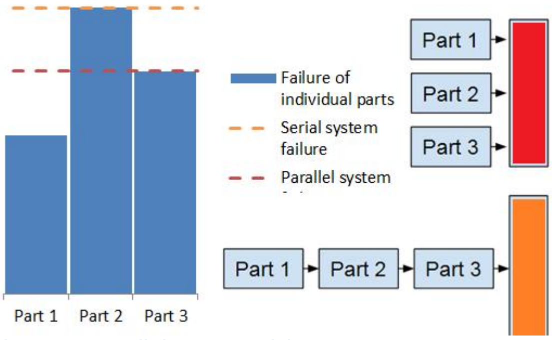

Figure 3-3 Parallel versus serial system

3.3.7 C.7 Risk calculation

Preceding process	Input	Process	Output
C.1, C3, C.4, C.5, C.6	Object list Probability of events Probability of effect given event Consequence of effect	C.7 Risk calculation	Annual risk values

The risk calculation process combines the information gathered in the previous processes. The flood risk of each terminal is calculated with the probability of the inundation event, the probability of the effect and the consequences. This calculation is performed for the each risk category.

Equation 1
$$E_k = \sum_{j=1}^{m} q_j \sum_{i=1}^{n} \left(p_{k,ij} \cdot C_{k,ij} \right)$$

$E_k = Risk\ of\ risk\ category\ k\ [see\ table\ below]$
$q_j = Probability\ of\ inundation\ event\ j\ [\#/year]$
$p_{k,ij} = Probability\ of\ failure\ object\ i\ when\ inundation\ event\ j\ for\ risk\ category\ k$ [%]
$C_{k,ij} = Consequence\ of\ failure\ object\ i\ with\ inundation\ event\ j\ for\ risk\ category\ k\ [see\ table\ below]$
$m = number\ of\ inundation\ events\ [\#]$
$n = number\ of\ objects\ considered\ for\ risk\ category\ k\ [\#]$

The risk calculation is performed with Equation 1. This equation summarizes the risk over different inundation events (from C.3) and over different objects (from C.1 and C.4). In this equation there is an object-specific consequence (from C.6) and probability of failure (from C.5) given the inundation event. For the reputation category the consequence for the system equals the largest consequence of one of the objects. Thus the largest consequence of an object is taken instead of summating the individual consequences.

With Equation 4 the flood risk of each risk category is expressed in Euros a year .

Equation 2
$$R_k = M_k \cdot E_k$$

$R_k = Monetized\ risk\ of\ risk\ category\ k$ [€/year]
$M_k = Monetizing\ value\ for\ risk\ category\ k$

Table 3-3 The risk categories and their respective units

Fatalities (k=1)	Environmental (k=2)	Economic (k=3)	Reputation (k=4)
Fatalities on site	Spills	Reparation costs, general clean up and cost of downtime	Downtime
$C_1\ [fatalities]$ $E_1\ [fatalities/year]$ $R_1\ [€/year]$	$C_2\ [litres]$ $E_2\ [litres/year]$ $R_2\ [€/year]$	C_3 [€] E_3 [€/year] $R_3 = E_3$ [€/year]	C_4 [weeks] $E_4\ [weeks/year]$ $R_4\ [€/year]$

This process calculated the annual risk for each risk category expressed in a category specific unit and in Euros a year.

3.3.8 C.8 Evaluation & Decision

Preceding process	Input	Process	Output
C.2 C.7	Annual risk value Net present value of annual gain Risk zones Optimal CB-ratios	C.8 Evaluation & Decision	List of possible measures Favourable measures

The risk as calculated in C.7 is evaluated with the evaluation criteria which result from C.2). In order to perform the evaluation possible risk reducing measures are introduced with their costs and the benefit of risk reduction is calculated.

Measures

First considerations will be given on the scale of different measures and the different layers of the multi-layered safety approach as was introduced in paragraph 1.1.3. This is followed by a grouped introduction of different possible measures from the different layers. The measures listed possibly influence the risk at a Vopak site.

In the list of possible measures a division is made between measures that are and are not potentially favourable measures. This division is made by discarding the measures that do not decrease the risk, the measures that are not possible to implement and measures that have an similar measure, in scale and layer, that is expected to more efficient. The costs of the potentially favourable measures are stated and compared to the benefit of the risk reduction.

The benefit of risk reduction

The benefit of the measures is calculated with Equation 4 and Equation 5. Equation 4 is the evaluation method of Vopak and Equation 5 is the evaluation method of the new national standard.

Equation 4
$$R_A = \max_{k=1}^{4}(R_k \cdot W_k)$$

$R_A = \ Risk\ value\ with\ ALARP$ [€/$year$]
$W_k = CB\ ratio\ for\ the\ risk\ category\ k$ [-]

Equation 5
$$R_C = \sum_{k=1}^{3}(R_k)$$

$R_C = \ Risk\ value\ with\ CBA$ [€/$year$]

In Equation 4 one of the risk categories in combination with their CB-ratio(Cost-Benefit ratio) is leading. It is chosen to present the benefit of the risk reducing measure instead of showing the CB-ratio of the measure. This choice is made to show directly what cost level enables a risk reduction measure.

Equation 5 is a summation of the risk values. The reputation risk, R_4, is not in the summation of Equation 5. The reputation risk (R_4) is also incorporated in the economic risk (R_3) and therefore summation over the four risk categories results in double counting of the reputation risk.

Favourable measures

When the net present value of an annual risk reduction is higher than the cost of an measure the measures is favourable. A value is presented how the risk reduction compares to the implementation costs of the measure. A value above 100% is favourable for the company. The favourability expressed in two types;

a) Favourable with R_A
b) Favourable with R_C

This chapter presented the method for the case study with details on its processes. In the following chapter the described processes are used on the case study. The outline of the case study chapter equals to the outline of this section 3.3 of this chapter.

4 Flood risk assessment: Vopak in 2050

Vopak is one of the companies that participated in the pilot 'Waterveiligheid Botlekgebied'. As a company that owns (parts of) eight BRZO establishments in the Rotterdam harbor it is a useful case study for identifying and evaluating the stance on flood risk of a BRZO company. In this chapter the method from chapter 3 is applied to answer the following question;

1. *What is the flood at Vopak terminals risk in 2050?*
2. *What are possible measures to influence the flood risk at Vopak terminals?*
3. *What are the benefits of the possible measures compared to their costs for Vopak terminals?*

4.1 The company and its operation

Vopak, or officially, Royal Vopak is an independent liquid bulk tank storage company. Here, independent means that it does not own, trade or produce the product it stores in its tanks. The company owns a global network of tank terminals and is the leading company providing independent tank storage. It is a 400 year-old Dutch company; one of its predecessors was established in 1616, which results in a large amount of Dutch terminals in its portfolio. Vopak employs over 6,000 people worldwide when joint ventures are included (Royal Vopak, 2016).

The product that Vopak stores ranges from oil, chemicals, gases, and LNG to biofuels and vegoils (components for the food industry). Its business is the safe, clean and efficient storage and handling of bulk liquids where the main bulk liquids are fuel and chemicals, both which are hazardous to the environment. In the Netherlands, Vopak complies with a multitude of regulations of which the BRZO is the most prominent regarding risk. Additionally, it has its own worldwide standards (Royal Vopak, 2016).

4.1.1 Terminal locations

Figure 4-1 Vopak terminals in the Rotterdam harbor area (adapted from the Vopak website)

The Vopak terminals assessed in this assessment are the Vopak terminals Botlek, Torontoweg, Chemiehaven, Laurenshaven and Europoort. These (100% owned) terminals are located in a part of the Rotterdam harbor that is depicted by the black box in Figure 4-1. It can be seen in this figure that there are other terminals of Vopak in the Rotterdam harbor which are not included in this assessment.

In this case study the method from chapter 3 is applied on these five terminals of Vopak. These terminals have a lot of similarities and accurate small scale inundation data is available for most of them (all except for the Europoort terminal). The other terminals in the same area in which Vopak is involved do not have sufficient inundation data readily available. In addition, the Maasvlakte Oil Terminal and the Gate terminal are joint ventures (the two terminals located at the Maasvlakte, west in Figure 4-1). They are not under direct Vopak control. When the terminals are not directly under control of Vopak, this influences the decision-making process for investments. Therefore, the assessment and the recommendations of the case study focus on the terminals that are under direct control of Vopak.

4.1.2 How a Vopak terminal operates

Figure 4-2 Part of the terminal of Chemiehaven (Vopak archive)

Product mostly arrives at a terminal by a vessel moored at one of its jetties. The product is transported by pumping it through pipelines to a tank. Pumps are used to transport product through the terminal to vessels, trucks, tanks or rail wagons. The pumps are located in pump pits and run on electricity. The tank pits are enclosed by containments walls to keep the product in if a tank fails.

The pump pits are located close to but outside the tank pits and are located at the level of the bottom of the tanks. The tank level is often below the surface level. The level of the pump pits is guided by efficiency and pumps work more efficiency when pushing product which results in a placement of the pump pits at or below the bottom of the tanks. Pump pits may be present inside the tank pits (PGS-beheerorganisatie, 2016) but this is not regular practice at Vopak sites.

Product in a tank can be heated, cooled, mixed, or blended. Sometimes the pipelines are heated if it is required to keep the product at the correct temperature. Heating is done electrically or with steam. Products are heated to make them more transportable or because products will (permanently) solidify below a certain temperature.

When a pipeline is used for multiple kinds of products it is cleared by pushing a device through it with the use of nitrogen pressure (pigging) or by flushing the line with nitrogen. Nitrogen is also used as a blanket for products that interact with air; this interaction can result in an unsafe situation or reduced quality of the product. (Europoort, 2016).

Pipelines have to be manually linked but at most sites more and more of the processes are automated. The processes are managed from the central control room (CCR) where information from sensors is seen and the pumps can be controlled.

Additional aspects of the terminal

- Vapours of the product are processed to reduce the hindrance of smell and to minimize emissions.
- Wastewater from the pump pits is processed onsite and sometimes further processed offsite.
- For safety multiple firefighting systems are present and emergency power is present for the firefighting pumps.

4.1.3 Systemized terminal

The operation of the terminal is schematized as a system with three main parts, this system is shown in Figure 4-3. The first part consists out of objects which are needed to safely operate the terminal. The second part consists of objects that help transport or manipulate the products. Due to isolation heating is mainly needed when transporting product and therefor heating is considered only in the second part. Lastly for storing the product tanks are needed, with a backup of tank dikes when storing hazardous products. In this system pipelines are considered as filled with product and therefor they are also classified as objects that store product.

The dependency on different utilities is considered. Of the first two parts of the system, all parts require electricity to function except for the part firefighting. This is since those pumps have their own emergency power. The heating is done with steam or with electricity. The steam supply is generated externally or is locally produced with gas. The central control room depends on gas for the heating. When transport of product takes place nitrogen is sometimes needed. The percentage of the tanks that need nitrogen when transport takes place depends on the terminal.

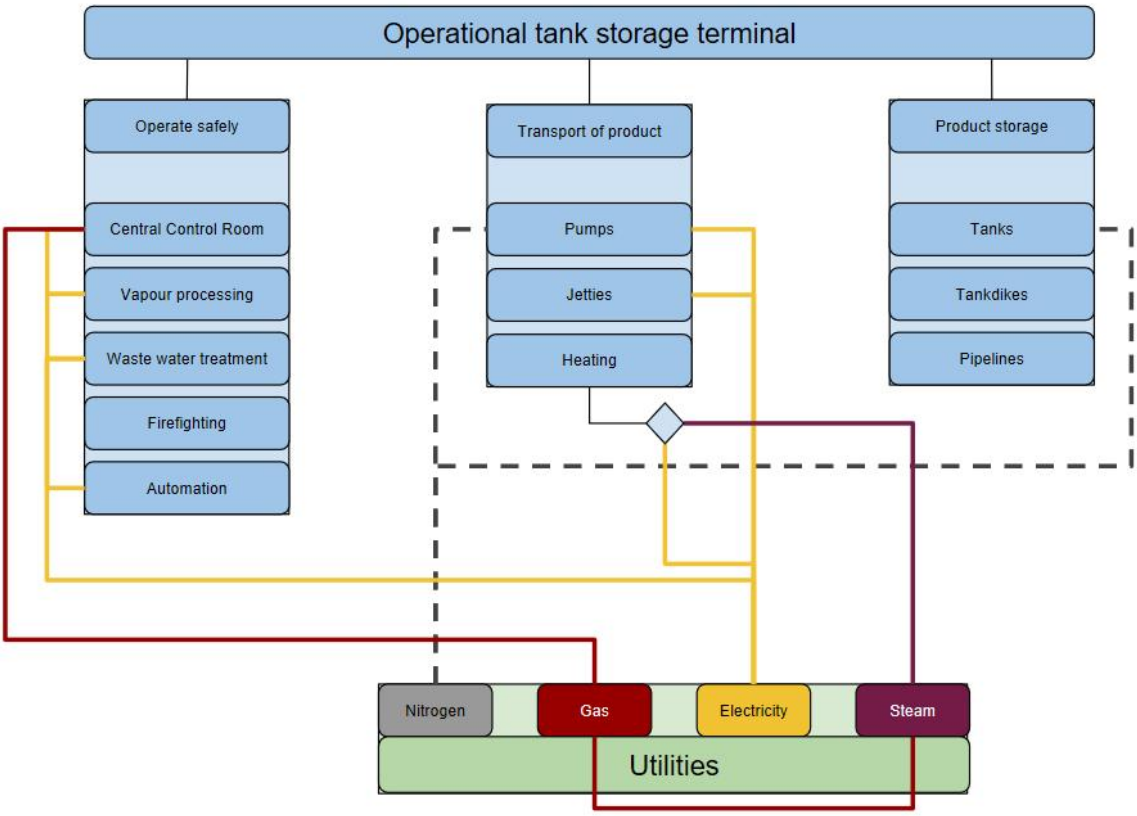

Figure 4-3 Systemized terminal

A more extensive description of the different objects and their importance to the terminal can be found in Appendix A.

4.2 Frame of reference & Evaluation criteria

This process has as output a visual description of the risk zones for the different risk categories, the corresponding guidance CB-ratios and a factor to calculate a net present value from an annual gain.

4.2.1 Risk zones

Vopak evaluates risk with its risk matrix, see Appendix A. This risk matrix is based on the company's preference as well as it is based on legal regulations. Vopak itself has an aversion for large consequences with regard to risk.

Vopak considers three zones in its risk matrix based on the damage size and its probability;

- Green zone: the risk is accepted. Actions to reduce risk further are assumed to be unbeneficial.
- Yellow zone: the risk is accepted if As Low As Reasonable Practical (ALARP). In this assessment the risk is deemed ALARP if no measures have a CB-ratio (Cost Benefit ratio) at or below the guidance ratio for the specific risk category.
- Red zone: the risk is intolerable and actions are required to reduce the risk to at least the yellow zone.

For the economic and reputation category the red zone is in this thesis called undesired instead of intolerable. For those risk categories the risk for Vopak can also be explicitly accepted by division management when situated in the red zone of the risk matrix. There is no legal limit.

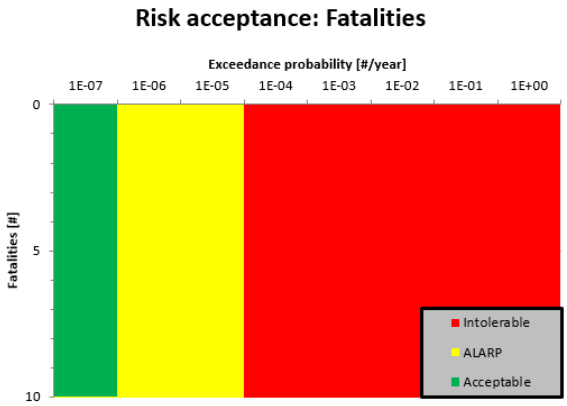

Figure 4-3 Vopak's risk matrix for fatalities

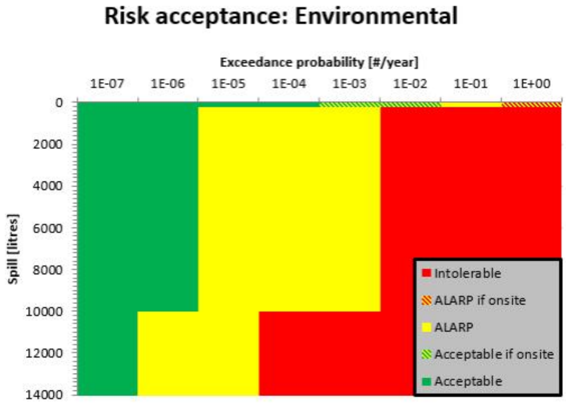

Figure 4-4 Vopak's risk matrix for environmental risk

In this thesis the risk in the undesired area of the risk matrix is still evaluated with the ALARP method but with an increased guidance value for the CB-ratio; the benefits have to be less compared to the costs for Vopak to implement the measure.

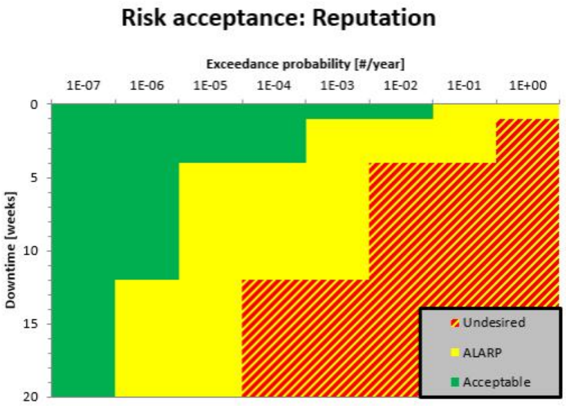

Figure 4-2a Vopak's risk matrix for Reputation risk

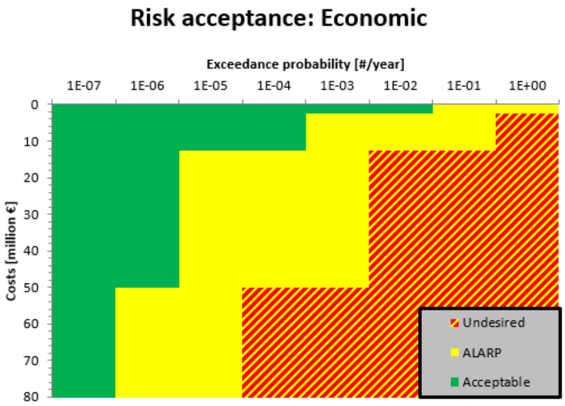

Figure 4-4b Vopak's risk matrix for Economic

4.2.2 Cost Benefit ratios

Currently Vopak has a case by case consideration of what kind of CB-ratio is ALARP. To formalize the approach for Vopak are in this thesis ranges of CB ratios defined in line with the theory from paragraph 2.2.2. Cost-benefit ratios are stated for which a risk is definitely ALARP, possible ALARP when considered by experts and compared to industry's common practice, not ALARP, and beneficial economically. The value of the cost-benefit ratio for which a risk is considered ALARP is also called the disproportion factor(DF).

The resulting guidance values used for the CB-ratios are shown in Table 4-1. When there are two numbers stated in the table, it will be read as follows; A ratio above the high value means the risk is ALARP, a ratio between the two numbers requires expert consideration, and a ratio below the low value means the risk is not ALARP. For flooding it is chosen to use the low value following the perception on flood risk by the public. The acceptance of such risk is higher and therefor expert consideration will lead to the low CB ratio.

For the risk categories environmental and fatalities costs are not a consideration for preventing a risk situated in the red zone, as stated by Vopak's risk department. This stance is incorporated in the CB-ratios by an infinite ratio between the cost and the benefit when a risk in one of those categories is situated in the red zone. For the undesired zones the CB ratio is multiplied when it is located in the undesired risk zone.

Table 4-1 The guidance values for the cost-benefit ratio

	CB-ratio (W_k)			
Risk Vopak is in the…	Fatalities (k=1)	Environmental (k=2)	Economic (k=3)	Reputation (k=4)
… Red zone	∞	∞	1-2	2-4
… Yellow zone	3-10	3-10	0.5	1
… Green zone	[The risk is accepted; no benefit of measures is assumed]			

An interesting aspect of Table 4-1 is that a ratio below 0.5 is considered beneficial economically instead of a ratio of 1. This is to account for additional costs which were stated in 2.2.3. This follows from the ratio that was found in flood risk reduction in Hamburg, see Appendix C. This ratio is assumed to take into account the not monetized downsides of the measure such as hindrance for operators.

The values for fatalities and environmental follow from the a authority on the aspect of ALARP; UK's health and safety agency. It states to "A DF of more than 10 is unlikely" as is stated by the, the duty holder would have to justify use of a smaller DF (HSE, 2016). And it states "NSD takes as its starting point the HSE submission to the 1987 Sizewell B Inquiry that a factor of up to 3 (i.e., costs three times larger than benefits) would apply for risks to workers; for low risks to members of the public a factor of 2, for high risks a factor of 10" (HSE, 2016)

4.2.3 Net present value of the risk

To compare the reduction of risk in the form of an annual gain with a one-time investment the NPV (net present value) of the risk reduction is used. The company specific the discount rate is relative to this risk-free rate of 3% (see paragraph 3.3.2). For Vopak a risk premium is assumed of 4% (Maverick, 2017). Therefore, the flood measure calculations in this thesis are performed with a discount factor of 7%. The annual increase in flood risk is 2.75% in the coming century[5].

The discount rate of 7%, the annual risk increase of 2.75% and the time horizon of 35 years results in the factor 18.122 with which the annual risk reduction is multiplied to result in the NPV.

4.2.4 Earlier implementation

The risk assessment uses a payback period from 2050 to 2085 years to evaluate the measures. The benefits are considered as the discounted annual risk reduction from the years 2050 – 2085 to a single value in 2050. The costs are the implementation costs in 2050. In practice implementation of measures can occur before 2050. The higher costs of earlier implementation are assumed to be balanced by a longer return period as the assumed end of such measures is still 2085.

The prize level used is the level of 2016, both for the risk as for the costs. The risk evaluation is based on the CB-ratio and is thus not influenced by price level and the 2016 values result in a better interpretation of the results.

4.2.5 Positive area effect

With Vopak owning multiple terminals in the area the measures can influence the risk at multiple terminals. Additionally, some measures will not solely benefit Vopak; other companies will benefit as well.

Vopak has a leasehold of 8% of the coloured area of Figure 4-5 and 16% of the orange area (Kilometerafstanden, 2016), as shown in Table 4-2. These are parts of the Botlek area. The numbers Botlek 1 and Botlek 2 are similar to the area used in the pilot 'Waterveiligheid Botlek' (Bonte, Dijk, Ledden, & Visch, 2016).

Figure 4-5 Botlek areas

The values of Table 4-2 are not used for the evaluation of the costs of different measures for Vopak. They are stated to give reference to possible options of restructuring the costs and the benefits and are used in the discussion.

Table 4-2 Vopak's part of the Botlek area

	Total area	Dry Area	Dry area of Vopak	
Botlek 1 (Red)	5.02 km^2	4.18 km^2	0	0%
Botlek 2a (Orange)	9.50 km^2	6.59 km^2	1.07 km^2	16%
Botlek 2b (Yellow)	2.73 km^2	1.92 km^2	0	0%
Total	16.25 km^2	12.69 km^2	1.07 km^2	8%

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[5] An increase of the probability of inundation event increases tenfold in 2100. This results in an 10^(1/85)=2.75% annual risk growth

4.3 The inundation probability

The data used for the risk assessment is inundation data made available by the harbor authority from within the pilot 'Waterveiligheid Botlek' (Bonte, van Dijk, van Ledden, & Visch, 2016). Data is available for a 5x5 metre grid size. For every cell in the Botlek the expected inundation level is known for stepwise exceedance probabilities. The type of flooding is coastal flooding.

The used data has an exceedance probability range from 1/100 to 1/10,000 a year in the year 2050. While the lower end is different from the basic guideline of 1/10 a year from the method it is seen that no inundation is present for the 1/100 probability at relevant locations for this risk assessment. This follows the more specific guideline on inundation data of the method; use the highest probability of inundation as the limit.

Probability of exceedance and the probability of a specific inundation event

When the water level is exceeding 1 meter it is also exceeding 0.5 meter. Therefor a summation of the different risks results in a double counting of parts of the risk. Summating the risk of different inundation events to a single annual risk requires the probability of exceeding a certain level without exceeding the next inundation level. This probability is acquired by subtracting the exceedance probability of the next inundation level from the exceedance probability of the considered exceedance probability, see Equation 6. The result is shown in Table 4-3.

Equation 6
$$q_j = qe_j - qe_{j+1}$$

$qe_j = Probability\ of\ exceeding\ event\ j\ [\#/year]$

Table 4-3 Exceedance probabilities used and their relations to probabilities

Probability of exceedance (q_e) (#/year)	Which equals the combined probability of events j		Inundation event (j)	Probability of event (q_j) (#/year)
1/100	1,2,3,4 and 5		$j = 1$	q=1/150
1/300	2,3,4 and 5		$j = 2$	q=1/430
1/1,000	3,4 and 5		$j = 3$	q=1/1,500
1/3,000	4 and 5		$j = 4$	q=1/4,300
1/10,000	5		$j = 5$	q=1/10,000

In 10,000 year it is the expectation that 'event 5' occurs once, 'event 4' occurs twice, 'event 3' occurs seven times, 'event 2' occurs twenty times and 'event 2' occurs 70 times. This results in 100 times an inundation event.

The uncertainty of the inundation levels

The local uncertainty in the inundation levels is 0.25m as is the quantitative estimation by Robin Nicolai (Nicolai, Botterhuis, Pleijter, Huizinga, & Stijnen, 2016) (Nicolai, Toelichting Waterdieptekaarten Pilot Botlek, 2016). This value is interpreted as follows; the standard deviation is half of 0.25m, 95% of the actual inundation values is between 0.25m above or 0.25 m below of the data value.

The local uncertainty is used for the reputation risk category while the other categories use the mean values. The reputation risk category is different since it is a serial system instead of a parallel system. An event tree is shown in also paragraph 4.4.2.

4.3.1 Flood risk reducing measures in the harbor

In the Rotterdam harbor are currently flood risk reducing measures present. Some of which are intended purely for the harbor. Some measures are intended to reduce the risk for the city of Rotterdam but also provide risk reduction for part of the Rotterdam harbor.

Elevated surface level

Flood risk reducing measures such as embankments cause hindrance to industrial activities. Therefor another option was chosen to reduce the risk of flooding in the harbor area. When the harbor was developed the surface levels were elevated to a level considerably higher than the nearby polders. For example, the Europoort, part of the Rotterdam harbor, is situated at 5.5 meter above NAP (Gemeente Rotterdam, 2004). The level of surface elevation has changed in time. The Botlek part of the Rotterdam harbor has been constructed mid-20th century and was constructed between 3.5 and 4.5 meter above NAP. The elevation height is based on an economic optimal risk between the costs of the flood risk and the cost of elevating the surface level.

The elevation of the surface level has an additional benefit compared to flood measures like embankments. The inundation level is lower when flooding occurs. A certain water level outside that leads to overtopping or failure of an embankment will result in a higher inundation level than the same water level overflowing an elevated surface level. An example is shown in Figure 4-6.

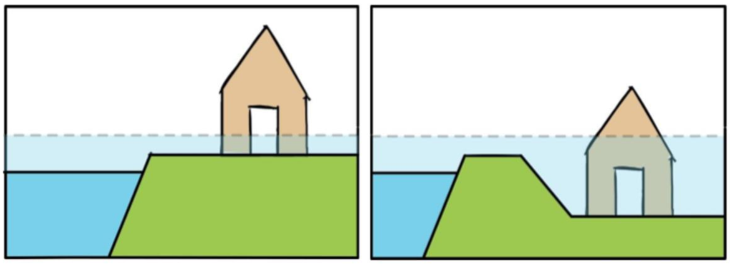


Figure 4-6 Left: elevated surface level. Right: Dike ring

Europoortkering

Part of the harbor benefits from the flood risk measure that was built to reduce the risk for the Rotterdam city. This flood risk measure is called the Europoortkering, it is depicted in Figure 4-7. It comprises the ‘Stormvloedkering Nieuwe Waterweg’, the Hartelkering, part of the dikes protecting ‘Rozenburg’ and higher situated grounds in between which serve as a wide embankment. This embankment is depicted by the black line next to number three in Figure 4-7. The wide embankment is allowed to overflow. The strength is large enough to allow overtopping and there is an adequate retention capacity in the harbor basin located behind the Europoortkering. (Publiekscentrum Water in Zuid-Holland, n.d.) (Rijkswaterstaat, n.d.). The fact that the embankment is allowed to overflow does reduce the benefit the directly hinter-lying harbor area, the Botlek, gains from this measure.

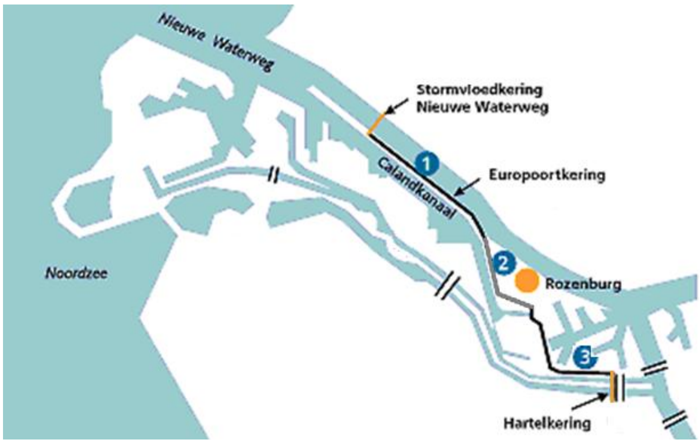


Figure 4-7 Europoortkering. Adapted from: (Publiekscentrum Water in Zuid-Holland, n.d.)

The Europoortkering is a B type of flood retaining structure. The failure probability of a B type of structure is not directly bound in a legal standard (Rijksoverheid, 2015). This means the area behind the Europoortkering is still legally regarded unembanked.

Tuimeldijk

This flood risk reducing measure in the form of a small embankment lowers the probability of low inundation levels for the most eastern part of the Europoort and the Botlek area, it is shown in Figure 4-8. The word Tuimeldijk literally means: A dike that is designed at such height that with certain flood levels overtopping takes place. Retaining low water levels can be expected but when overtopping takes place this will erode the Tuimeldijk.

Figure 4-8 Tuimeldijk. The red line depicts the location.

The 'Tuimeldijk' has in practice an height of 5.2 meter (Actueel Hoogtebestand Nederland, 2016) which is lower than the design height of the Tuimeldijk of 5.5 meter. When considering the amount of overtopping it is common practice that the run-up of the waves results in overtopping (van der Meer, 2002). However, with the top of the Tuimeldijk being located below the water level for multiple return periods an alternative approach is used to calculate the amount of overtopping. The Tuimeldijk is considered as a spillway. This yields results as can be seen in the Table 4-4. The Dutch standard for allowable overtopping is currently at 0.1 l/s/m (Bos, 2006). While the exact value for failure of the grass cover is under reconsideration the amount of overtopping as seen in the table is will lead to failure of the Tuimeldijk.

Table 4-4 Overtopping over the Tuimeldijk, modelled as spillway

	2050			
Exceedance probability a year	1:300	1:1000	1:3000	1:10000
Water level	4.71	5.1	5.37	5.73
Level of Tuimeldijk(m)	5.2	5.2	5.2	5.2
Overtopping height(m)	0	0	0.17	0.53
Overtopping (l/s/m)	0	0	119	656

The current models take the presence of the Tuimeldijk into account without failure. The models might be more accurate when they take into account a partly broken Tuimeldijk. A failure of the Tuimeldijk will results in a lower effect of the Tuimeldijk on the reduction of the inundation level in the area.

4.3.2 How flooding will occur in the Rotterdam harbor

For the flooding scenarios in the Rotterdam harbor there are three main routes for the water to flow through. The routes are shown in Figure 4-9 with the following numbers:

1. The Hartelkanaal (including the Beerkanaal)
2. The Calandkanaal
3. The Nieuwe Waterweg

From following these three routes, four distinct zones emerge. These zones are based on a zone having a distinct type of flooding. These zones, depicted in Figure 4-10 follow from different types of flooding. For zone 1 the water level needs to surpass the elevated surface levels. In zone 2 the water level needs to partly surpass the elevated surface levels and/or tip over the Tuimeldijk. For zone 3 water needs to be present in Botlek 1 (depicted almost entirely by zone 2) and/or flow over the A15. This is shown in detail in Figure 4-11. For zone 4 flooding will occur if the Maeslantkering does not close and the resulting water level exceeds the elevated surface levels.

1. Zone 1: Maasvlakte I, Maasvlakte II, Europoort
2. Zone 2: Botlek 1
3. Zone 3: Part of Botlek 2
4. Zone 4: Part of Botlek 2, Botlek 3, Vondelingenplaat

In Figure 4-11 the boxed areas show where the terminals of Vopak are located. The arrows in the figure also indicate how flooding will occur.

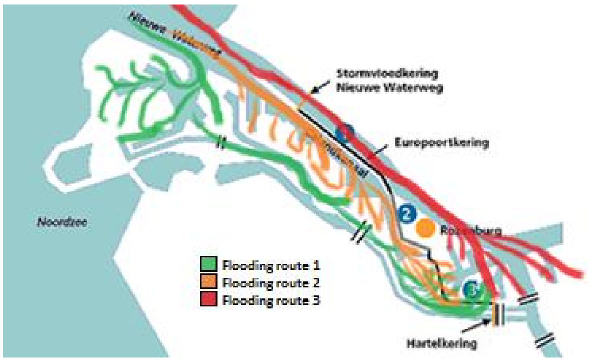


Figure 4-9 Flooding routes

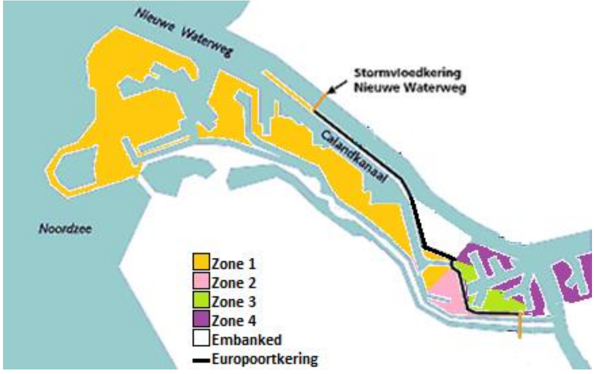


Figure 4-10 Flooding zones

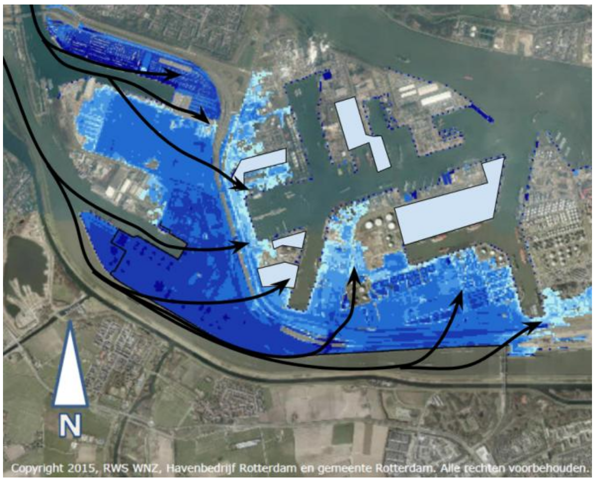


Figure 4-11 Flooding of zone 3 in detail
(Event with a probability of 1/10,000 in 2050)

4.4 Possible effects of inundation

The effect of an inundation event is possible damage to objects. Table 4-5 results from an evaluation of the terminal system as defined in paragraph 4.1.3 with qualitative risk assessments performed by Vopak and in the pilot 'Waterveiligheid Botlek'. Of the system considered in 4.1.3 only the utility gas is not considered to be damaged by inundation.

Table 4-5 Objects that are considered to be possible damaged by inundation

		Pilot 'Waterveiligheid Botlek) (Bonte, van Dijk, van Ledden, & Visch, 2016)	Vopak (Laurenshaven) (Royal Vopak, 2016)	Vopak (Neuhof) (Vopak Terminal Hamburg, 2014)
Electrical infrastructure		X	X	X
Central Control Room		X	X	X
Automation		X	X	X
Water treatment		X	X	X
Firefighting		X	X	X
Heating / Steam supply		X	X	X
Tank pits	Tanks	X	X	X
	Dikes	X	X	X
Pump pits		X	X	X
Pipelines		X	X	X
Nitrogen supply		X		X
General area (Loading stations, roads and other)				X
The utility gas				
Vapour treatment			X	

The risk assessment in this thesis considers an object from the system possible damaged by inundation if this results from one of these qualitative risk studies.

4.4.1 Influence of objects on risk categories

Of the possible damaged objects not all influence the risk in every category. In Table 4-6 it is stated which objects are considered for which risk category. This is based on the system of paragraph 4.1.3, and Table 4-5.

For the risk category fatalities the whole terminal is seen as the single object that is of influences. No other object has an influence on this risk category.

The objects that are of influence on the environmental risk follow from the storage part of the system; Pipelines, tank dikes/containment walls and tanks.

An object that is expected to receive damage from inundation and is owned by Vopak is included as direct damage in the economic risk category. The nitrogen supply is external and therefor excluded as direct damage but the effect of damage to the nitrogen supply is included as indirect damage. The choice is made to exclude damage to a tank or pipelines. The effect of such damage will be included in the environmental failure.

For the reputation damage the expected leading repair times of the assumed most critical systems are used. The pump pits, while expected to be critical for a functioning of the terminal, are expected to have less significant damage compared to the electrical infrastructure, automation, the central control room and the nitrogen supply.

Table 4-6 Considered objects and their assumed influence on the different risk categories

		Object effects the following risk categories:			
		Fatalities	Environmental	Economic	Reputation
Starred objects (*) are later seen to have no influence for the considered probabilities of flooding		Fatalities on site	Spills	Reparation costs General clean up Cost of downtime Does not include: Repair costs by tank failure	Downtime
Electrical infrastructure				X	X
Central Control Room				X	X
Automation				X	X
Water treatment*				X	
Firefighting*				X	
Steam supply*				X	
Tankpits	Tanks		X		
	Dikes		X	X	
Pump pits					
Pipelines*			X		
Nitrogen supply					X
General area (Loading stations, roads and other)				X	
Vapour treatment*				X	
‘Terminal’		X			

4.4.2 Event tree for each risk category

The event tree for fatalities

For a fatality due to inundation there needs to be inundation of the terminal. A inundation of part of the terminal leads to a number of fatalities in which this number can be below zero.

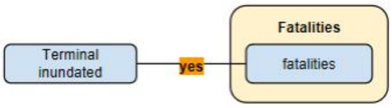


Figure 4-12 The fault tree for the risk category fatalities

The object list for the list of fatalities is limited to the object 'Terminal'.

Table 4-7 Object list for risk category fatalities

Object	Amount (#)				
	VTC	VTB	VTTTR	VTE	VTL
Terminal	1	1	1	[Fatalities were not considered for these terminals]	

The environmental event tree

When inundation of the terminal occurs water levels will not immediately rise inside the tank pits due a tank dike as containment wall. A tank spill will occur if a tank dike will fail and the tank fails with the inundation level that is present in the tank pit. There are however multiple tank pits, failure of one of those results in failure. Furthermore are there in a tank pit multiple tanks present. If there is tank dike failure, failure of one of those tanks results in a tank spill. For pipelines different types are considered for failure. If a pipeline fails, there is directly a pipe spill.

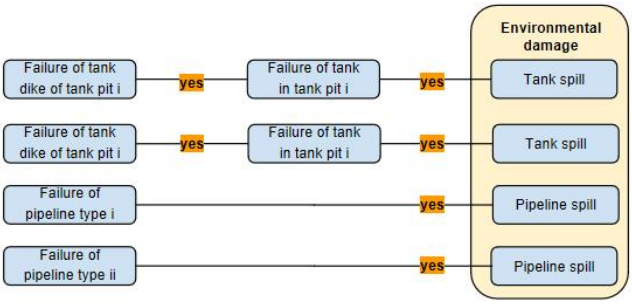


Table 4-8 Object list for risk category environmental

Object	Amount (#)				
	VTC	VTB	VTTTR	VTE	VTL
Tank pit (equals tank dikes)	10	30	9	20	5
Tanks	100	196	89	99	15
Pipeline types	8	8	8	8	8

Economic: the event tree for direct damage

The economic risk contains two parts. Indirect damage by downtime and direct damage by damage to installations. Figure 4-14 presents the event tree for the direct damage part. The direct damage only takes place when inundation of the object takes place onsite.

For example: multiple electrical stations, a CCR, multiple tank pits.

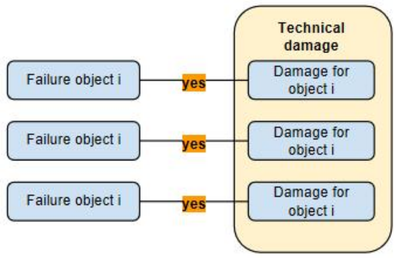


Figure 4-14 The event tree for direct damage of the risk category economical

Table 4-9 Object list for risk category direct damage

Object	Amount (#)				
	VTC	VTB	VTTTR	VTE	VTL
Electrical main station	1	[Information was not required due to no inundation onsite for the considered events]			1
Electrical sub station	3				3
Electrical sub sub station	10				0
Central Control Room	1				0
Water treatment	1				1
Firefighting	1				1
Steam supply	1				0
Tankpit dikes	10				5
Pump pits	7				1
General area (Loading stations, roads and other)	1				1
Vapour treatment	1				0

The event tree for the reputation damage

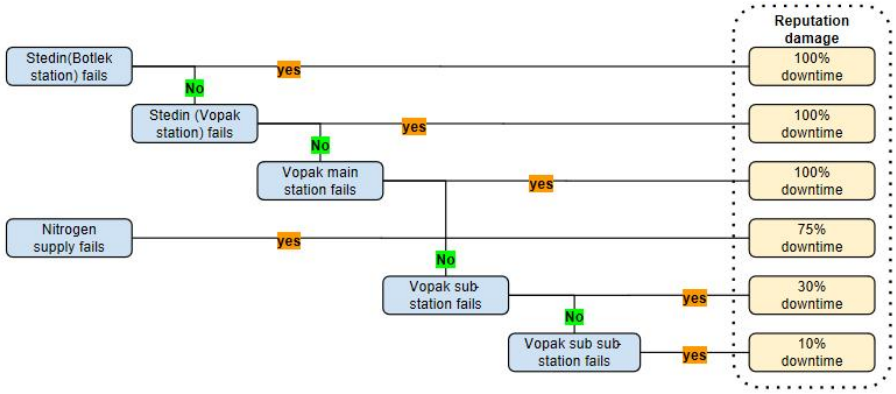


Figure 4-155 The event tree for the risk category reputation

For the reputation damage the event tree is a bit more extensive since offsite electrical stations are incorporated and failure of one of the electrical stations results in failure of the system. The fault tree is shown in Figure 4-15 with a visual explanation in Figure 4-16. Failure of the terminal of Vopak can occur due to failing of the Stedin station Botlek, Stedin station at Vopak or Vopak main station at Vopak. Failure of part of the terminal can occur to failure of the nitrogen supply, failure of a substation at Vopak or failure of a sub sub station at Vopak. The choice of this level of detail of the electrical utility is explained in Appendix E. The total damage or consequence is the highest of the different possibility damages.

Table 4-10 Object list for risk category reputation damage

Object	Amount (#)				
	VTC	VTB	VTTTR	VTE	VTL
Botlek station Stedin	1	1	1	[Reputation damage was not considered for these terminals]	
Mersey Station TenneT	0	0	1		
Connecting station Stedin	1	1	1		
Electrical main station Vopak	1	[Information was not required due to no inundation onsite for the considered events]			
Electrical sub station Vopak	3				
Electrical sub sub station Vopak	10				
Central Control Room	1				
Nitrogen supplier	1	1	1		

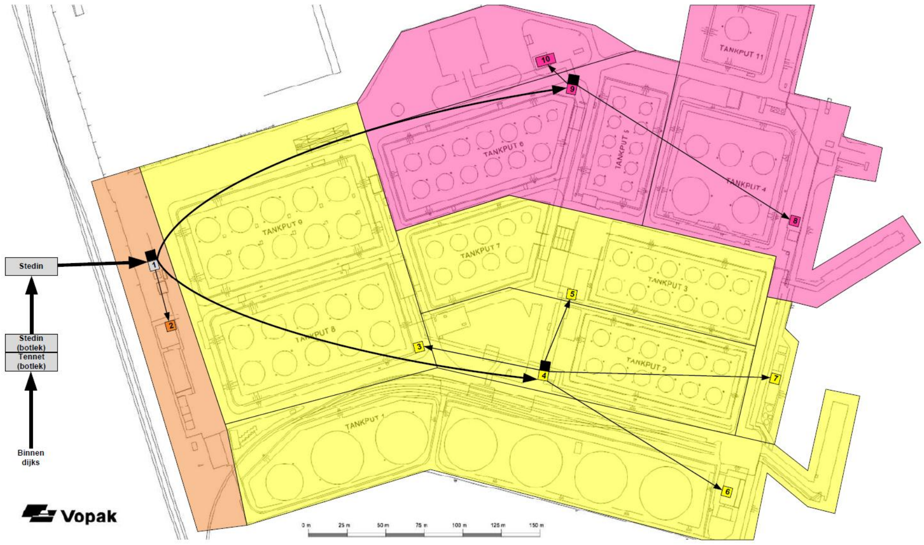


Figure 4-6 Electrical infrastructure to and on Vopak location Vopak terminal Chemiehaven

4.5 The probability of effects when inundated

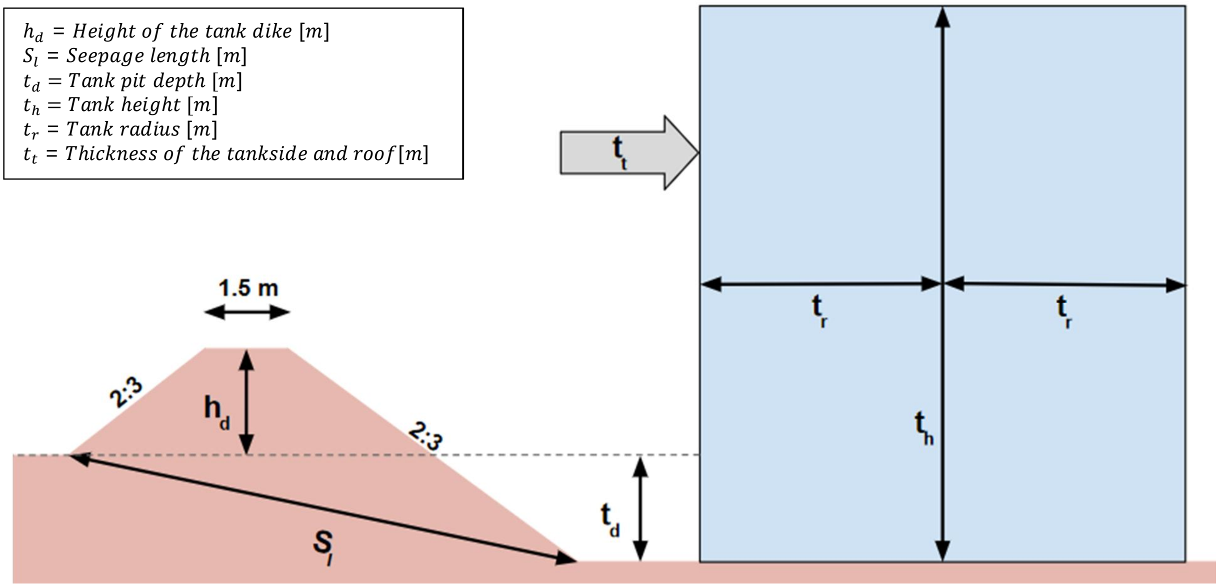
In this section the probability of the effect is stated given the undesired event. For k=1, k=3 and k=4 this probability is 1 and the inundation level is incorporated into the size of the consequence. For k=2, the environmental risk, the probability is defined in this section. For the environmental risk three objects are of influence; tank dikes, tanks and pipelines. These three objects are covered in this section.

4.5.1 Failure probability of the tank dike

In this thesis a failure limit is calculated for the tank dike type of containment wall. The failure limit used defines a inundation level wherefore a tank dike has a 0% probability of tank dike failure. If it exceeds the failure level, there is a 100% probability of tank dike failure and the tank pit is directly inundated equal to the terminal inundation level. Two approaches were considered for calculating the failure level of the tank dikes;

- Consider tank dikes as embankments to prevent inundation and calculate the strength accordingly with respect to stability, piping and overtopping. This an established approach for calculating strength of dikes.
- Consider tank dikes as containment dikes and mirror the design conditions. Normally product is inside in the tank pit, now the product is outside. This approach follows more closely the standards for tank dikes.

A combination of both approaches is used. The basic consideration is that the tank dikes are considered as containment dikes which hold the product out supplemented with considering them as river dikes to account for overtopping and conductivity (seepage).



h_d = Height of the tank dike [m]
S_l = Seepage length [m]
t_d = Tank pit depth [m]
t_h = Tank height [m]
t_r = Tank radius [m]
t_t = Thickness of the tankside and roof [m]

Figure 4-16 Dimension parameters for tank and tank dike failure calculations

Sliding

The tank dike is designed for a certain level of liquid inside the pond and has a symmetrical inner and outer slope. Therefor it is used that the strength on the outside is equal to the design strength of the inside. This results in meeting failure when the difference between water level and ground level on the other side for inundation has to be larger compared to inundation by tank failure for failure to occur due to sliding. The choice is made to assume a minimum stability against sliding which provides resistance for 0.5 meter of inundation.

Equation 7 $$d_s > \max(0.5, h_d - t_d)$$

d_s = Inundation level of failure of the tank dike due to sliding [m]

Overtopping

The second condition for non-failure is an adequate amount of freeboard to prevent the amount of overtopping. Failure due to erosion of the inner slope will otherwise occur. The wave height formula for shallow water gives a maximum of ½ times the water level as wave height.
In the inundation models for the Botlek the assumed value for the wave height is 0.3 m at the Hartelkanaal (half of the calculated height) (Nicolai, Botterhuis, Pleijter, Huizinga, & Stijnen, 2016).
The wave run-up from the practice at embankments (van der Meer, 2002) results in a required freeboard of ~3 times the wave height.
These pieces of information combined result in a required freeboard of 0.75 times the inundation level.

Equation 8 $$d_o > \frac{h_d}{1 + 0.75}$$

$d_o = Inundation\ level\ of\ failure\ of\ the\ tank\ dike\ due\ to\ overtopping\ [m]$

Conductivity

The water pressure can propagate into the soil with a velocity following Darcy's law. A flood duration of 2 days (Bonte, van Dijk, van Ledden, & Visch, 2016) with a linear increase and decrease to the inundation peak is assumed. Therefor for the pressure difference the average is used; which a duration of 2 days this equals one day of the peak inundation. The tank dike is assumed to be made of the same material as the local soil except for a liquid tight top layer. The local soil for the Chemiehaven is for example a combination of clay and fine sand (Industrial Design and Development services B.V. Milieu en Techniek, 1999). The average hydraulic conductivity of fine sand (5 m/day) is therefor used. The seepage is considered to occur from the surface level to the tank pit bottom. The slopes of a tank dike are 2:3 and the width of the crest is 1.5 meter (Royal Vopak, 2002). This results in a seepage length as is shown in Figure 4-17 and calculated with Equation 9.

Equation 9 $$S_l = \sqrt{}((1.5 + h_d \cdot \tfrac{3}{2} + (h_d + t_d) \cdot \tfrac{3}{2})^2 + t_d{}^2)$$

Equation 10 $$d_c > {}^{S_l}\!/_{S_c} - t_d = \frac{\sqrt{}((1.5 + h_d \cdot \frac{3}{2} + (h_d + t_d) \cdot \frac{3}{2})^2 + t_d{}^2)}{S_c} - t_d$$

$d_c = Inundation\ level\ of\ failure\ of\ the\ tank\ dike\ due\ to\ conductivity\ [m]$
$S_c\ = Soil\ conductivity\ = 5\ [\ m/day]$

Combined failure

It depends on the specific tank dike which failure mechanism occurs first. For the failure of the tank dike the lowest value of the three mechanism is used after it is calculated for each inundated tank dike. Equation 11 combines Equation 7,8 and 10 to calculate the inundation level of failure of the tank dike

Equation 11 $$d_f = Min(d_s, d_o, d_c)$$

$d_f = Inundation\ level\ of\ failure\ of\ the\ tank\ dike\ [m]$

Observations on tank dike height are convenient in everyday practice. Therefore, for general application purposes the inundation level of failure is in Figure 4-18 given relative to the tank dike height. In this figure a relation between the tank dike height and the tank pit depth is used from Appendix G. In this appendix an relation for the Vopak tank dikes is deducted which outperforms the known tank pits on the aspect of failure level of the tank dikes.
The horizontal line results from the fact that the tank dike strength is also related to the tank pit depth.

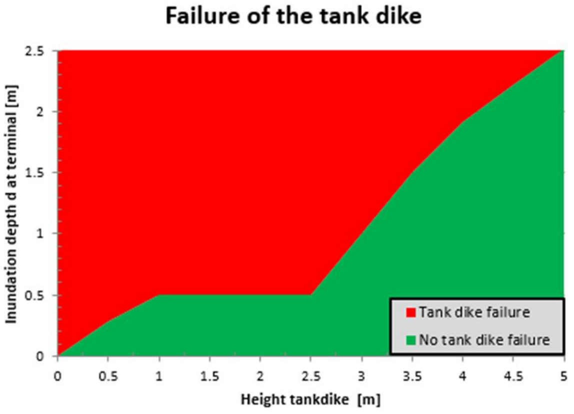


Figure 4-17 Failure of the tank dike

4.5.2 Failure probability of the tanks

When the tank dike fails the inundation level inside the tank pit will be higher than the inundation level outside of the pit. This follows from the location of the tank pits; these are located below surface level.

Failure of the tank is occurring due to floating or when it buckles due to an outside pressure. Following the literature about failure at tank storage, as introduced in 2.3.3, it is chosen to consider floating without anchoring of the tanks as the failure mechanism with a uniform distributed filling level of the tank. This results in the failure function as Equation 12 with the dimension parameters explained in Figure 4-19.

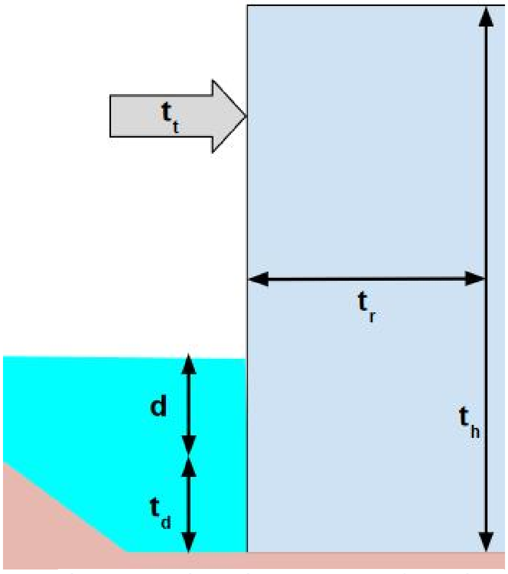


Figure 4-18 Dimension parameters for tank failure calculations

Equation 12
$$p\,(d) = \frac{(d + t_d)\cdot\left({}^{\rho_w}/_{\rho_l}\right) - {}^{t_w}/_{\rho_w}}{t_h}$$

$p(d) = Probability\ of\ failure\ tank\ as\ a\ function\ of\ the\ inundation\ level$ [%]
$\rho_w = Density\ of\ salt\ water$ = 1025 $[kg/m^3]$
$\rho_l = Density\ of\ the\ liquid\ stored\ [kg/m^3]$

The t_w is the downwards pressure of the tank as will be defined with Equation 13.

Equation 13
$$t_w = \frac{(\pi {t_r}^2 \cdot t_t + t_h \cdot 2\pi t_r \cdot t_t)\cdot \rho_s}{\pi \cdot {t_r}^2}\ [kg/m^2]$$

$\rho_s = Density\ of\ steel$ = 7800 $[kg/m^3]$
$t_w = Downwards\ pressure\ of\ the\ tank\ [kg/m^2]$

For every tank that is possible inundated the tank failure probability is calculated with Equation 12.

Examples

In Figure 4-23 failure probability functions for tanks are depicted relative to the inundation level at the terminal surface level. Tanks at Vopak are near always located below surface as is shown in figure 4-20. Therefor a limited inundation at surface level will result in a possible inundation of meters in the tank pit.
This leads to:
- *For an inundation level of 0 meter the probability of failure is still zero*
- *For an inundation level of >0 meter the probability of failure jumps after which the failure function rises gradually*

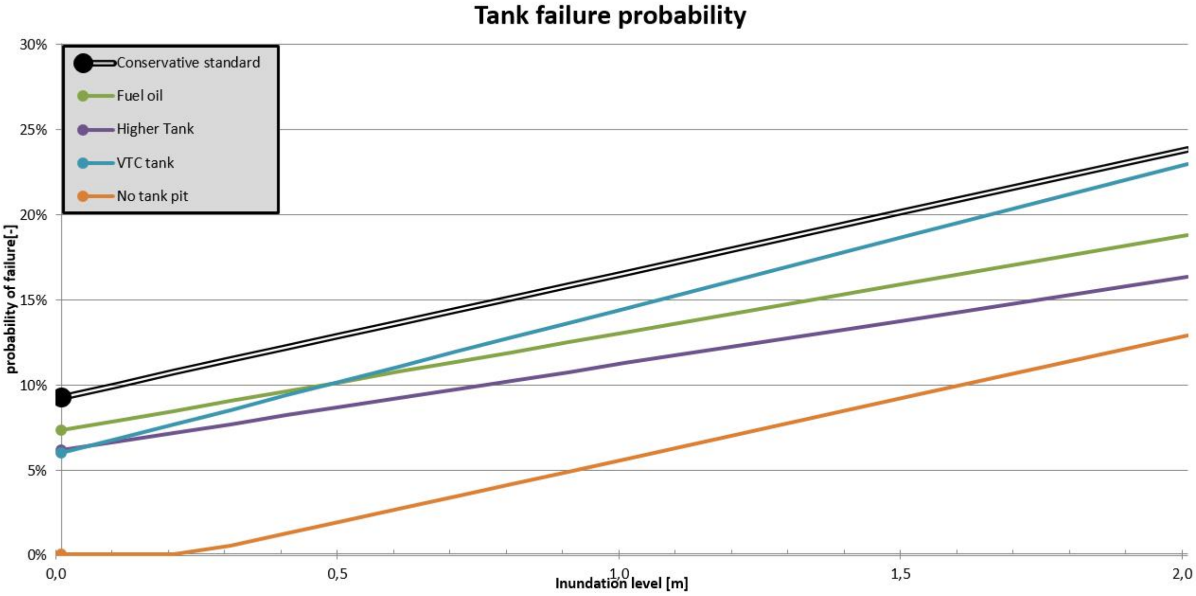


Figure 4-19 Example of Tank failure probability functions

In Figure 4-20 examples of tank failure probability functions are shown if the tank dike fails. The input is shown in Table 4-11. where the grey cells depict the cells that are altered from the conservative standard value. The 'conservative standard' presents a tank with combination of parameters that negatively influence the failure probability within reason. Reason in this case means. Unique parameters and combinations that do not occur in reality are filtered.

Table 4-11 Tank failure parameters

Name:	$t_d[m]$	$\rho_l\ [kg/m^3]$	$T_h[m]$	$t_r[m]$
Conservative standard	1.5	670	21	20
Fuel oil	1.5	850	21	20
Higher tank	1.5	670	30	20
VTC tank	1	670	18	12
No tank pit	0	670	21	20

Failure of multiple tanks

For Vopak it is interesting to know the probability of failure of one or more tanks of a tank pit. With this information Vopak can adhere to legal limits. The probability of failure of a tank in a tank pit is calculated with Equation 14.

Equation 14 $$p_x = 1-(1-p(d))^{t_n}$$

$p_x = likelihood\ one\ or\ more\ tanks\ will\ fail\ due\ to\ inundation\ [\%]$
$t_n = number\ of\ tanks\ in\ tank\ pit\ [\#]$

4.5.3 Floating of pipelines

When the pipelines will inundate the uplift force might cause them to float and possible break. To consider the probability of this effect for Vopak pipeline sizes it is calculated what the possible uplift force due floating is compared to the downforce.

The connection of the pipelines is not solely gravity based at Vopak. They are also connected by clamps which increase the resistance against floating. The strength of these clamps is however uncertain. It is estimated to be over 25 kg/m by the technical feedback session (Westerduin, Oorschot, & Blom, 2016). The total resisting force against floating consists of the weight of the pipes, the weight of the product and strength of the clamps.

Equation 15 $$L_d = \rho_s \cdot ((2 \cdot \pi \cdot L_r) \cdot L_t) + \rho_l \cdot (\pi \cdot (L_r - L_t)^2)$$

$L_d = Downward\ force\ on\ filled\ pipeline [kg/m]$
$L_r = Pipeline\ radius\ [mm]$
$L_t = Pipeline\ thickness\ [mm]$

Equation 16 $$L_f = (\pi \cdot {L_r}^2) \cdot \rho_w$$

$L_f = Maximum\ floating\ force\ on\ pipeline [kg/m]$

Failure occurs if $L_d \leq L_f$.

With Equation 15, Equation 16 and the data from Table 4-12 it is calculated that without taking the clamps into account at filled pipelines the downforce will be larger than the floating force The weight of the pipeline itself balances the lesser weight of the product compared to the salt water. With these results the probability of this effect is zero. This is even the case for the nitrogen lines, where the density of the product transported is equal to the density of air.

Table 4-12 Pipeline data from Vopak

	Fuel Oil lines				Naphtha lines		Nitrogen lines		
	36 inch	24 inch	20 inch	16 inch	20 inch	16 inch	8 inch	4 inch	
Thickness (L_t):	7.92	6.35	6.35	6.35	6.3	6.3	6.3	6.3	mm
Diameter ($L_r \cdot 2$):	914.4	609.6	508	406.4	508	406.4	203.2	101.6	mm
Steel density (ρ_s):	7800	7800	7800	7800	7800	7800	7800	7800	kg/m^3
Water density (ρ_w):	1025	1025	1025	1025	1025	1025	1025	1025	kg/m^3
Product density (ρ_l):	850	850	850	850	670	670	1.2	1.2	kg/m^3
Downward force (L_d):	177	95	79	63	78	63	31	16	kg/m
Max. floating force (L_f):	111	49	34	21	68	43	29	6	kg/m
Effective downforce	+66	+46	+45	+42	+10	+20	+2	+10	kg/m
Uplift force:	NO	NO	NO	NO	NO	NO	NO	NO	

4.5.4 Total Failure function

Pipeline failure will not occur with the assumptions made. An environmental consequence will therefor occur when there is failure of a tank dike and a successive failure of the tank. The equation for the probability of environmental consequence is shown in Equation 17.

Equation 17
$$p_{2,ji} = \begin{cases} \dfrac{(d_{ji} + t_{di}) \cdot \left({}^{\rho_w}/_{\rho_{li}}\right) - {}^{t_{wi}}/_{\rho_w}}{t_{hi}} & if\ \ d_{ji} > d_{fi} \\ 0 & if\ d_{ji} \leq d_{fi} \end{cases}$$

$p_{2,ij} = Probability\ of\ failure\ tank\ pit\ i\ for\ inundation\ event\ j$

Table 4-13 shows the tank pits that are inundated for one of the inundation events are stated, grouped by terminal. The shifting of all the tank pits to the ones that are inundated is made by an visual representation of the inundation data. The list is supplemented with tanks that are close to the inundated area. ‘Close’ is defined as 50 meters.

Table 4-13 Inundated tank dikes, and the failure probability of the tank pit

							$j = 5$	$j \leq 4$	$j = 5$
Terminal	Number	i	t_{di}	h_{di}	d_{fi}		d_{ji}	d_{ji}	$p_{2,i}$
VTL	2001-2003	1	0.8	1.1	0.5		<0.25	0	0
VTL	2004-2006	2	1.4	0.8	0.2		0.14	0	0
VTL	2007-2009	3	1.4	0.8	0.2		0	0	0
		i							
VTC	1	1	0.5	0.5	0.3		0.12	0	0
VTC	3	2	1.1	2.6	1.4		0	0	0
VTC	6	3	2	2.4	0.5		0	0	0
VTC	8	4	1	2	1.0		<0.1	0	0
VTC	9	5	1	1.4	0.5		<0.1	0	0
		i							
VTE	030	1	1.5	3.5	1.8		<0.25	0	0
VTE	100	2	1.5	3.3	1.7		<0.25	0	0
VTE	101	3	1.3	3.4	1.8		<0.25	0	0
VTE	103	4	1.3	2.5	1.2		<0.25	0	0
VTE	104	5	1.8	4.6	2.4		<0.25	0	0
VTE	107	6	0.9	3.3	1.9		<0.25	0	0
VTE	140	7	1.1	3	1.7		<0.25	0	0
VTE	902	8	5	1.3	0.0		0.31	0	13%

4.6 The consequence of failure

In this section the consequences are stated for effects that occur due to inundation. For some of the effects from section 4.4 the probability is zero for the considered inundation events. This results from a zero inundation level at the object(s) for every inundation event or it results from a calculated failure probability of zero independent from the inundation level. In Table 4-14 it is stated for which objects this applies and hence there is no consequence size defined for these objects.

Table 4-14 Effects from the qualitative studies that have a zero probability of occurrence

Object	Parameter
Pipelines	$p_{2,j} = 0$
Water treatment	$q_j = 0$
Firefighting	$q_j = 0$
Steam supply	$q_j = 0$
Vapour treatment	$q_j = 0$

4.6.1 Fatalities

The consequence of inundation for the risk category fatalities is the drowning of the people present at the terminal. An assumption is made of an operating crew present on a terminal during inundation; ten persons will be present during such event. This is in line with the average night time shift. The mortality fraction is within the pilot 'Waterveiligheid Botlek' estimated on 0.2% for the kind of flooding the Vopak terminals experience (Bonte, Dijk, Ledden, & Visch, 2016).

Equation 18

$$C_{1,j} = {}^{A_j}\!/_{A_t} \cdot M \cdot F$$

$C_{1,j} = Consequence\ fatalities$
$M = Mortality\ fraction = 0.2$ [%]
$F = Number\ of\ people\ present\ on\ a\ terminal = 10$ [#]
$A_j = Area\ of\ the\ terminal\ inundated\ with\ inundation\ event\ j$ $[m^2]$
$A_t = Total\ area\ of\ the\ terminal$ $[m^2]$

Table 4-15 Inundated area for the different terminals

	VTC	VTB	VTTTR
	A_t = 140,000 $[m^2]$	A_t = 580,000 $[m^2]$	A_t = 220,000 $[m^2]$
	$A_j[m^2]$	$A_j[m^2]$	$A_j[m^2]$
$j = 1$	0	0	0
$j = 2$	0	0	0
$j = 3$	7000	0	0
$j = 4$	8400	0	0
$j = 5$	10400	0	0

Monetizing the consequence

For the monetizing of fatalities, the VOSL will be used (Value Of a Statistic Life). This follows the same approach of an economical weighing of the protection in dike rings. This VOSL is based on research into how much people were willing to spend individually to reduce flood risk. A monetary value for a fatality of €7.4 million is used in this thesis which is the 2016 value of €6.8 million (Bockarjova, Rietveld, & Verhoef, 2012).This value is higher than the value used for road safety, this would be €2,240,000 in current day prices (Mobility and transport, Road Safety, n.d.). Or higher than the value the UK government proposes to assess flood risk with; this is at €1,850,000 (Defra, 2008).

M_1 = 7,400,000 [€/fatality]

The VOSL is not an exact figure it ranges between 400,000 to 30 million in 1996 U.S. dollars (Blaeij, Florax, Rietveld, & Verhoef, 2000). This uncertainty is not considered extensively in this thesis. With the results of the following chapter it can be seen that when the high end of these numbers is chosen this still results in a 200 fold smaller expected costs of human life than the expected economic costs.[6]

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[6] For VTC: 1.07*10E-6 x max VOSL= €43 a year. Compared to an economic risk of €7,373 a year

4.6.2 Environmental

An environmental consequence results from a failure of the tank. Assumed is a loss of 25% of the tank content present. This follows the spill percentage of damage by a flood in Louisiana, USA (Atherton & Ash, 2006). In line with the literature a uniform filling distribution was assumed for the failure function, hence the same is done for the consequence. This results in an average filling of half the level of the tank for which the tank fails. This results in Equation 19.

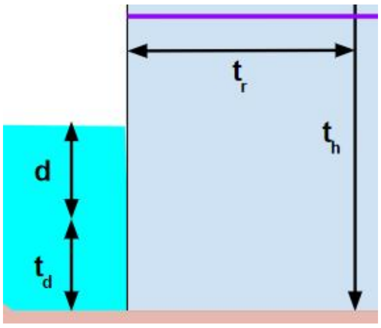


Figure 4-21 Spill size dimension parameters. Purple depicts maximum fluid level for failure

Equation 19
$$C_{2,ji} = S_p\left(0.5\cdot\left(\left((d_{ji}+t_{di})\cdot\left({}^{\rho_w}/_{\rho_{li}}\right)-{}^{w_t}/_{\rho_w}\right)\cdot\pi t_{ri}{}^2\right)\right)\cdot t_n$$

$C_{2,j} = Consequence\ environmental\ [litres]$
$S_p = Spill\ percentage$ = 25 [%]

Table 4-16 Example values with an fictive assumed d_{ji} of 0.5m

Tank	(*i* is here tank dependent and therefor equal to Table 4-13) i	t_d $[m]$	t_r $[m]$	w_t $[kg/m^2]$	ρ_l $[kg/m^3]$	ρ_w $[kg/m^3]$	C_2	
								$[litre]$
VTE030	1	1.5	21	343	670	1025	à	471,928
VTE103	4	1.3	21	281	670	1025	à	429,415
VTE902	8	5	30	312	850	1025	à	2,236,487
	i							
VTC8	4	1	12	312	670	1025	à	112,554
VTC9	5	1	12	312	670	1025	à	112,554

Practical example: For VTE902 the inundation level d_{ji} is 0.31 meter for inundation event j=5 (q_5=1/10,000) which results in the size of a spill of;

$$C_{2,5,8} = 0.25\left(0.5\cdot\left(\left((0.31+5)\cdot\left({}^{1025}/_{850}\right)-{}^{429}/_{1025}\right)\cdot\pi\cdot 30^2\right)\right) = 2{,}155{,}510\ [litres]$$

Monetizing the consequence

For the environmental consequence the costs are assumed to be linearly related to the amount of the product spilled. A monetary value is set on a litre of spill.

The clean-up cost of spills is in this thesis based on the following data:

- A tank collapse at the Ashland oil company in 1988 would cost around €10.4/litre when adjusted for inflation (Sovacool, 2008).
- The paper ‘a taxonomy of oil spill costs’ (Cohen, 2010). It is from sea based tankers where the cleaning cost has an average value of €4/litre
- A Worldwide Analysis of Marine Oil Spill Clean-up Cost Factors (Schmidt Etkin, 2000) With the density of naphtha (670kg/1000 litre) and using the location Europe the costs are would be €8/litre on average.

The value of €10 a litre is used since this is a spill by a tank collapse. The possible extra costs due to spread of the spill due to the flooding is not taken into account.
$M_2 = 10\ [€/\text{litre}]$

This results in 21.6 million Euro for the failure of the tank VTE902 due to 0.31 meter inundation on site and a 5.31 meter inundation in the tank pit.

The floating of small spills that are located inside pump pits are not a significant risk, this is contrary to common assumptions. This is shown with the following example: With the current method and a assumed consequence of 100 litres this will results in an annual risk at Laurenshaven of €0.5. Of the Botlek terminals only the Laurenshaven experiences inundation of a pump pit.

4.6.3 Economical

For the different objects different consequence functions are used as stated in Equation 20. Option A relates the damage as percentage of the RV to the inundation level at a specific point where option B and C relate to a percentage of the considered object inundated. In Table 4-17 is the RV or damage value for each object stated. These values are based on the assessment of the flood risk at the Vopak terminal Neuhof (Appendix B), in combination with Vopak engineering estimates (Westerduin, Oorschot, & Blom, 2016).

Equation 20
$$C_{3,j} = \left(C_{4,j} \cdot M_k\right) + \left(\sum_{i=1}^{n_A} \left(DP_{ij} \cdot RV_i\right) + \sum_{i=1+n_A}^{n_B+n_A} \left(A_{ij} \cdot DA_i\right) + \sum_{i=1+n_B+n_A}^{n_C+n_B+n_A} \left(DV_i \cdot IP_{ij}\right)\right)$$

$C_{3,j} = Consequence\ for\ the\ economic\ risk\ category\ for\ inundation\ event\ j\ [€]$
$DP_{ij} = Damage\ percentage\ for\ object\ i\ for\ inundation\ event\ j\ [\%]$
$RV_i = Replacement\ value\ of\ object\ i\ [€]$
$A_{ij} = Object\ area\ i\ that\ is\ inundated\ for\ event\ j\ [m^2]$
$DA_i = Damage\ value\ of\ object\ with\ an\ area\ i\ [€/m^2]$
$DV_i = Damage\ value\ of\ object\ i\ [€]$
$n_A = Objects\ calculated\ with\ damage\ function\ [\#]$
$n_B = Objects\ calculated\ with\ a\ damage\ value\ per\ square\ meter\ inundated\ [\#]$
$n_C = Objects\ calculated\ with\ with\ a\ value\ per\ object\ inundated\ [\#]$

Table 4-17 Replacement and damage values

		Unit	RV_i	Remarks
n_A	Electrical infrastructure	Electrical substation	€500,000	Added factor of 2.5 over base cost substation to include smaller electrical infrastructure
	Central Control Room	CCR	€1,000,000	One per terminal
	Automation	Electrical substation	€200,000	Same unit as electrical infrastructure
	Pump pits	Pump pit	€1,000,000	
			DA_i	
n_B	General area	€/m^2	€150	Includes washed out streets and railroads. Assumed 10% of terminal site when no further data is present
			DV_i	
n_C	Tank pit dikes	€/Tank pit	€250,000	
	General area clean up	€/Terminal	€1,000,000	

Damage functions

A damage function is defined for the object groups that have their consequence defined with option A. These functions are shown in Figure 4-22.

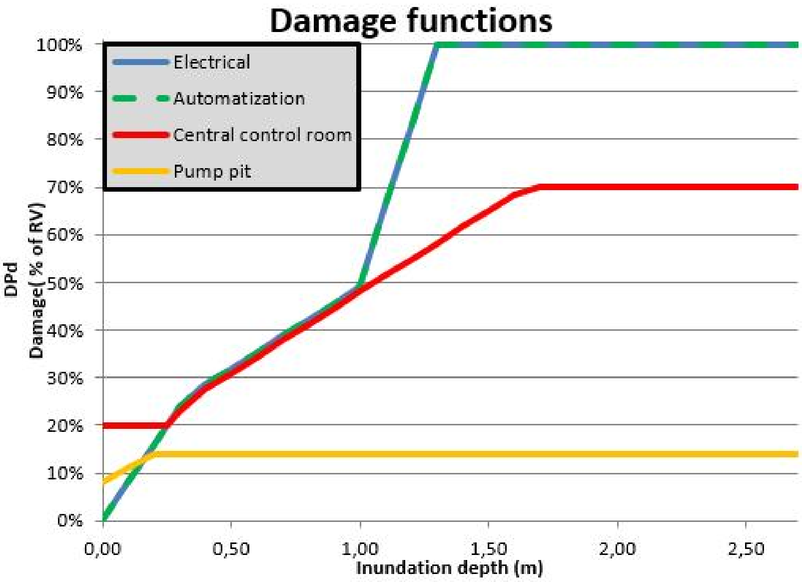


Figure 4-20 Damage percentages relative to the inundation level

<u>Electrical</u>

The damage by flooding is assessed with the damage functions from Rijkswaterstaat (Kok, Huizinga, Vrouwenvelder, & Barendregt, 2004). This electrical damage function is non-specific and is an average over a large area. Non-specific in this case means that the same function can be used for urban, industrial, and rural land uses in the Netherlands. For unembanked areas a reduction factor is advised for the data from the standard method (Zethof, Huizinga, Kok, & Maaskant, 2011). The assessment in this thesis uses detailed surface levels and object levels instead of applying this reduction factor. The use of an individual object level introduces this reduction factor implicitly.

The numbers of Rijkswaterstaat have been compared with indications from Stedin and TenneT, this showed similar expected damage percentages (Appendix F). Additionally, in the range of 0-1 m inundation the damage function was in line with expectations by Vopak engineers (Westerduin, Oorschot, & Blom, 2016). For higher inundation levels Vopak is more likely to fully replace a damaged unit. This stance results in a 100% damage value at a lower inundation level compared to the original damage function. The line of electrical damage in Figure 4-22 depicts the end result of the three steps.

<u>Automation</u>

The automation part is considered equal as electrical systems in the standard method (Kok, Huizinga, Vrouwenvelder, & Barendregt, 2004). The category that covers damage to automation is named Electrical & Communication. Even more, almost all infrastructure for the automation of the terminal is placed in electrical (sub)stations. Therefor the same damage function is used as for electrical. This was in line with expectation by Vopak engineers. Where however a specific sensitive point was indicated; the processing backbone of the automation is the costliest part to replace (Westerduin, Oorschot, & Blom, 2016). This specific sensitive point is not shown in the damage function.

<u>CCR</u>

The damage function for the CCR building is assumed similar to the one of automation and electrical with a certain modification. The CCR is assumed to have higher initial damage and a lower amount of maximum damage. Figure 4-22 shows the damage function.

<u>Pump pits</u>

The location of the pumps below surface level result in a relative high level of damage for a low inundation level. However, in practice it is seen that the level of damage to such pump pit is, for fresh water, very low to near zero. In this type of flooding the water is salt and therefor higher damage values are assumed, the result is shown in Figure 4-22.

Table 4-18 Chemiehaven economic consequence

	Inundated parts	i	RV x1000	DP_j					C_j (x€1000)				
				j = 1	j = 2	j = 3	j = 4	j = 5	j = 1	j = 2	j = 3	j = 4	j = 5
n_A	Electrical main station	1	€500	-	-	18%	23%	29%	-	-	90	115	145
	Automation main station	2	€200	-	-	18%	23%	29%	-	-	36	46	58
	CCR	3	€1,000	-	-	30%	32%	34%	-	-	300	320	340
				A_{ij}									
			DV_A x1000	j = 1	j = 2	j = 3	j = 4	j = 5	j = 1	j = 2	j = 3	j = 4	j = 5
n_B	General area, Roads	4	€150 /m²	-	-	7000 m²	8400 m²	10400 m²	-	-	1050	1260	1560
				IP_j									
			DV_i x1000	j = 1	j = 2	j = 3	j = 4	j = 5	j = 1	j = 2	j = 3	j = 4	j = 5
n_C	Tankdikes 8	5	€250	-	-	50%	50%	50%	-	-	125	125	125
	Tankdikes 9	6	€250	-	-	50%	50%	50%	-	-	125	125	125
	Tankdikes 1	7	€250	-	-	50%	50%	50%	-	-	125	125	125
	'Terminal cleaning'	8	€1,000	-	-	25%	25%	25%	-	-	250	250	250
				$C_{4,j}$									
			M_k x1000	j = 1	j = 2	j = 3	j = 4	j = 5	j = 1	j = 2	j = 3	j = 4	j = 5
Downtime			375 €/week	-	0.32	9.6	15.7	18.3	-	120	3600	5888	6863
								C_3 à	-	120	5698	8008	9342

4.6.4 Reputation

The reputation is expressed in downtime of the terminal. Therefor the recovery and repair time are the leading factor for this category.

Repair time

The information on the electrical repair time is acquired from Stedin (Stedin, 2016 (received)) and are supported by TenneT. For the repair time of the CCR the relation with electrical works as in Figure 4-22 is followed. For the repair time of the nitrogen, values are estimated by the nitrogen supplying company (Air Products, 2016). For the nitrogen company this is specific for the Rotterdam situation. The results of this are shown in Table 4-19.

Recovery time

The recovery time and the repair time of the terminal are correlated but not equal. The recovery time also takes temporary fixes into account. Temporary fixes can provide function while structural repairs are under way and reduce the effective downtime. For example, the expected time to get a terminal running on an emergency aggregate is a few days in a normal situation.

The recovery time depends on the extent of the damage. When the power failure is external it is relatively easy. When damage is present in multiple substations of the terminal the difficulty of recovery rises steeply. The Vopak engineering expectation is three weeks downtime for the kind of inundation that occurs at the Chemiehaven with a 1/10,000 year probability until temporary fixes are in place (Westerduin, Oorschot, & Blom, 2016).

In a disaster situation the temporary fixes are more difficult or not an option at all, due to scarcity of equipment and/or manpower (Appendix D). Therefor the probability of a successful temporary fix in three weeks is assumed at 50% by the author. This results in Equation 21 to calculate the reputation consequence.

Equation 21

$$C_{4,j} = z \cdot 3 + (1 - z) \cdot \frac{1}{s} \sum_{l=1}^{s} \max_{i}(S_{li})$$

$C_{4,j} = Consequence\ reputation\ for\ inundation\ event\ j\ [weeks]$
$z = Probability\ of\ succesfully\ appliance\ of\ temporary\ fixes\ = 50\ [\%]$
$s = Number\ of\ simulations\ used\ to\ account\ for\ local\ uncertainty\ in\ unindation\ level\ = 10{,}000\ [\#]$
$S_{li} = Repair\ time\ of\ object\ i\ for\ simulation\ l\ [weeks]$
$x_{li} = random\ generated\ number\ on\ [0{,}1]\ for\ each\ scenario\ l, object\ i\ [-]$
$d_{ji} = inundation\ depth\ at\ object\ i\ for\ inundation\ event\ j\ \ [m]$
$d_{ln} = adjusted\ inundation\ depth\ at\ object\ n\ for\ scenario\ l\ \ [m]$
$\sigma = standard\ deviation\ of\ inundation\ depth\ = 0.125\ [m]$
$DT_{iu} = Repair\ time\ of\ object\ i\ for\ an\ inundation\ level\ between\ b_u\ and\ b_{u+1}\ [weeks]$
$\mathrm{b}_u = Inundation\ boundary\ b\ for\ repair\ time\ DT\ \ [m]$

Where S_{li} results from Equation 22.

Equation 22

$$S_{li} = \begin{cases} DT_1 & \text{if } b_1 \le norminv(x_{li}, d_{ji}, \sigma) < b_2 \\ DT_2 & \text{if } b_2 \le norminv(x_{li}, d_{ji}, \sigma) < b_3 \\ DT_3 & \text{if } b_3 \le norminv(x_{li}, d_{ji}, \sigma) < b_4 \\ DT_4 & \text{if } b_4 \le norminv(x_{li}, d_{ji}, \sigma) < b_5 \\ DT_4 & \text{if } b_5 \le norminv(x_{li}, d_{ji}, \sigma) \end{cases} \qquad [weeks]$$

The repair time *DT* for different inundation boundaries is in Table 4-19 presented for the different objects.

Table 4-19 Repair time

Inundation boundary		Repair time DT_i [weeks]				
		Electrical substations			CCR	Nitrogen
		Vopak	Stedin	TenneT	Vopak	Air Products
u	b	DT	DT	DT	DT	DT
1	0.00 m	0	0	0	0	0
2	0.25 m	2.5	2.5	0	2.5	0
3	0.50 m	32.5	32.5	0	5	2.5
4	1.00 m	32.5	104	104	5	11.5
5	2.00 m	32.5	104	104	5	18

When the numbers from Stedin and TenneT for the substations, Table 4-19, were evaluated with Vopak experience, it was considered that in a normal situation a half year to repair (read: replace) an electrical substation is applicable. However, the expectation was that this is done quicker when necessary, which is likely balance to the increased repair times due to scarcity of resources and personnel (Appendix D). For the higher inundation levels, the lower increase in repair time was expected. The inundation of smaller electric parts increase the repair time. However Vopak engineers expected the short inundation duration and water resistant parts to result in less extensive repairs (Westerduin, Oorschot, & Blom, 2016).

For the loss of the nitrogen supply this thesis uses an equivalent weeks value. When the repair time of the nitrogen supply leads the amount of downtime, the downtime is multiplied by the percentage of the terminal that requires nitrogen to function.

Table 4-20 Inundation level input from model

	Objects			
	Stedin Botlek	Vopak VTC main	Vopak CCR	Nitrogen
	i = 1	i = 2	i = 3	i = 4
	$d_{ji}[m]$	$d_{ji}[m]$	$d_{ji}[m]$	$d_{ji}[m]$
j = 1	0	0	0	0
j = 2	0.1	0	0	0.26
j = 3	0.48	0.22	0.44	0.63
j = 4	0.63	0.29	0.51	0.78
j = 5	0.75	0.40	0.57	0.93

Table 4-21 Calculating reputation consequence for inundation event j=3 at terminal Chemiehaven

Scenario	Objects												Max S_{ln}
	Stedin Botlek i=1 d=0.48			Vopak main i=2 d=0.22			Vopak CCR i=3 d=0.28			Nitrogen i=4 d=0.63			
	x_l	d_l	S_l	x_l	d_l	S_l	x_l	d_l	S_l	x_l	d_l	S_l	
1	0.59	0.51	32.5	0.55	0.24	0	0.97	0.51	5	0.21	0.53	2.5	32.5
…	0.53	0.49	2.5	0.58	0.24	0	0.11	0.13	0	0.64	0.67	2.5	2.5
s=10000	0.69	0.54	32.5	0.86	0.35	2.5	0.74	0.36	2.5	0.57	0.65	2.5	32.5
Average repair time over s scenarios in weeks à													16.2
$C_{4,3}$ $[Weeks]$ à													9.6

Monetizing the consequence

The reputation consequence is expressed in weeks' downtime and therefor the consequence is monetized by using the missed income. The additional reputation costs next to the missed income are not covered in monetizing the consequence when using this method. One can presume that the reputation consequence will always lead to an equal or lower monetized costs than the economic consequence. However, the reputation consequence can be a leading risk category since in the risk evaluation a reduction of the reputation risk is valued higher which lead in a higher value of the CB-ratio for reputation category.

Table 4-22 Terminal area and estimated weekly income

Terminal	$A_t\ [km^2]$	M_4 [€/$week$]	[€/m^2/week
Hamburg Neuhof	0.29	0.75 million	2.586
Botlek	0.58	1.5 million	2.586
Chemiehaven	0.14	0.375 million	
TTR	0.22	0.55 million	

4.7 The flood risk

Vopak terminal Chemiehaven: Flood Risk ‘2050’

General information	
Terminal area	0.14 km^2
Terminal value	€250 million
Return period of an inundation	1,000 years
Maximum d_{ij} on terminal site, highest inundation level for the inundation events	0.8 m

Flood risk characteristics

Flood risk at the VTC (Vopak terminal Chemiehaven) lies mainly within damage to the electricity connection and the central control room. Interlocking connections to multiple customers are present. The customers will experience more inundation from a flooding event than the Vopak terminal.

Risk calculation		
k	E_k	R_k
Risk of fatalities (k=1)	1.07E-06 [fatalities/year]	8 [€/year]
Environmental risk (k=2)	0 [litre/year]	0 [€/year]
Economic risk (k=3)	7,373 [€/year]	7,373 [€/year]
Reputation risk (k=4)	0.09 [days/year]	4,780 [€/year]
Flood risk method: ALARP (Vopak)	$R_A = 19,120$ [€/year]	
Flood risk method: CBA (Dutch government)	$R_C = 7,381$ [€/year]	

Figure 4-23 Inundation image for inundation event j=5; a probability of 1/10,000 a year in 2050

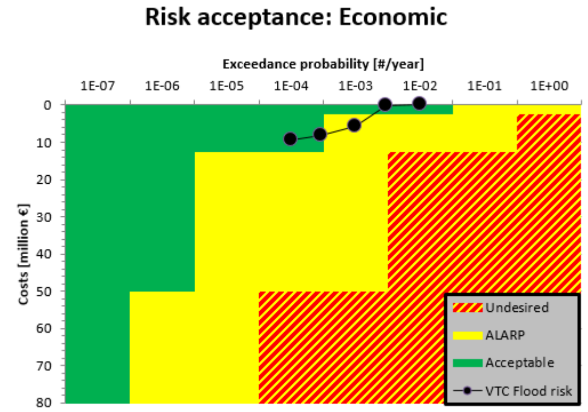


Figure 4-24

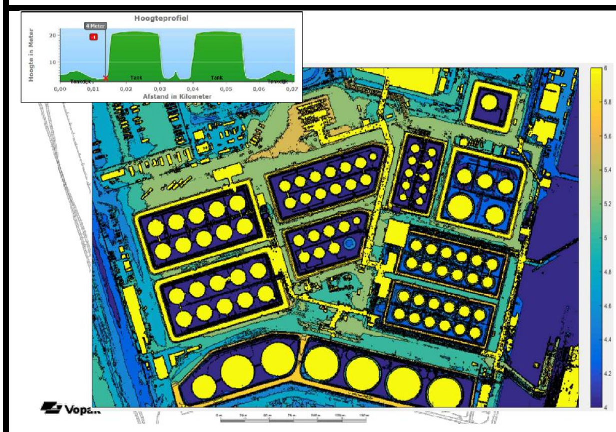


Figure 4-25 Surface level VTC

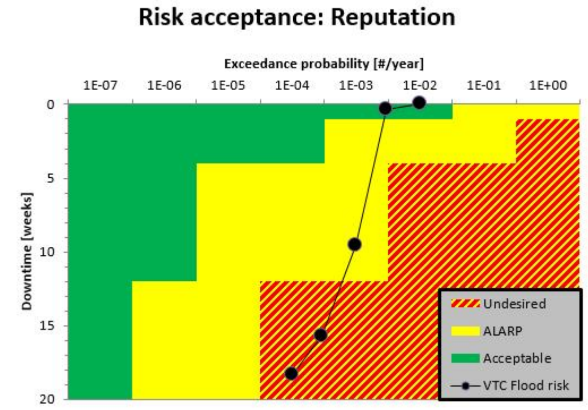


Figure 4-26

Vopak terminal Botlek: Flood Risk '2050'

General information

Terminal area	0.58km^2
Terminal value	€1000 million
Return period of an inundation	>30,000 years
Maximum d_{ij} on terminal site, highest inundation level for the inundation events	0.0 m

Flood risk characteristics

Flood risk at the VTB (Vopak terminal Botlek) lies solely external with damage to the electricity connection, the external CCR (central control room) and the nitrogen supply. The external CCR loses power more quickly but does not get damaged, a switchback to local CCR is possible.

The amount of downtime is exactly the same as for the VTC due to the same externalities.

Risk calculation

k	E_k	R_k
Risk of fatalities (k=1)	0 [fatalities/year]	0 [€/year]
Environmental risk (k=2)	0 [litre/year]	0 [€/year]
Economic risk (k=3)	18,960 [€/year]	18,960 [€/year]
Reputation risk (k=4)	0.09 [days/year]	18,960 [€/year]
Vopak risk method: ALARP (Vopak)	R_A =37,840 [€/year]	
Flood risk method: CBA (Dutch government)	R_C =18,960 [€/year]	

[No flooding present at site itself]

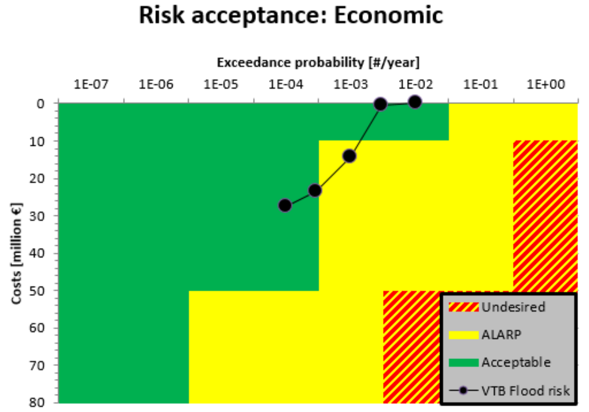


Figure 4-28

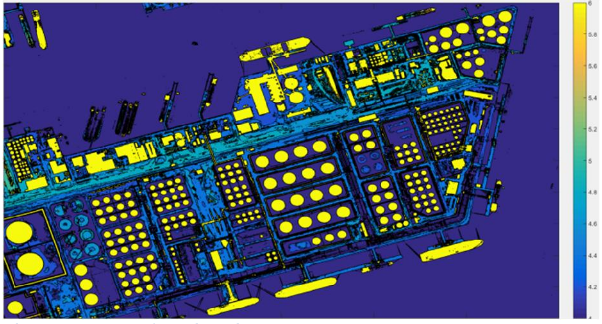


Figure 4-29 Surface level VTB

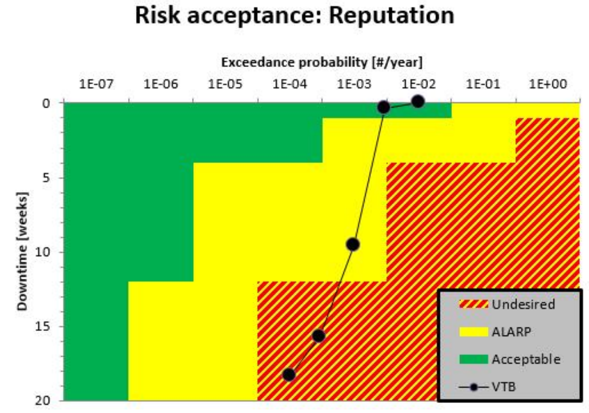


Figure 4-30

Vopak terminal TTR: Flood Risk '2050'

General information	
Terminal area	0.22km^2
Terminal value	€400 million
Return period of an inundation	>30,000 years
Maximum d_{ij} on terminal site, highest inundation level for the inundation events	0.0 m

Flood risk characteristics

VTTTR (Vopak terminal Torontoweg) does not experience flooding within the considered scenarios. It risk lies solely external with damage to the electricity connection, the external CCR (central control room) and the nitrogen supply.

The risk to the VTTTR is relatively low compare to the VTB and VTC

Risk calculation		
k	**E_k**	**R_k**
Risk of fatalities (k=1)	0 [fatalities/year]	0 [€/year]
Environmental risk (k=2)	0 [litre/year]	0 [€/year]
Economic risk (k=3)	1,130 [€/year]	1,130 [€/year]
Reputation risk (k=4)	0.014 [days/year]	1,130 [€/year]
Vopak risk method: ALARP (Vopak)	R_A =1,130 [€/year]	
Flood risk method: CBA (Dutch government)	R_C =1,130 [€/year]	

[No flooding present at site itself]

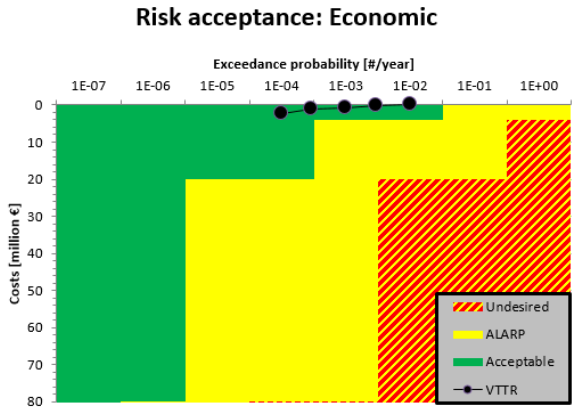


Figure 4-31

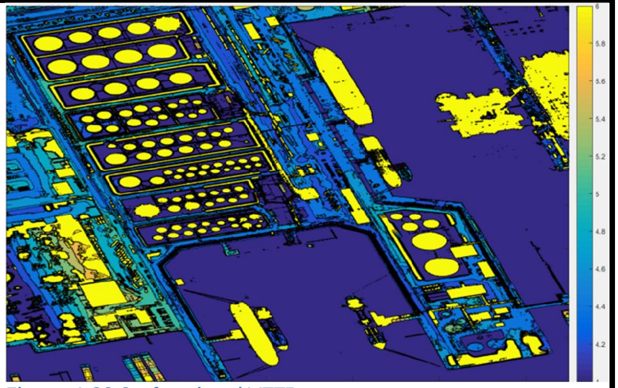


Figure 4-32 Surface level VTTR

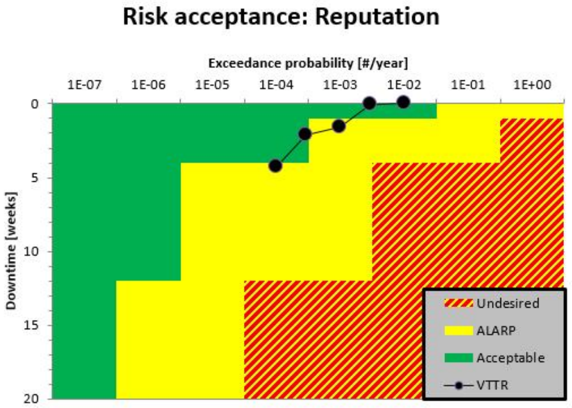


Figure 4-33

Vopak terminal Laurenshaven: Flood Risk ‘2050’

General information	
Terminal area	0.13km^2
Terminal value	-
Return period of an inundation	1,000 years
Maximum d_{ij} on terminal site, highest inundation level for the inundation events	0.3 m
Flood risk characteristics Flood risk at the VTL (Vopak terminal Laurenshaven) is limited. It is a satellite of Vopak terminal Europoort therefor no downtime is considered to be of value and no people are present. Furthermore, it has only a single pump pit present.	

Risk calculation		
$\boldsymbol{k}$	$\boldsymbol{E_k}$	$\boldsymbol{R_k}$
Environmental risk (k=2)	0 [litre/year]	0 [€/year]
Economic risk (k=3)	894 [€/year]	894 [€/year]
Vopak risk method: ALARP (Vopak)	$\boldsymbol{R_A}$ =447 [€/year]	
Flood risk method: CBA (Dutch government)	$\boldsymbol{R_C}$ =894 [€/year]	

Summary: Flood Risk ‘2050’ for the terminals in the Botlek

General information	
Terminal locations	4

Risk calculation	
$\boldsymbol{k}$	$\boldsymbol{R_k}$
Risk of fatalities (k=1)	8 [€/year]
Environmental risk (k=2)	0 [€/year]
Economic risk (k=3)	28,357 [€/year]
Reputation risk (k=4)	24,130 [€/year]
Vopak risk method: ALARP (Vopak)	$\boldsymbol{R_A}$ =between 24,830 and 49,660 [€/year]
Flood risk method: CBA (Dutch government)	$\boldsymbol{R_C}$ =28,365 [€/year]

Vopak terminal Europoort: Flood Risk ‘2050’

General information	
Terminal area	0.58km^2
Terminal value	€1000 million
Return period of an inundation	10,000 years
Maximum d_{ij} on terminal site, highest inundation level for the inundation events	0.3 m

Risk calculation		
$\boldsymbol{k}$	$\boldsymbol{E_k}$	$\boldsymbol{R_k}$
Risk of fatalities (k=1)	3*10^-7 [fatalities/year]	3 [€/year]
Environmental risk (k=2)	29 [litre/year]	290 [€/year]
Vopak risk method: ALARP (Vopak)	$\boldsymbol{R_A}$ =870 [€/year]	
Flood risk method: CBA (Dutch government)	$\boldsymbol{R_C}$ =293 [€/year]	

Flood risk characteristics

The flood risk at Vopak terminal Europoort is only considered at the terminal Europoort and not at its satellites Laurenshaven or Neckarhaven. Also offsite influences are neglected. Compared to the other terminals less detailed inundation data are present. Therefor only the risk categories fatalities and environmental risk are considered.

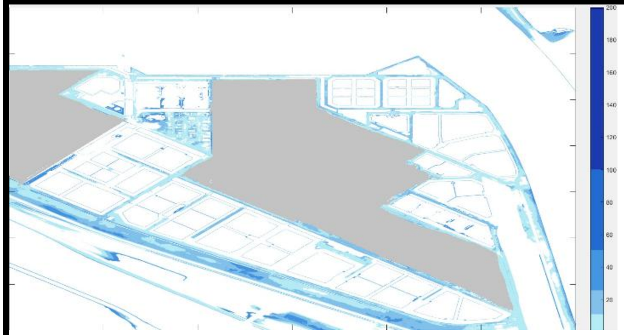


Figure 4-34 Inundation image for inundation event 5; a probability of 1/10,000 a year in 2050

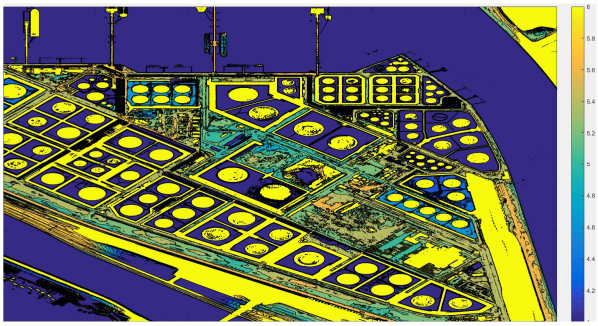
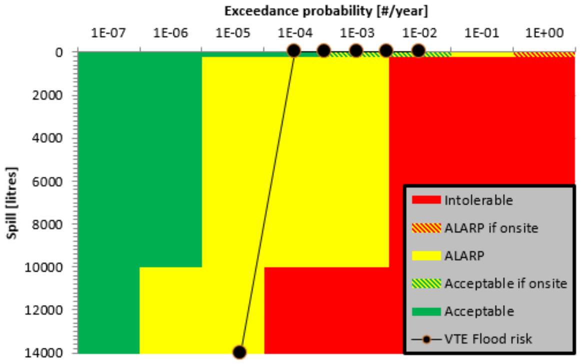


Figure 4-35 Surface level VTE

The environmental risk comes from the failure probability of one deep tank pit with a single tank; VTE0902. The probability of failure is 13% chance which results in an average spill of 2,258,828 litre of fuel oil for an inundation event with an probability of 1/10,000 a year. The used method predicts failure of the tank dike due to the 31 cm inundation level on surface level. This seems unlikely but follows from a tank pit depth of 5 meter. The tank is also located at the waterside of the terminal where wave action is more likely.



Risk acceptance: Environmental

Figure 4-36

4.8 Risk evaluation

The initial evaluation of risk advised Vopak to look into measures to reduce the flood risk since the risk was located in the ALARP and undesired risk zones of the Vopak risk matrix.

The risk evaluation is performed by first stating general considerations about the layers of multilayered safety and the scale of possible measures. Secondly by describing possible measures which differ in scale and in type. As third the most promising measures are evaluated on their costs and benefits. This is done with the ALARP method, which is the approach of Vopak and with the CBA method which is the approach of the government.

Note: all the introduced measures will have a assumed failure probability of zero for all inundation events considered unless stated otherwise. This assumption is made for simplicity since the inundation levels are limited and therefor the failure probability of most measures is practically zero.

4.8.1 Considerations on multilayered safety and scale benefits

The layers of flood rik measures used follow the multilayered safety approach. In this thesis the first layer, prevention, is considered as the layer that contains measures that reduce the inundation probability of a terminal or of the area the terminal is located in. The second layer, spatial planning, is considered measures that reduce the risk of damage to individual objects and for the positioning of objects. And the third layer, crisis management is for actions that are implemented when inundation occurs; in the days before, during or in the aftermath of the inundation event.

For some of the measures there is a efficiency of scale. When building dikes or dams the length of the measure compared to the protected area reduces when constructing them for a larger area. The costs are related to the length of the measure results in a reduced costs per area when protecting a larger area.

At the terminal of Vopak in Hamburg cooperation with neighbouring companies for a combined polder was advised by the harbor authority to reduce the costs of the measure for an individual company. Vopak decided not to work together on flood risk measures after initial talks revealed different levels of willingness and an unclear timeline. The matter of using the flood prevention measure was more urgent at the Hamburg site than it is in the Rotterdam harbor.

For the spatial planning layer the size of the area protected has no influence on the cost per area. The time scale does; the adjustment or relocation of an object cost less when an object is constructed or replaced. This is compared to the cost of the modification or relocation of an object that is in place.

Crisis management measures have a relatively high probability of failure compared to preventive measure (Hoss, 2010). They are often not tested, are made in a limited amount of time and for the Dutch situation an event is not likely to occur more than once in a lifetime. Training for such an event is difficult and therefore such options have a limited reliability. There is a low awareness of flood risk in the Netherlands because of the low recurrence period of floods (Organisation for Economic Co-operation and Development (OECD), 2014). The warning time for the Rotterdam harbor is expected to be 48 hours. This is the amount of time that is available to implement the crisis management measures.

4.8.2 Possible measures to reduce flood risk

Layer 1: Dikes, dams and barriers

For Vopak and the Botlek there are several possibilities for preventive measures in the form of dikes, dams or barriers. There are three scales sizes considered.

To reduce water level in the total Botlek area with an new barrier in the Hartelkanaal is one option which is shown in Figure 4-37. This also prevents inundation of the Neckarhaven, a satellite location of terminal Europoort. Flooding through the Calandkanaal is with this option still be possible (for flooding routes see 4.3.2).

In Figure 4-38 the red line shows the Europoortkering which, when improved with the gates that can close the road underpasses and a limited heightening, prevents inundation of the Vopak sites. This option will also prevent inundation of the electrical infrastructure in the area. This option does not protect the nitrogen supplier.

Two of the terminals in the Botlek area are prone to inundation onsite. Of those the Chemiehaven is depicted as it has an higher flood risk per area. A measure is possible in the form of a flood wall or ditch around the Vopak terminal Chemiehaven, the location of which is shown in Figure 4-39. The inundation is expected to occur one directional and therefor it is possible to dewater to the harbor basin. The basin has sufficient retention capacity for dewatering (Slootjes & Wagenaar, 2015). The option to protect the terminal will prevent damage at the site itself. The external sources of nitrogen and electricity are still prone to damage by inundation.

All these measures reduce the probability of inundation but do not reduce the damage sustained when an inundation event will occur when the flood level surpasses the design value of the flood risk reduction measure.

For all of the measures the costs of a measure per area decreases when the increasing the project scale.

Figure 4-37 Area Scale: Barrier at Hartelkanaal

Figure 4-38 Area Scale: Improvement of Europoortkering/A15

Figure 4-39 Terminal Scale; Flood wall or Ditch at the Terminal Chemiehaven

Layer 1: Surface elevation

Elevating the surface level means soil is used to heighten the terminal area. It is an measures that has been applied to the area. This was done when the harbor area was developed. It is an difficult (read: impossible) option to perform when an area is in use. This measure does reduce the probability as well as the effect when the inundation occurs. Surface elevation does not have a significant scale efficiency (Wolthuis, 2011).

Layer 2: Horizontal spatial planning

A national government can use the aspect of flooding to determine where to allow certain vulnerably industries. Even companies use a risk approach for choosing an optimal location (Rath, 2007). However, multiple aspects are of influence on the choice of location in addition to the risks. For Vopak the importance of transportation by ships means that a terminal is located in a harbor or nearby waterways. Furthermore, such decisions are made before settling. When looking at spatial solutions as an option to reduce the risk a relocation of the whole terminal is an unwanted option for Vopak. This is due to the associated costs and the dependency on harbor access. The government does not aim at such kind of spatial planning (Milieu- en Natuurplanbureau, 2004).

Spatial planning at a company level influences the layout of a terminal. The horizontal layout of a terminal that has a uniform surface level can be influenced by taking into account the wave level present at the waterfront. When taking waves into account a water level below the surface level can still introduce inundation at installations that are located close to the waterfront. This is especially true for pump pits since their object level is below surface level. When the surface level is not uniform the lower parts are best used for parking or storage of slob tanks. These can be moved when a flood warning is given. The immovable, more critical or expensive parts are in such case to be located on the higher grounds of the terminal. For example a DVI (vapour processing unit) and the CCR.

The location of objects at a terminal cannot solely depend on flooding. An example; the placement of pump pits is guided by the most efficient use of pumps (Europoort, 2016). A change of location can reduce the flood risk but has to outweigh the decreased efficiency. Other parts can be moved more easily. The location of CCR's is often very flexible. However the costs of relocation are equal to the replacement costs.

Layer 2: Hardening of objects

The reduction of the failure probability or damage of an object is called hardening. This hardening can take place by waterproofing an object, by elevating an object or by preventing water from flowing in by placing a flood wall around an individual object. An example of a possible flood wall is shown in Figure 4-40.

Figure 4-40 Flood wall

Waterproofing means that an object can be inundated without damage to the object. This is often performed by raising the utilities inside the object above the design inundation level, this makes it unsuited for protecting utilities itself (US Army Corps of Engineers, 2017).


Figure 4-41 Elevation of electrical station

For electrical infrastructure an flood wall around the object hinders access therefore elevation is often preferred. Elevating an object, as shown in Figure 4-41, reduces the inundation probability as well as the size of the consequence. Elevating electrical infrastructure is considered a cheap measure; the costs of adapting the design for an elevated placement is €10,000 a station[7] as estimated by Vopak (Westerduin, Oorschot, & Blom, 2016).

At the Vopak terminal Chemiehaven a few critical parts for functioning of the terminal are located lower than the average level of electrical substations. Most risk is however located offsite in the infrastructure of Stedin. A measure to reduce the risk has to include that part of the chain as well for Vopak to benefit from the measure. If an electrical substation is protected but the connecting stations of Stedin are not there is limited benefit in risk reduction at the Vopak stations since the risk of downtime still originates from the connecting stations.

For pump pits the vertical elevation is guided by the most efficient use of pumps and change is not preferred. The reduced risk is not expected to outweigh the decreased efficiency. (Europoort, 2016).

Vopak's new electrical stations are often located above ground for other reasons that flood risk reduction. It is more easy to change the cables when there is space under an electrical station. The elevating of electrical stations is not consistently executed, however. An example of a station that is not elevated is the connecting station at the VTTTR that is partly owned by Stedin. This is because Stedin's initial stance is that the cables are covered with earth to protect them against damage. Vopak did not bring up the flooding aspect.


Figure 4-42 Shared CCR backbone

An example of risky vertical placement of an object is the location of the newly located combined CCR for the two Botlek terminals and the automation backbone. It is located at the bottom floor which is located 1.5 meters below surface level, as seen in Figure 4-42. Even without coastal flooding, partial inundation was present when a gardener watered the grass around the building.

Layer 2: Hardening of environmental objects
The environmental objects of the terminal are the pipelines, the tank dikes and the tanks. For all three of those it is possible to harden to them. A measure to reduce the probability of failure of the pipelines is increasing the strength of the clamps or increase the weight of the pipelines.

The tank dikes can be improved by reducing the slope or increasing the height. A reduced relation between the tank dike height and the tank pit depth also reduces the allowable inundation height. If no space for

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[7] This is the costs of elevating a new station. The cost of elevating an existing station are higher.

these options is available there are also options for dike improvement with require no space such as inserting an sheet pile wall into the dike.

The failure probability of the tanks can be reduced by increasing the weight of the tank and by anchoring them to the ground. Both decrease the floating probability which equals the failure probability.

Layer 2/Layer 3: Backup options

A measure to reduce the consequences of failure of external utilities is to have backup options present to continue services. For example for firefighting emergency power is present onsite. This is because of regulations.

Figure 4-21 Mobile back-up generator

The electrical demand of a terminal can be sustained by aggregates (FEMA, 1999) (Office of Electricity Delivery and Energy Reliability, 2010),(Appendix H). It is however not beneficial to have enough emergency power for a fully functioning terminal, the depreciation on the aggregates is too large (FEMA, 1999). Additionally, if a backup option is present onsite it can be damaged by inundation as well.

A measure considered as a combination of spatial planning in combination with crisis management is having the infrastructure ready for backup options. If the terminal itself is protected but there is a long-term power outage it is beneficial to be able to connect an electrical aggregate. A dedicated plug-in connection is a measure to accommodate this. The gain is limited since it is Vopak's expectation is that connecting an aggregate is possible in a matter of days without such a plug-in connection (Westerduin, Oorschot, & Blom, 2016).

The same measure can be applied for a disruption of the nitrogen supply. Combined for all Vopak Botlek Terminals one road based liquid nitrogen tanker (30 m^3) a day is sufficient to provide for the average nitrogen usage (Appendix H). For this it is required that there is at each terminal an installation which is able to feed the nitrogen with the right amount of pressure in the local infrastructure. Such plug and play installation are available in normal situations. In a situation with a inundation event that had impact on a large area it is expected to be increasingly difficult to acquire such an installation.

Layer 3: Evacuation and relocation

Part of the measures of layer three focus on the reduction the risk by evacuation of people. The simple logic is that with less people present, less people will die.

This approach can also be used for movable equipment. A measure in the form of the relocation of cars from car parks as well as relocating equipment and materials out of the possible inundated area. For the terminal this is done by moving cars, slob tanks and other equipment to higher grounds of the terminal. The terminals have a quite uniform surface level so the possible influence on the risk is limited.

Layer 3: Temporary inundation prevention measures


Figure 4-43 Sandbags as temporary flood measure

Prevention measures that are implemented when an inundation event is predicted are part of layer three. An example is shown in Figure 4-43 where sandbags are placed in an entrance of a terminal. A large advantage of such measure is that an expenditure is done when it is highly likely that an inundation event will take place. The disadvantage is the that such temporary measures have a limited reliability. The materials have to be available, they have to be well placed and placed in time, all of which are not likely for large areas.

When looking at measures for small areas it can be useful for Vopak for specific locations as the CCR. The walls might be watertight and when the entrance can be blocked with sandbags, or something similar, no water will enter the building. When people are present in the CCR a logical response of them is to try to keep it dry. For such small stretches a lot of materials are applicable to close the entrance. It is also likely that without reading the emergency plan or having trained for such occasions, personnel will implement measures. This increases the chance of a successful implementation of the flood protection.

Another option is the sealing of metal doors of electrical stations by welding them shut. This is expected to make them watertight. The doors have to be replaced after an inundation event but this damage is expected to be lower than inundation of the station. However often there are other ways water can enter a building.

Layer 3: Temporary environmental measures

For measures that specifically influence the environmental risk there are measures that can be performed in layer three. To prevent floating of tanks and pipelines they can be filled with product. For tanks this results in filling them to an appropriate level to prevent floating. At liquid bulk terminals there are often multiple tanks with (near) similar products and they can be redistributed over the tanks. At the moment Vopak's emergency plan in Houston, Texas covers the filling of the tanks to reduce the risk (Vopak Terminal Houston, 2015). Such redistributing influences the product specification of customers of Vopak which is a negative effect of this measure.

To remove product from pump pits or the water treatment facility on site reduces the amount of small spills. To clean the pump pits of product is difficult but floating product in the water facility can be easily skimmed (Europoort, 2016).

Summary of measures

The possible measures are arranged by their layer and by their scale in Table 4-23. The measures are arranged in three different classes of scale. The largest scale is the area scale. A measure of this scale effects the flood risk for Vopak and companies located in the same area. Second the terminal scale is used; measures in this scale class effect the whole terminal or a large amount of objects. The smallest scale considered is at an object level.

Table 4-23 Summary of possible measures

Type	Layer	Size	Measure	Effects	Short description
Dikes, dams and barriers	1	Area	Barrier	q_j	Reduces the water level in Hartelkanaal
	1	Area	Improve the Europoortkering	q_j	Reduces the overflow over the A15
	1	Area	Improve the Tuimeldijk	q_j	Improve quality and height of the Tuimeldijk
	1	Terminal	Dike	q_j	Build a dike or flood wall around the terminal site
	1	Terminal	Flood wall	q_j	
	1	Terminal	Dewatering ditch	q_j	Relocate water to harbor basin instead of onsite
Surface elevation	1	Terminal	Surface level elevation	q_j	Heighten the surface level of the whole terminal
Horizontal spatial planning	2	Area	Spatial planning	q_j	Relocate the terminal to another location
	2	Terminal	Spatial planning	d_{ji}	Put sensitive equipment on the higher grounds of the terminal.
Hardening of objects	2	Object	Elevation	p_{ji}	Elevate objects above inundation level.
	2	Object	Waterproofing	C	Reduce damage an object sustains by inundation
	2	Object	Flood wall	p_{ji}	Place a flood wall around a single object
Hardening of environmental objects	2	Object	Water retaining tank dikes	$p_{2,ji}$	Improve the tank dikes to enable an flood retaining function
	2	Object	Clamps for pipelines	$p_{2,ji}$	Decrease the floating probability of pipelines by increasing the strength of clamps.
	2	Object	Anchoring of tanks	$p_{2,ji}$	Decrease the floating probability of inundated tanks by increasing by anchoring them.
Backup options	2/3	Object	Backup options	C_4	Keep backup possibilities in place for essential services.
Evacuation and relocation	3	Terminal	Evacuation of objects	C_3	Relocate objects on the terminal to dry grounds.
	3	Terminal	Evacuation of people	C_1	Reduce the workforce on site an during inundation event.

Temporary inundation prevention measures	3	Terminal	Temporary flood measures	q_j	Put flood shields around the terminal when an inundation event is expected
	3	Object	Temporary flood measures	p_{ji}	Place sandbags or waterproof doors of objects when an inundation event is expected
Temporary environmental measures	3	Object	Filling of tank	p_{ji}	Fill tanks when an inundation event is expected to reduce the floating probability
	3	Object	Cleaning of pump pits	C_2	Clean pump pits of spills when an inundation event is expected to reduce the consequence

4.8.3 Favourable measures

Measures are considered favourable if the benefits exceed the costs. The benefits are calculated by rerunning the risk calculation of 4.7 with adjusted input parameters. The costs and their origin and/or reasoning are explained in this paragraph.

Improvement of the Tuimeldijk; The cost for the improvement of the Tuimeldijk follow the calculation made in the pilot Waterveiligheid Botlek (Royal HaskoningDHV, 2016). The costs were estimated at €15,000,000.

Improvement of the Europoortkering; The cost for the improvement of the Europoortkering follow from the costs made to insert a low level flood wall adjacent to the a lower part of the A15 and measures to close off the underpasses when a inundation event occurs. It is estimated at a third less than the Tuimeldijk; €10 million. This follows from a reduced length and required strength of the flood wall.

The measures to close off the underpasses are potential cost drivers for this option however for Vopak the measures might be adequate without any.

Flood wall; The cost for the flood wall follow the implementation costs of a flood wall at the Vopak terminal Hamburg where a floodwall of 2 km was built with 12 flood gates for 6 million euro (Vopak Terminal Hamburg, 2014). For The Vopak terminal Chemiehaven there are two flood gates required and a length of 0.8 km.

$$\frac{6{,}000{,}000}{2}\cdot 0.8 = 2{,}400{,}000\ [€]$$

Dewatering ditch; The cost for a ditch to relocate inundation water into the basin is estimated at 20% of an flood wall. The drainage ditch does not require any special installations.

Object elevation; The object elevation is implemented for the electrical infrastructure. This is done to reduce the reputation risk which requires measures onsite and offsite. The costs are €10,000 a station when it is implemented when the a station is replaced. There are 18 stations at Vopak sites that will be elevated (all stations of VTC and VTL, see Table 4-9) and an assumption is made that the same amount is required for convincing Stedin to implement the same measures at their infrastructure.

Evacuation; The cost of evacuation is only there when an evacuation takes place. The costs are monetized as a day missed income of the VTC with a probability of evacuation of 10 times the probability of an inundation event at VTC (with is the combined probability of inundation event 3,4 & 5). This follows from the fact that an evacuation will also take place when the actual inundation event will not occur. The costs are multiplied with 18.122 to change the yearly value to a one time value.

$$54000 \cdot \left(10 \cdot \left(\frac{1}{1500} + \frac{1}{4300} + \frac{1}{10000}\right)\right) \cdot 18.122 = 9700\ [€]$$

Table 4-24 Potentially favourable measures (after an initial shifting of Table 4-23)

Measure	Layer	Size	Effects	Costs	Benefit		
					CBA method	ALARP method	
						ALARP zone	Undesired zone
Improve the Europoortkering	1	Area	q_j	€10,000,000	€ 423,549	€ 359,523	€ 719,046
Improve the Tuimeldijk	1	Area	q_j	€15,000,000	€ 513,747	€ 449,721	€ 899,442
Flood wall	1	Terminal	q_j	€2,400,000	€ 47,834	€ 23,916	€ 47,832
Dewatering ditch	1	Terminal	q_j	€480,000	€ 47,834	€ 23,916	€ 47,832
Object elevation	2	Object	p_{ji}	€360,000	€ 423,549	€ 359,523	€ 719,046
Evacuation of people	3	Terminal	C_1	€9700	€145	€435	∞

The results of the updated risk calculation and the costs of the measures result in Table 4-24. In this table the yearly risk reduction is stated as a onetime value for the benefit. The size of the benefit depends on the calculation method of the risk and in which risk zone the risk was originally located. The appropriate cells are grey.

Table 4-25 The favourability of different measures

Measure	Favourability with	
	CBA method	ALARP method
Improve the Europoortkering	4%	7%
Improve the Tuimeldijk	3%	6%
Flood wall	2%	1%
Dewatering ditch	16%	8%
Object elevation	106%	180%
Evacuation of people	1%	4%

There is one measure that is favourable for Vopak to implement, the object elevation of electrical substation, as is shown in Table 4-25. The measure is favourable with the ALARP method as well as with CBA method. All other measures are not favourable for Vopak.

5 Discussion

This chapter is a discussion on the risk assessment performed for Vopak. In the first section the value of the flood risk for Vopak is placed in perspective. The second section is an elaboration on possible options for authorities to influence the flood risk at a company. In the third section the differences is presented between an optimal risk from Vopak's point of view and from a governments point of view. The fourth section covers the uncertainty in the risk assessment performed. The fifth section of this chapter combines the first three sections and the case study itself to discuss the current approach to flood risk in the unembanked Botlek area.

With this discussion the answers are presented to the following research questions:

4. *What is the relative value of the flood risk at Vopak terminals? Section 5.1*
5. *What are options for an authority to influence Vopak to reduce its flood risk? Section 5.2*
6. *Does stimulation of flood risk measures lead to an optimal flood risk in the Botlek area? Section 5.5*

5.1 The relative flood risk at Vopak terminals

This section shows the level of flood risk at Vopak in perspective for the different risk categories. The risk shown is the risk in 2050 without implementation of any flood risk measures.

Fatalities

Figure 5-1 shows that the flood risk of fatalities on a Vopak site is in the ALARP zone for Vopak and below the target value of the new national standard, the LIR, of 10E-5/year (Ministerie van Infrastructuur en Milieu, 2014).

It can be deducted from the figure that the flood risk of fatalities is more than 10 times below the national flood risk standard (LIR).

The flood risk of fatalities on a Vopak site is low relative to the national standard which is expected following the limited water levels in the unembanked area of the Botlek.

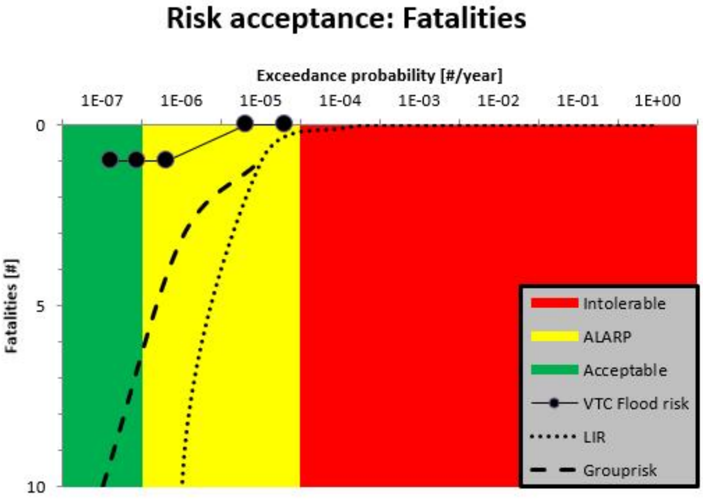


Figure 5-1 Vopak's risk of fatalities in perspective

In Figure 5-1 the risk zones of Vopak are depicted in combination with the target values from the national standard for the local individual risk and for the group risk. Additionally Vopak's risk on fatalities in the Botlek is shown. This equals the risk on fatalities at Vopak Terminal Chemiehaven(VTC). For this figure the flood risk data from the category fatalities is used where the values for the probabilities are adjusted to result in one fatality instead of very small value for clarity; 0.1 fatality with a probability of 1E-5 is adjusted to 1 fatality with a probability of 1E-6.

Note: Vopak's risk matrix does not consider more than one fatality as a separate consequence size. This is different compared to the QRA as performed in the safety report where the target values for individual and group risk follow from the BEVI, Besluit Externe Veiligheid Inrichtingen (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, 2004) (SenterNovem, 2006).

Environmental

For the environmental risk category the flood risk is put in perspective by comparing the environmental flood risk to the environmental risk at a Vopak site originating from other sources.

Figure 5-2 shows that the flood risk has a large consequence compared to other environmental risks that are present at Vopak. The large consequence indicates that it is important to weigh the flood risk for environmental risk evaluation. However it was seen that in this case the flood risk is optimal.

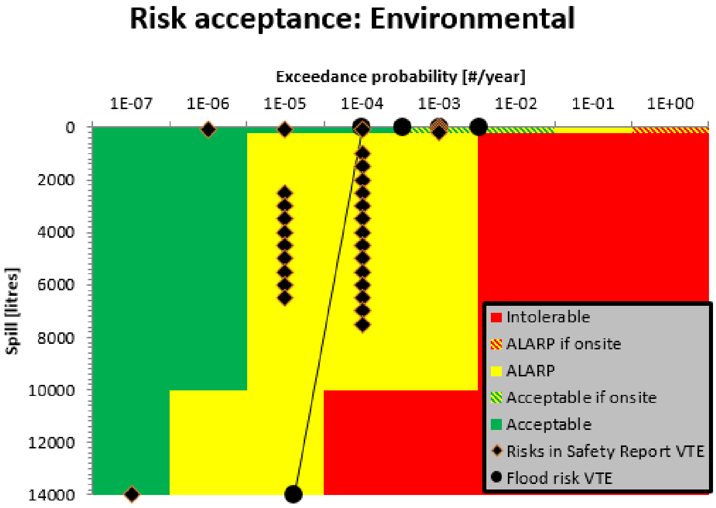


Figure 5-2 Vopak's environmental risk in perspective

The environmental risk in the Botlek is zero and therefor the depicted data is from the environmental flood risk at the Vopak Terminal Europoort. The environmental risk from other sources originates from the safety report of Vopak Europoort (Vopak Terminal Europoort B.V., 27 Juni 2016). Consequences are expressed in four classes which are visually spread for clarity; a risk of 14,000 litres is of the class above 10,000 litres.

Category: Economic risk

The economic risk is put in visual perspective by using an upper level for the annual embanked value which will be predominantly below €100/hectare in 2050 following the new national standard (Van der Most, Slootjes, & Schasfoort, 2014).

To account for variations in this value, the value itself, a value a tenfold higher and a value a tenfold lower are shown as reference lines in Figure 5-3.

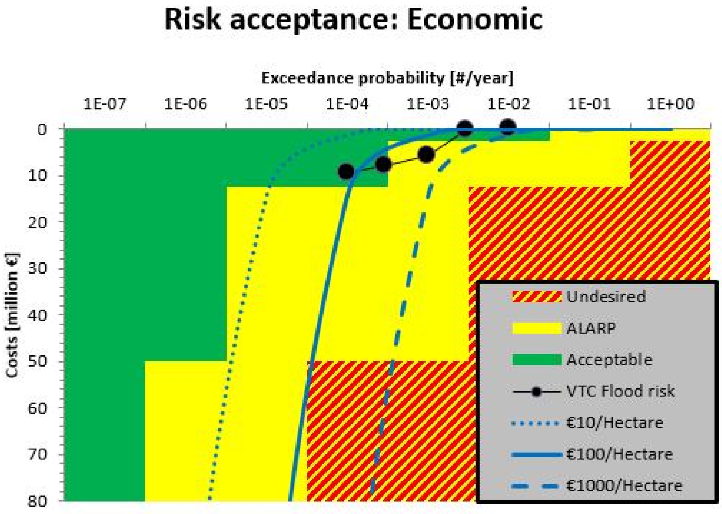


Figure 5-3 Vopak's economic risk in perspective

From this figure it can be deducted that the economic risk at Vopak terminal Chemiehaven, which has the largest risk/hectare, is slightly above the €100/hectare. The economic risk on a Vopak terminal is in the range of the future upper average value.

Note: Figure 5-3 does not represent the optimal risk level at an individual location. The upper values per hectare are averaged over large areas in dike rings.
Note: The economic risk for Vopak covers excludes the monetized risk of fatalities or environmental risk. However for the Vopak terminal Chemiehaven this does not significantly alter the results (<0.1%)

Category: Reputation risk

The reputation risk is put in visual perspective by using the policy of the Province of Zuid-Holland. That policy has a standard for social disruption with a guidance value of 10 days/hectare/year for an company (Huizinga, Nederpel, de Groot, & Batterink, 2011). In what guidance value this results for Vopak is shown in Figure 5-4.

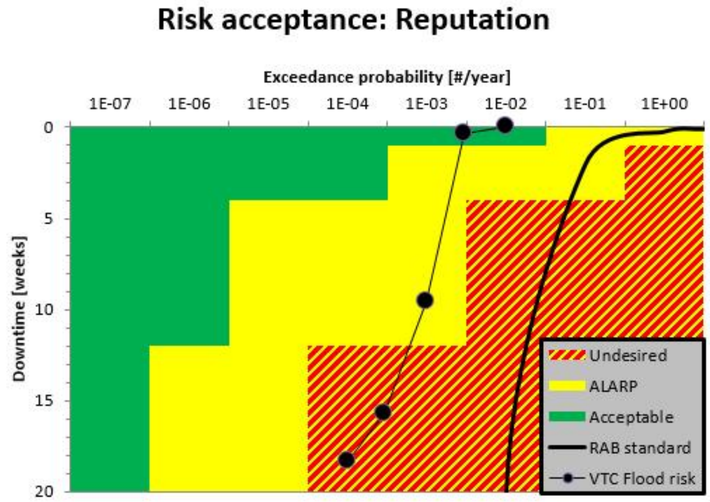


Figure 5-4 Vopak's reputation risk in perspective

The social disruption standard does not include chain effects to other companies. The social disruption included is the disruption to Vopak employees. A liquid bulk terminal has a low amount of employees/hectare which partly contributes to outperforming the standard considerately (roughly 200 times).

The resulting aim value is calculated for the VTC location with 100 employees of Vopak attributed to the terminal location.

5.2 Influencing options for authorities

If an authority decides that the current flood risk is not the preferred level of risk, it has in basic the following options to influence the risk:

1. Take over: An authority builds flood protection
2. Mandate: Set standards to which companies has to comply
3. Promote: Give information, subsidize protection

All of which address a part of market failure associated with flood risk.

An authority that takes over the responsibility for flood risk management by building flood protection is the most economic efficient option if there is efficiency of scale (see paragraph 4.8.1). The market failure this action addresses is the difficulty for companies of working together, especially since large scale flood risk reduction measures are public goods. An authority can more easily chose for a larger scale of measures which is more cost-efficient. However, this negatively influences the likelihood a company will reduce its own risk.

Mandate standards can be used to reach a preferred risk level. The costs of risk reduction lie with the company in such situation. To mandate standards for existing sites is more difficult than for newly developed ones. In paragraph 2.1.2 it was already mentioned that the common denominator of the current policy was that there was no modification of existing structures mandated. The market failure this option addresses is that a company neglect certain external factors and therefor mandated standard are required.

The action promote risk reduction can be executed in two ways. Provide information on the amount of flood risk is and how to reduce it and/or subsidize certain risk reducing measures. The first option is cheap for an authority while the second option is not. The market failure this option addresses is incomplete information. When supplying the flood data as information the authority fixes this problem. Subsidy transfers some of the societal gains which results from the company reducing its risk back to the company. This addresses the market failure of one stakeholder that bears the costs and a multitude of stakeholders that receive the gains.

Combinations or variations on this three basics options are also a possibility. If an authority would implement flood risk reducing measures, an increased rent for the company's property can be set. This is a combination of reversed subsidy and taking over responsibility. Another option is to have mandated standards but subsidizing measures to reach the standards. This ensures action while redistributing the costs.

Influencing flood risk evaluation: Vopak specific

To increase the likelihood of action by Vopak a parameter has to change in its risk evaluation; an increase in the benefits of a measure or a decrease of the costs.

An example of changing the gains: Currently the risk of power disruption by a failing electrical grid is equally located onsite and offsite. This results in only slight benefits when protecting the onsite grid if the offsite grid protection is not improved. If an authority mandates that the utility company improves protection of the offsite grid this improves the gains of protecting the onside electrical grid. This results in an increased likelihood of Vopak implementing this measure.

An example of changing the costs: A subsidy for certain measures changes the costs for Vopak. The total costs remain the same but for Vopak it changes. Another option is to provide loans for flood reduction measures.

5.3 An optimal risk for Vopak and for the government

The evaluation of the optimal risk at a liquid bulk terminal is different when performed by Vopak compared to the approach of the national standard. The differences result from the use of a different evaluation method, a different valuation of the net present value of the risk and the possibility of cooperation.

For the Botlek case, with a predominant contribution of reputation risk both risk evaluation methods, ALARP and the CBA, created similar outcomes. If a measures was deemed favourable with the CBA method it was as well with the ALARP method.

However, the valuation of the flood risk with the ALARP method is considerately higher for measures when the risk is located in the undesired zone of the risk matrix. The difference is shown in Table 5-1. For the cost effective measure of object the ALARP method results in a 70% higher valuation of the risk.

Table 5-1 Relative value of risk reduction between CBA and ALARP (based on Table 4-24) The bold values represent the appropriate zoning of the risk.

Measure	Benefit		
	CBA method	ALARP method	
		ALARP zone	Undesired zone
Improve the Europoortkering(A)	100%	85%	170%
Improve the Tuimeldijk	100%	88%	176%
Flood wall	100%	50%	100%
Dewatering ditch	100%	50%	100%
Object elevation	100%	85%	170%
Evacuation of people	100%	300%	∞

The net present value of a risk is not equal for Vopak and the government. The discount rate used for flood risk evaluation by the government is 5.5% (Deltares, 2011). This differs from the value used by Vopak of 7%. The difference results from a difference in the costs of lending and it results in a 19% lower risk estimation by Vopak compared to a risk estimation by the government.

For the government an optimal risk is considered for areas. Flood risk measures at a larger scale are therefore an option if those are more efficient. Line type of flood defenses have an large increase in efficiency for when the area protected increases. Vopak is a single company and the optimal flood risk is evaluated for its own terminals. Flood risk reduction for other companies does not benefit Vopak unless other companies are willing to contribute to a measure. Cooperation is voluntarily and in practice it is seen that cooperation does not take place.

5.4 Uncertainty in the flood risk assessment

In this part of the discussion the uncertainty is addressed by qualitative descriptions by the author. The descriptions are divided in two parts. The first part is about general uncertainties for flood risk assessments and the second is about uncertainties that are specifically relevant for the topic of this thesis.

General uncertainties for flood risk assessments
An uncertainty that is an important one for every risk assessment is the possibility that certain failure mechanisms are missed. Even though every input in the considered mechanism is in practice exactly the theoretical expectation, the system might fail through a not considered mechanism. For example: in this thesis it is assumed that failure of a tank will occur through floating of the tank. Chain effects such as getting hit by another tank are not included.

The inundation levels have a large influence on the results for unembanked flood risk assessments (Way, 2016). They influence which objects are inundated with which probability as well as the size of the damage. Since the inundation levels are in the range of the local uncertainty of the inundation levels the relative influence is large. Additionally, the certainty and the local accuracy of inundation data is limited. For this thesis specifically the local accuracy of the data is stretched to the limit since the objects evaluated are similar in size to the cells of the inundation models.

The real situation is simplified to make an analysis possible. While this method considers objects in relative high amount of detail the system is still simplified. To simplify the assessment it excludes empty pipelines and the effects of product interactions with water. Another simplification is the linearization of costs. The risks of the reputation category and the environmental category are linearly monetized. However an environmental risk, a spill, is more expensive a litre for small spills and less for larger spills. To use of average values results in a lower risk for small spills and a higher risk for larger spills. For the reputation risk the damage can be linear, but it can also be focussed in the first few weeks or a peak after a few weeks of downtime.

Uncertainties that are specifically relevant for this thesis
The four uncertainties that are specific for this flood risk assessment are:

- Repair and recovery time of utilities for a large scale inundation event
- Damage values, specifically for pump pits
- The CB ratios that are ALARP
- The failure height of tank dikes

The repair time estimates of electrical infrastructure has a large influence on the results of the risk assessment of this thesis. This results from the large contribution of the reputation damage to the flood risk for Vopak. The repair time estimates are based on the inundation independent on the total area affected by inundation and do not take into account a preferential order of the repairs. All which could change the repair estimates.

The damage values originate from expert estimates and are not based on inundation experience, further increase of data on the damage to industries would strengthen the reliability of these numbers. One of the unknowns with an expected large impact is the damage by salt water on the pump pits (Europoort, 2016). The simplification with the use a generalized pump pit creates additional uncertainty. The pump pits are quite diverse in size and the content is quite diverse as well.

The economic and reputation CB ratio for the flood risk stance of Vopak originate from one practical case and the indication on the how much a flood risk reducing measure has to outperform its costs was in that case influenced by the risk policy of the Hamburg port authority. The CB ratios benefit from more information or clear choices on this end. However, if ALARP is applied consequently, it is of limited influence if the environmental risk is leading. Those CB-ratios follow jurisdiction instead of a Vopak case.

The failure height of tanks dikes is expected to be of little influence for the assessment of this thesis. The calculation on the failure of the tank dike is limited in depth and underestimation of tank dike strength is expected. Since the soil properties are used uniformly throughout the area an conservative assumptions are made because of this. When the method is used for another location with higher inundation levels for the considered probabilities the failure function require further improvement. The conservative assumptions made for the strength of the tank and the content of the tank are expected to result in a overestimation of the probability of the tank pit. Especially if the tanks are anchored in practice this decreases failure probability of the tank significantly.

5.5 Stimulating companies and an optimal flood risk

The current practice in the Botlek area is to provide information and stimulate companies through the pilot 'Waterveiligheid Botlek' in combination with mandated flood risk assessments for BRZO companies. If this approach leads to the optimal flood risk does not have a singular answer. This results from the fact that there is not a single optimal level of flood risk.

In section 5.1 the flood risk at Vopak is compared to indicative optimal flood risk values. Solely based on the risk values without taking costs of measures into account one could presume that the Vopak values are optimal. However in the case study of chapter 4 it was already seen that the flood risk was not at an optimal level. The object elevation of the electrical stations leads to an optimal flood risk at the Vopak terminals.

Section 5.3 covered the difference in the optimal flood risk with the method of Vopak and the method of the government. Even if the used evaluation method is identical there is a difference in the costs of lending which results in a different optimal risk level. For the Vopak Botlek case both methods resulted in the same measure that leads to an optimal level of risk for the Vopak terminals.

When considering the whole area the improvement of the Tuimeldijk leads to the optimal risk for the Botlek area (Royal HaskoningDHV, 2016). For Vopak this measure outperforms the measure object elevation if Vopak has to contribute less than 3.1% of the implementation costs. Which is significantly less than the 8%, which is Vopak's percentage of the area that benefits from the improvement of the Tuimeldijk (See paragraph 4.2.5). The Vopak terminals are located in the parts of the Botlek that are less prone to inundation (see also paragraph 4.3.2) which results in the low value of contribution.

The current approach of providing information and mandate individual flood risk assessments lead to flood risk assessments at Vopak. The assessment at Vopak lead to a reduction of the total costs and an optimal risk from the view of Vopak. However if an optimal risk level for the Botlek area is the goal Vopak's measure of object elevation should not be implemented. Vopak implementing the measures leads to deviation of the optimal risk for the Botlek area.

It is an logical assumption that the optimal flood risk for the Botlek area is only reached when an authority takes over. This is based on observations during the case study that indicated that cooperation by multiple companies for a large scale flood reduction measure is not likely. The conclusion on the current approach of stimulation of flood risk measures is that it does not lead to an optimal risk for the whole area but if the 'Take over' approach is not an option the current approach does lead to an optimal risk for a single company.

6 Conclusion & Recommendations

In the first part of this chapter the conclusions of this thesis are formulated. These follow from the risk assessment for the Vopak terminals and the following discussion on the results. In the second part recommendations are presented.

6.1 Conclusion

Firstly, the annual flood risk for the Vopak terminals in the Botlek area in 2050 is twenty eight thousand euro's. This follows for less than 0.1% from the risk on fatalities on Chemiehaven, 12% from the damages on Chemiehaven and Laurenshaven and 88% from the downtime on all four terminals of the Botlek. The downtime originates from the repair time of the externally damaged electrical utilities. The environmental risk is zero which follows from limited inundation levels at the Vopak terminals for which there is no expected failure of the tank dikes. Spills from pump pits do not contribute significantly to the flood risk; the only occurring inundation is at a pump pit at Laurenshaven which leads to a very limited risk due to floating of product of €0.5 annually.

Secondly, the flood risk in 2050 is in comparison limited for Vopak. The risk of fatalities is more than ten time below the national embanked standard for flood risk, the economic risk around the national embanked average, the risk scores low on the social disruption standard for unembanked areas and there is no environmental risk in the Botlek. At the Vopak terminal Europoort the environmental risk due to flooding is in line with other environmental risks on site.

Thirdly, this expected annual flood risk in 2050 is not at the cost optimum for Vopak. The measure that will lead to an optimal flood risk is the elevation of electrical stations. Additionally, this is the only measure that reduces the combined value of the flood risk and costs of prevention. The costs of other measures were at least six times higher than the risk prevented.

Fourthly, there is a difference between the optimal flood risk for Vopak and for the government. The differences result from a different evaluation method, a different valuation of the net present value of the risk and the costs contributed to cooperation. For the Vopak Botlek case the ALARP method used by Vopak leads to a higher (+70%) valuation of the flood risk. The discount factor for Vopak as a company leads to a lower valuation of the a risk reduction (-19%). For an Vopak terminal site the approach of the company Vopak leads to a lower level of flood risk compared to an assessment with the approach of the national flood risk approach for the embanked areas.

Fifthly, findings in this thesis indicate that the current approach of stimulating individual risk assessments leads to a higher level of risk than the choice of 'Take over'. The level of flood risk at Vopak is lower with the measure that is deemed cost-effective for the Botlek area. From Vopak's point of view that measure is however not cost-effective. Observations during the case study indicated that cooperation by multiple companies for a large scale flood reduction measure is not likely. This suggests that the current unembanked flood risk practice of stimulating individual risk assessments is not in line with the principle of cost optimum as is the goal with the national flood risk policy for embanked areas. However if the 'Take over' approach is not an option the current approach does lead to an optimal risk for a single company.

6.2 Recommendations

Two types of recommendations are given. The recommendation for Vopak to reduce its flood risk efficiently with object elevation of electrical stations is specified and recommendations on improvement of this type of risk assessment with future research into this subject.

6.2.1 Recommendations for Vopak

In the case study it was calculated that the risk for Vopak is not optimal and Vopak is therefore advised to implement the measure elevation of its electrical stations. The measures will reduce the reputation risk (downtime). It comprise out of two parts:

1. On Vopak sites the floor of every electrical station has to be constructed, when replaced, above the possible inundation level for an inundation event with an probability of 1/10,000 a year in 2050. This equals an a floor height of:

VTC:	5.4 m +NAP
VT Laurenshaven:	5.4 m +NAP
VTE:	5.65 m +NAP
VTB:	[no height specification needed]
VTTTR:	[no height specification needed]

2. Off-site the connecting electrical grid of Stedin and TenneT has to constructed, when replaced, above the possible inundation level for an inundation event with an probability of 1/10,000 a year in 2050 or protected at a similar level. Vopak should propose that the harbor, in the form of DeltaLinqs or the harbor Authority) requires Stedin and TenneT to provide this.

6.2.2 Recommendations for further research

Based on the qualitative assessment of the uncertainties in the flood risk assessment in section 5.4 the four subjects are considered valuable for improvement. To improve a risk assessment for liquid bulk terminals the following research is recommended:

- Define a standard on the value of risk reduction for Vopak. As Low As Reasonably Practical(ALARP) is a broad statement that does not directly define a guidance value for a cost-benefit ratio. Additionally, it is beneficial for any cost-benefit analysis to have the value of risk reduction for the different categories defined. A basis can be formed by the values suggested and used in this thesis.
- Consider the strength of the tank dikes or containment walls in more detail. Especially how liquid tight the tank dikes are and the tank pit depths are important factors. It is concluded that the tank pits are not inundated for certain inundation levels outside the tank pits. This conclusion has a large influence on the environmental consequence and therefore more detail in the strength consideration would result in an increased reliability of this conclusion.
- Improve the damage data, costs and repair time for pump pits. The impact of salt water inundation on the pump pits as function of inundation height has a large uncertainty. With the possible flooding on multiple pump pits the delivery time of parts might increase and create an extensive repair time.
- Additional research or foundation for the repair and recovery time of the electrical infrastructure following inundation. The repair time of electrical installations in this thesis has a large influence on the recovery time of a terminal. An increase in the reliability of the repair time estimates in respect the damage would results in an increase in the reliability of the assessment.

Table 6-1 Glossary

Term	Meaning. Main source (if applicable).	Translation (Dutch)
Risk	Probability of an effect times the consequence of an effect	Risico
Inundation	Flooding of an site that is not normally flooded	Inundatie
Multi-layer safety	Safety through multiple different kind of measures Layer 1: Prevention. Layer 2: Spatial planning. Layer 3: Crisis management. (Rijksoverheid, 2009)	Meerlaags veiligheid
Environmental damage	Spill of liquid product that is hazardous to the environment.	Milieuschade
Economic damage	The combination of direct damage and damage due to downtime of the installation. Following from Vopak's 'Risk Matrix' (Royal Vopak, 2013)	Financieel risico
Reputation damage	A combination of five subcategories: reduced or non-performance, financial liability, negative news coverage, loss of customers, negative influence reputation Vopak. In this thesis assumed as downtime	Bedrijfsimpact
Unembanked areas	Area which is not (officially) protected by flood protection. River banks, harbor areas. Does not directly mean that the area is prone to frequent flooding.	Buitendijks Gebied
Hardening	refers to physically changing the infrastructure to make it less susceptible to damage from extreme wind, flooding, or flying debris. Hardening improves the durability and stability of energy infrastructure, making it better able to withstand the impacts of hurricanes and weather events without sustaining major damage.	Weerbaar maken
Utilities	Water, wastewater, electricity, gas, transportation and telecommunication	Nutsvoorzieningen
CBA	Cost-Benefit analysis. A evaluation on the costs and benefits of an action.	KBA
ALARP	As Low As Reasonably Practical. For Vopak defined in Vopak's risk matrix (Royal Vopak, 2013)	Zo laag als redelijkerwijs verwacht kan worden
Containment wall / Tank dike	A (often earthen) wall to contain product in a limited area when a tank fails. It is built to keep liquid in.	Tankdijk
Qualitative Assessment	Assessing a risk by use of experts and discussion groups.	Kwalitatieve evaluatie
Quantitative Assessment	Assessing the risk by use numbers from for example models, measurements or inquiries.	Kwantitatieve Evaluatie
'Tuimeldijk'	A low dike, designed to overflow with high water levels. (Kennisbank-waterbouw, 2016)	Tuimeldijk
Optimal risk	A level of risk for which the total costs (Risk+Prevention) are at the lowest level.	Risico optimum

Bibliography

Actueel Hoogtebestand Nederland. (2016, June-September). AHN viewer. Amersfoort, Nederland.

Air Products. (2016, May). *Repair estimate.* Freddy Koetse.

Air Products and Chemicals, Inc,. (2015). *Safetygram-7.* Allentown: Air Products and Chemicals.

Ale, p. (2006). *Risk is of all time.* Delft: Delft University of Technology.

Amy Glenn. (sd). *Econ Basics.* Opgeroepen op 11 01, 2016, van AmyGlenn: http://www.amyglenn.com/ECON/econ2302basics.htm

Arcadis. (2011). *Buitendijks in beeld.* Rotterdam: Ministerie van Infrastructuur en Milieu.

Arthurs, C. (2015, February 20). *Recover, Repair, Prepare: Calgary After the 2013 Flood*. Opgeroepen op August 17, 2016, van World Conference on Disaster Management: https://www.wcdm.org/blog/recover-repair-prepare-calgary-after-the-2013-flood.html

Assessment Methods. (2009). In M. J. Bresciani, M. Moore Gardner, & J. Hickmott, *Demonstrating Student Success* (p. Chapter 4). Sterling: Stylus Publishing.

Atherton, W., & Ash, J. (2006). *Review of failures, causes & consequences in the bulk storage industry.* Liverpool: Liverpool John Moores Universit.

Basta, C. (2009). *Risk, Territory and Society: Challenge for a Joint European Regulation.* Delft: TU Delft.

Blaeij, A. d., Florax, R., Rietveld, P., & Verhoef, E. (2000). The value of statistical life in Road Safety. *Accident Analysis and Prevention*, pp. 973-986.

Bockarjova, M., Rietveld, P., & Verhoef, E. (2012). *Composite valuation of immaterial damage in flooding: Value of a statistacal life, Value of statistical evacuation and Value of Statistical injury.* Tinbergen institute.

Bonte, R., Dijk, S. v., Ledden, M. v., & Visch, J. v. (2016). *02/Concept: Overstromingsrisicoanalyse Botlek.* Rotterdam: Royal HaskoningDHV.

Bonte, R., van Dijk, S., van Ledden, M., & Visch, J. (2016). *Overstromingsrisicoanalyse Botlek.* Rotterdam: Havenbedrijf Rotterdam.

Bos, W. v. (2006). *Erosiebestendigheid grasbekleding tijdens golfoverslag.* Delft: Rijkswaterstaat.

Bowles, D. (2002). *ALARP evaluation: Using cost effectiveness and disproportionality to justify risk reduction.* Ancold Conference on Dams.

BPL. (2016, December 10). *Correction wording flood risks for the Netherlands in IPCC report.* Opgehaald van BPL.nl: http://www.pbl.nl/en/dossiers/Climatechange/content/correction-wording-flood-risks

Bureau BRZO+. (2016). *BRZO Bedrijvenlijst.* Utrecht: Rijkswaterstaat.

Chemiehaven, V. o. (2016, 07 12). Job shadowing VTC operations. (K. Knulst, Interviewer)

Cohen, M. (2010). *A taxonomy of Oil Spill Costs.* Washting D.C.: Resources for the future.

Defra. (2008). *Defra Flood and Coastal Defence Appraisal Guidance: Assessing and valuing the risk to life from Flooding.*

Deltaprogramma Nieuwbouw en Herstructurering. (2011). *Notitie Ruimtelijke inrichting en Waterveiligheid.* Deltaprogramma.

Deltares. (2011). *Maatschappelijke Kosten Baten Analyse Waterveiligheid 21e Eeuw.* Delft: Deltares.

Environmental Protection Agency. (2016). *BAT reference documents (BREFs) and BAT Conclusions*. Opgeroepen op 11 7, 2016, van EPA.ie: http://www.epa.ie/licensing/info/bat/

Ershdal, G., & Aven, T. (2008). *Risk informed decision-making and its ethical basis.* Stavanger: University of Stavanger.

European Central Bank. (2017, 01 23). *The definition of price stability*. Opgehaald van ECB: https://www.ecb.europa.eu/mopo/strategy/pricestab/html/index.en.html

Europoort, V. o. (2016, 04 28-30). Job shadowing VTE. (K. Knulst, Interviewer)

Expertise Netwerk Waterveiligheid. (2012). *Meerlaagsveiligheid nuchter bekeken.* Rijkswaterstaat.

FEMA. (1999). *Protecting Building Utilities From Flood Damage: Principles and Practices.* Washington: Mitigation Directorate.

Gemeente Rotterdam. (2004). *Havenplan 2020.* Rotterdam: Gemeente Rotterdam.

Gemeente Rotterdam. (2013). *De Herijking van Waterplan 2 Rotterdam.* Rotterdam: Gemeente Rotterdam.

Hamburg Port Authority. (2016). *Port Flood Waters*. Opgeroepen op July 15, 2016, van Hamburg-Port-Authority.de: http://www.hamburg-port-authority.de/en/the-port-of-hamburg/port-flood-waters/Seiten/default.aspx

Helpdesk water. (Augustus 2007). *Hydraulische Randvoorwaarden primaire waterkeringen.* Den Haag: Ministerie van Verkeer en Waterstaat.

Hoss, F. (2010). *A comprehensive assessment of Multilayered Safety(Meerlaagsveiligheid) in flood risk management.* Delft: Delft University of Technology.

HSE. (2016, 09 16). *ALARP ChecK*. Opgeroepen op 09 16, 2016, van hse.gov.uk: http://www.hse.gov.uk/risk/theory/alarpcheck.htm

Huizinga, J., Nederpel, A., de Groot, K., & Batterink, M. (2011). *Risicomethode buitendijks: Methodiek ter bepaling van risico's als gevolg van hoogwater.* Rotterdam: Province Zuid-Holland.

Industrial Design and Development services B.V. Milieu en Techniek. (1999). *Rapport nader bodemonderzoek Fase 2 Rotterdam Botlek.* Katwijk: Tank installatie Chemiehaven.

Jongejan, R. (2008). *How safe is safe enough?* Delft: Technische Universiteit Delft.

Kameshwar , S., & Padgett, J. (2015). *Fragility Assessment of Above Ground Petroleum Storage Tanks under Storm Surge.* Vancouver: ICASP12.

Kennisbank-waterbouw. (2016). *Translation box for online translations* . Opgeroepen op 08 15, 2016, van Virtual Knowledge Centre - Hydraulic Engineering: http://www.kennisbank-waterbouw.nl/Glossary/lijstje.php?nr=366&taal=NL

Kilometerafstanden. (2016, 06 23). *Oppervlakte berekenen*. Opgehaald van Kilometerafstanden: http://www.kilometerafstanden.nl/oppervlakte-berekenen.htm

Klostermann, J., Koperberg, Y., Smale, A., & Slager, K. (2013). *Adaptief vermogen van bedrijven in buitendijks gebied.* Wageningen: Alterra Wageningen UR.

KNMI. (2015). *KNMI'14 climate scenarios for the Netherlands.* De Bilt: KNMI.

Kok, M., Huizinga, H., Vrouwenvelder, A., & Barendregt, A. (2004). *Standard Method 2004 Damage and Casualties by Flooding.* Ministerie van Verkeer en Waterstaat.

Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., . . . Thieken, A. (2009). Is flow velocity a significant parameter in flood damage modelling? *Natural Hazards and Earth System Sciences, Volume 9, Issue 5*, 1679-1692.

Landucci, G., Antonioni, G., Tugnoli, A., & Cozzani, V. (2012). Release of hazardous substances in flood events: Damage model for atmospheric storage tanks. *Elsevier*, 200-216.

Lansen, A., & Jonkman, d. (2010). *Flood in unembanked areas - Part D - Vulnerability of port infrastructure.* Utrecht&Wageningen: Knowledge for Climate.

Maverick, J. (2017, 01 31). *What is the historical market risk premium?* Opgehaald van Investopedia: http://www.investopedia.com/ask/answers/040715/what-historical-market-risk-premium.asp

Milieu- en Natuurplanbureau. (2003). *Nuchter omgaan met risico's.* Bilthoven: RIVM.

Milieu- en Natuurplanbureau. (2004). *Risico's in bedijkte termen.* Bilthoven: RIVM.

Ministerie van Infrastructuur en Milieu . (2009). *Nationaal waterplan.* Den Haag: Ministerie van Infrastructuur en Milieu .

Ministerie van Infrastructuur en Milieu. (2011). *BKO notitie Beleid waterveiligheid buitendijks: huidige situatie en voorgenomen besluit over rijksbeleid.* Den Haah: Ministerie van Infrastructuur en Milieu.

Ministerie van Infrastructuur en Milieu. (2014). *Deltaprogramma 2015: Werk aan de Delta.*

Ministerie van Infrastructuur en Milieu. (2014). *Water in Beeld 2014.* Den Haag: Ministerie van Infrastructuur en Milieu.

Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. (2004). *Besluit externe veiligheid inrichtingen.* Staatsblad 250.

Mobility and transport, Road Safety. (sd). Opgeroepen op 10 29, 2016, van Ec.europa.eu: http://ec.europa.eu/transport/road_safety/specialist/knowledge/measures/monetary_valuation_of_road_safety_en

Moet, D., & Eshuis, L. (2009). *Impressie spelers en belangen regio Rotterdam.* Rotterdam: Arcadis.

Mollee, A. (2016). *Overstromingsrisico's in het Rotterdamse havengebied.* Deventer: Antea Group.

Nationaal Coördinator Terrorismebestrijding en Veiligheid. (2015). *Resultaten herijking vitale infrastructuur.* Den Haag: Ministerie van Veiligheid en Justitie.

National Center for Health Statistics. (2013). *Mortality Data for 2013, as compiled from data provided by the 57 vital statistics jurisdictions through the Vital Statistics Cooperative Program.* National Safety Council.

National Oceanic and Atmospheric Administration. (sd). *Storm surge and Coastal inundation*. Opgeroepen op september 26, 2016, van NOAA.gov: http://www.stormsurge.noaa.gov/

Nederland 30-Jaar Obligatierendement. (2016, July). Opgeroepen op July 19, 2016, van Investing.com: http://nl.investing.com/rates-bonds/netherlands-30-year-bond-yield-historical-data

Nicolai, R. (2016). *Toelichting Waterdieptekaarten Pilot Botlek.* Lelystad: HKV lijn in water.

Nicolai, R., Botterhuis, T., Pleijter, G., Huizinga, J., & Stijnen, J. (2016). *Waterdieptekaarten Pilot Botlek definitief.* Delft: HKV.

OECD. (2016). *Financial Management of Flood Risk.* OECDpublishing.

Office of Electricity Delivery and Energy Reliability. (2010). *Hardening and Resiliency: U.S. Energy Industry Response to Recent Hurricane Seasons.* Washington D.C.: U.S. Department of Energy.

Organisation for Economic Co-operation and Development (OECD). (2014). *Water Governance in the Netherlands.* The Hague: OECD.

Pawirokromo, J. (2014). *Design of a flood proof storage tank.* Delft: Delft University of Technolog.

PGS-beheerorganisatie. (2016). *Publicatiereeks Gevaarlijke Stoffen 29(PGS29).* PGS-beheerorganisatie.

PGS-projectbureau. (2016). *CONCEPT: Publicatiereeks Gevaarlijke Stoffen 6: Aanwijzingen voor de implementatie van het Brzo 2015.* PGS programmaraad.

Programmateam Rijnmond-Drechtsteden. (2014). *Synthesedocument Rijnmond-Drechtsteden.* Ministerie van Infrastructuur en Milieu: Deltaprogramma.

Provincie Zuid-Holland. (2013). *Nieuw Zuid-Hollands beleidskader voor buitendijks bouwen.* Bureau Mediadiensten provincie Zuid-Holland.

Publiekscentrum Water in Zuid-Holland. (sd). *Europoortkering*. Opgeroepen op July 14, 2016, van Keringhuis.nl: http://www.keringhuis.nl/index.php?id=14

Rath, J. (2007). *Data Center Site Selection.* San Franciso: Rath Consulting.

Rijksoverheid. (2009). *Nationaal Waterplan.* Den Haag: Rijksoverheid.

Rijksoverheid. (2015, April 22). *memorie van toelichting wijziging van de Waterwet*. Opgeroepen op July 19, 2016, van Internetconsultatie.nl: https://www.internetconsultatie.nl/ontwerpwijziging_waterwet

Rijkswaterstaat. (sd). *Hartelkering*. Opgeroepen op July 14, 2016, van Rijkswaterstaat.nl: https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/deltawerken/hartelkering.aspx

Royal HaskoningDHV. (2016). *Rapportage Pilot Waterveiligheid Botlek 2C.* Rotterdam: Havenbedrijf Rotterdam.

Royal Vopak. (2002). *Drawing of tank dike VTC.* Rotterdam: Vopak.

Royal Vopak. (2013). *Risk Matrix.* Watt, Andy.

Royal Vopak. (2014). *Business Continuity Standard.* Rotterdam: Vopak Global Operations Safety, Health and Enviroment.

Royal Vopak. (2016). *At a glance*. Opgeroepen op July 7, 2016, van www.Vopak.com: https://www.vopak.com/at-a-glance

Royal Vopak. (2016). *Overstromingsrisico inventerisatie Laurenshaven.* Roterdam: Vopak.

Rushton, A., & Reston, S. D. (2006). *CBA, ALARP and industrial safety in the United Kingdom.* Crown.

Scheuren, P. (2011, September 12). *choosing-a-discount-rate*. Opgeroepen op July 19, 2016, van IMPACT DataSource: http://www.impactdatasource.com/choosing-a-discount-rate/

Schmidt Etkin, D. (2000). *A Worldwide Analysis of Marine Oil Spill Cleanup Cost Factors.* Winchester, Massachusetts, USA: Environmental Research, Consulting.

SenterNovem. (2006). *Handleiding Besluit externe veiligheid inrichting.* Den Haag: Vrom - Ministerie van Verkeer en Waterstaat.

Siepman, E., & Blom, U. (2012). *Waterveiligheid in het bebouwd buitendijks gebied in Rotterdam.* Rotterdam: Arcadis.

Slootjes, N., & Wagenaar, D. (2015). *Potentiële inundatie Botlek.* Delft: Deltares.

Smith, S. (2012, november 1). *What Salt Water Does to Houses*. Opgeroepen op July 7, 2016, van networx.com: http://www.networx.com/article/what-salt-water-does-to-houses

Sorrel, S. (2001). *"The Meaning of BATNEEC: Interpreting Excessive Costs in UK Industrial Pollution Regulation.* Sussex: SPRU.

Sovacool, B. K. (2008, May). The cost of failure: A preliminary assessment of major energy accidents, 1907-2007. *Energy Policy*, pp. 1802-1820.

Staf deltacommissaris. (2015). *Deltaplan 2015: Werk aan de Delta.* Den Haag: Het ministerie van Infrastructuur en Milieu en het ministerie van Economisch Zaken.

Stedin. (2016 (received)). *Informatie met betrekking tot elektriciteits- en gasnetten v0.99.* Rotterdam: Stedin.

URS. (2003). *Thames coast flood risk.* Thames-Coromandel: New Zealand Limited.

US Army Corps of Engineers. (2017, January 26). *Nonstructural Flood Risk Management Measures.* Opgehaald van USACE NW division: http://www.nwd-mr.usace.army.mil/rcc/MRFTF/docs/USACE-NFPC%20Nonstructural%20Measures%20Definitions.pdf

van Dantzig, D. (1956). Economic decision problems for flood prevention. *Econometrica*, 276-287.

van den Bosch, P., & Volberda, P. (2011). *The Strategic Value of the Port of Rotterdam for the International Competitiveness of the Netherlands.* Rotterdam: Port of Rotterdam.

van der Meer, D. J. (2002). *Technical Report Wave Run-Up and wave overtopping at Dikes.* Delft: Technical Advisory Committee on Flood Defence.

Van der Most, H., Slootjes, N., & Schasfoort, F. (2014, September 29). Nieuwe normering van waterveiligheid. *Deltafact*.

Van Veelen, P. (2013). *Adaptive strategies for the Rotterdam unembanked area.* Rotterdam: Knowledge for Climate.

Voorendt, M. (2013). *Flood risk in the Netherlands.* Delft University of Technology: Department of Hydraulic Engineering.

Vopak Terminal Botlek B.V. (26 May 2016). *Veiligheidsrapport BRZO 2015.* Rotterdam: Vopak Terminal Botlek B.V.

Vopak Terminal Chemiehaven B.V. (31 May 2016). *Veiligheidsrapport BRZO 2015.* Rotterdam: Vopak Terminal Chemiehaven B.V.

Vopak Terminal Europoort B.V. (27 Juni 2016). *Veiligheidsrapport Europoort.* Rotterdam: Vopak Terminal Europoort B.V.

Vopak Terminal Hamburg. (2014). *Flood Protection Terminal Neuhoff.* Internal document: Vopak.

Vopak Terminal Houston. (2015). *Gulf Coast Hurricane Preparedness Plan.* Houston: Royal Vopak.

Vrouwenvelder, T., Lind, N., & Faber, M. (2015). *Protocols for Communcation and Governance of Risks.* Vancouver: ICASP12.

Westerduin, B., Oorschot, B., & Blom, C. (2016, September 1). Technical feedback session Vopak. (K. Knulst, Interviewer)

WHO. (2016). *Risk Perception.* Opgeroepen op 11 09, 2016, van Vaccine Safety Basics: http://vaccine-safety-training.org/risk-perception.html

Wolthuis, M. (2011). *Unembanked areas - A risk assessment approach.* Delft: Delft University of Technology.

X-Rates. (2016, 01 18). *Montly average*. Opgehaald van X-rates: http://www.x-rates.com/average/?from=GBP&to=EUR&amount=1&year=2016

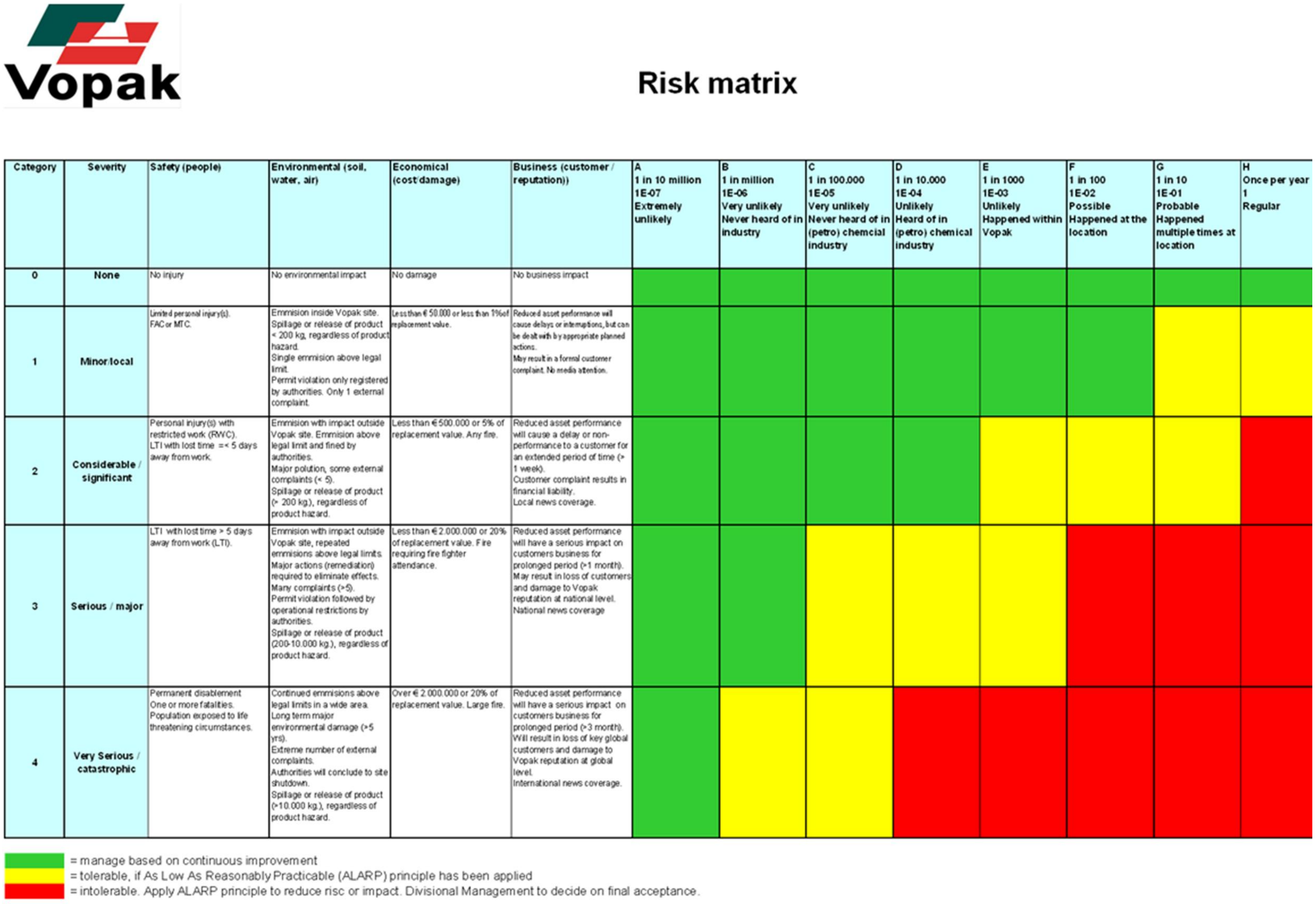
Zethof, M., Huizinga, H., Kok, M., & Maaskant, B. (2011). *Verbeteringen aan de methode voor bepaling van de schade in buitendijkse gebieden.* Lelystad: Deltares.

Zimmerman, H. J. (2000, April 16). An application-oriented view of modeling uncertainty. *European Journal of Operational Research Volume 122 Issue 2*, pp. 190-198.

List of variables

A_b = Area of the Botlek that benefits from a risk reducing measure $[m^2]$
A = Object area that is inundated $[m^2]$
A_j = Area of the terminal inundated when inundation event j $[m^2]$
A_t = Total area of the terminal $[m^2]$
A_V = Area of Vopak in the Botlek that benefits from a risk reducing measure $[m^2]$
b = Inundation boundary b for repair time DT $[m]$
$C_{k,j}$ = Consequence of inundation event j for risk category k [fatalities, litres, €, weeks]
d = Inundation level $[m]$
d_f = Inundation level of failure of the tank dike $[m]$
d_s = Inundation level of failure of the tank dike due to sliding $[m]$
d_o = Inundation level of failure of the tank dike due to overtopping $[m]$
d_c = Inundation level of failure of the tank dike to conductivity $[m]$
DP = Damage percentage for an inundation event [%]
DT = Time needed to repair damage to object [weeks]
DA = Damage value per area $[€/m^2]$
DV = Damage value per object [€]
E_k = Risk of risk category k [fatalities/year, litres/year, €/year, weeks/year]
F = Number of people present on a terminal [#]
h_d = Height of the tank dike $[m]$
I_T = Investment costs of a measure [€]
I_V = Investment costs of a measure for Vopak [€]
k = Risk category [#]
L_d = Downward force by filled pipeline $[kg/m]$
L_r = Pipeline radius $[mm]$
L_t = Pipeline thickness $[mm]$
L_d = Maximum floating force on pipeline $[kg/m]$
m = Number of inundation events [#]
M = Mortality fraction [%]
M_k = Monetizing factor for risk category k [€/fatality, €/litre, €/week]
n = Number of objects considered for risk category k [#]
n_A = Objects calculated with damage function [#]
n_B = Objects calculated with a damage value per square meter inundated [#]
n_C = Objects calculated with with a value per object inundated [#]
N = Net present value of an annual risk reduction [€]
$p_{k,ij}$ = Probability of failure object i when inundation event j for risk category k [%]
z = Probability of succesfully appliance of temporary fixes [%]
p_x = Probability of failure of one or more tanks in a tank pit [%]
q_j = Probability of inundation event j [#/year]
qe_j = Probability of exceeding event j [#/year]
r = discount rate [%/year]
r_g = risk growth rate [%/year]
R_A = Risk value with ALARP [€/year]
R_C = Risk value with CBA [€/year]
R_k = Monetized risk of risk category k [€/year]
R_r = Annual risk reduction [€/year]
RV = Replacement value [€]
s = Number of simulations used to account for local uncertainty in unindation level = 10,000 [#]
S_p = Spill percentage [%]
S_l = Seepage length $[m]$
S_c = Soil conductivity $[m/day]$
t_d = Tank pit depth $[m]$
t_h = Tank height $[m]$
t_n = Number of tanks in tank pit [#]
t_r = Tank radius $[m]$
t_t = Thickness of the tankside and roof $[m]$
t_w = Downwards pressure of the tank $[kg/m^2]$
T = Payback period [year]
W_k = CB factor for the risk category k $[-]$
x = random generated number on [0,1] $[-]$
σ = standard deviation of inundation level $[m]$
ρ_s = Density of steel $[kg/m^3]$
ρ_w = Density of salt water $[kg/m^3]$
ρ_l = Density of the liquid stored $[kg/m^3]$

Appendix A. Vopak's risk matrix



Vopak

Risk matrix

Category	Severity	Safety (people)	Environmental (soil, water, air)	Economical (cost damage)	Business (customer / reputation))	A 1 in 10 million 1E-07 Extremely unlikely	B 1 in million 1E-06 Very unlikely Never heard of in industry	C 1 in 100.000 1E-05 Very unlikely Never heard of in (petro) chemcial industry	D 1 in 10.000 1E-04 Unlikely Heard of in (petro) chemical industry	E 1 in 1000 1E-03 Unlikely Happened within Vopak	F 1 in 100 1E-02 Possible Happened at the location	G 1 in 10 1E-01 Probable Happened multiple times at location	H Once per year 1 Regular
0	**None**	No injury	No environmental impact	No damage	No business impact	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1	**Minor/local**	Limited personal injury(s). FAC or MTC.	Emmision inside Vopak site. Spillage or release of product < 200 kg, regardless of product hazard. Single emmision above legal limit. Permit violation only registered by authorities. Only 1 external complaint.	Less than € 50.000 or less than 1%of replacement value.	Reduced asset performance will cause delays or interruptions, but can be dealt with by appropriate planned actions. May result in a formal customer complaint. No media attention.	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨
2	**Considerable / significant**	Personal injury(s) with restricted work (RWC). LTI with lost time =< 5 days away from work.	Emmision with impact outside Vopak site. Emmision above legal limit and fined by authorities. Major polution, some external complaints (< 5). Spillage or release of product (> 200 kg.), regardless of product hazard.	Less than € 500.000 or 5% of replacement value. Any fire.	Reduced asset performance will cause a delay or non-performance to a customer for an extended period of time (> 1 week). Customer complaint results in financial liability. Local news coverage.	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟥
3	**Serious / major**	LTI with lost time > 5 days away from work (LTI).	Emmision with impact outside Vopak site, repeated emmisions above legal limits. Major actions (remediation) required to eliminate effects. Many complaints (>5). Permit violation followed by operational restrictions by authorities. Spillage or release of product (200-10.000 kg.), regardless of product hazard.	Less than € 2.000.000 or 20% of replacement value. Fire requiring fire fighter attendance.	Reduced asset performance will have a serious impact on customers business for prolonged period (>1 month). May result in loss of customers and damage to Vopak reputation at national level. National news coverage	🟩	🟩	🟨	🟨	🟨	🟥	🟥	🟥
4	**Very Serious / catastrophic**	Permanent disablement One or more fatalities. Population exposed to life threatening circumstances.	Continued emmisions above legal limits in a wide area. Long term major environmental damage (>5 yrs). Extreme number of external complaints. Authorities will conclude to site shutdown. Spillage or release of product (>10.000 kg.), regardless of product hazard.	Over € 2.000.000 or 20% of replacement value. Large fire.	Reduced asset performance will have a serious impact on customers business for prolonged period (>3 month). Will result in loss of key global customers and damage to Vopak reputation at global level. International news coverage.	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥

🟩 = manage based on continuous improvement
🟨 = tolerable, if As Low As Reasonably Practicable (ALARP) principle has been applied
🟥 = intolerable. Apply ALARP principle to reduce risc or impact. Divisional Management to decide on final acceptance.

Figure 1 Risk matrix of Vopak

Appendix B. Summary of Terminal Neuhof site visit

Date of visit	31-08-2016	Project leader:	Jens Gerundt
Visit by:	Kees Knulst	Received presentation and tour by:	Frank Hammerle
Goal:	Receive information from flooding practice, hear how flood risk evaluation was applied and see how flood measures were implemented.		
Received information	- Presentation: Flood protection terminal Neuhof 24-03-2016 - Presentation: Flood Protection terminal Neuhof 31-08-2016 - 2016-09-01_Orientierungsrahmen - 2016-09-01_Bemessungsverfahren Sturmflut		

What kind of flood risk reducing measure is implemented?
A flood wall with flood gates is built around the whole site except the office and control room. Those two objects are built at an adequate level to provide dry feet.

Which design levels are used?
7,3 meter plus freeboard. The design levels follow from the harbor authority, which subsidizes a certain flood wall level. A higher protection level was considered not beneficial since a higher protection was not additionally subsidized. In the future an increase of the design level is expected and an additional subsidy is expected to support the adjustment to that level. Therefor the foundation of the floodwall is made ready for this future increase of flood wall height while it is not implemented yet. This is to make full use of the expected future subsidy.

How large is the risk now?
The risk is 0.7 million a year. In 2013 there a flooding occurred at the Hamburg terminal. The risk originates from a fresh water flood. After the 2013 food there were three scenarios defined with an according flood level. The probability of the current flood levels was not known to Jens Gerund or Frank Hammerle. The probability a year in 2050 for the 8.1 level is 1:5000. Other probabilities were estimated by Kees Knulst from the data supplied by Frank Hammerle originating from the Hamburg authorities. A lower sea level rise is assumed by the Hamburg authorities compared to the Netherlands. 20 cm versus an average of 35cm in the Netherlands.

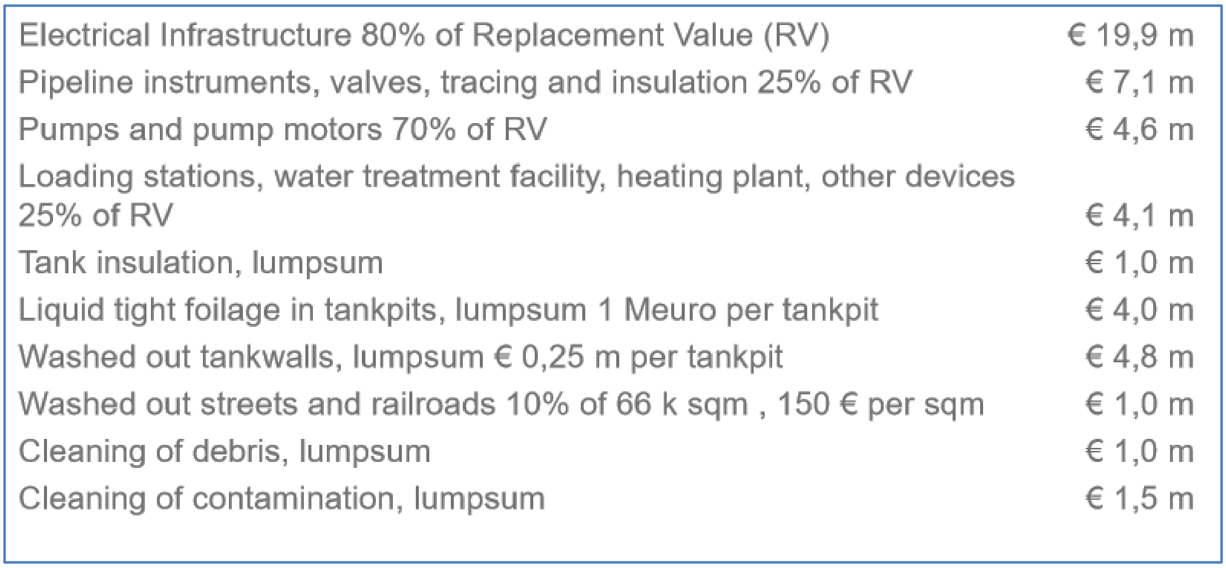
	7.3 m	8.1 m
2015	1:1000 a year	1:10000 a year
2050	1:500 a year	1:5000 a year
2050(with Dutch sea level rise)	1:300 a year	1:3000 a year

Is there cooperation with other companies?
The project is subsidized by the harbor authority. Vopak was advised by the harbor authority to look into combining efforts with neighbours, which was done. However due to the neighbours being already protected by a flood wall (of a lower height) there was less urgency and will from their side. Vopak decided to implement flood protection for solely its own terminal.

Interesting facts about the tank dike and flooding:
The flood of 2013 did flood a tank pit which was presumed to be liquid tight, also from the outside. The tank dike was not damaged however. Inundation occurred through holes' rabbits made in the tank dike.

The flood level on the outside and inside of the dike was equal during the flood. The flooding of the tank pit did not increase the damage substantially. It does raise questions however on the presumed liquid tightness of a tank pit and resulting compliance with regulations.

Figure 2 Flood at terminal Neuhof



Electrical Infrastructure 80% of Replacement Value (RV)	€ 19,9 m
Pipeline instruments, valves, tracing and insulation 25% of RV	€ 7,1 m
Pumps and pump motors 70% of RV	€ 4,6 m
Loading stations, water treatment facility, heating plant, other devices 25% of RV	€ 4,1 m
Tank insulation, lumpsum	€ 1,0 m
Liquid tight foilage in tankpits, lumpsum 1 Meuro per tankpit	€ 4,0 m
Washed out tankwalls, lumpsum € 0,25 m per tankpit	€ 4,8 m
Washed out streets and railroads 10% of 66 k sqm , 150 € per sqm	€ 1,0 m
Cleaning of debris, lumpsum	€ 1,0 m
Cleaning of contamination, lumpsum	€ 1,5 m

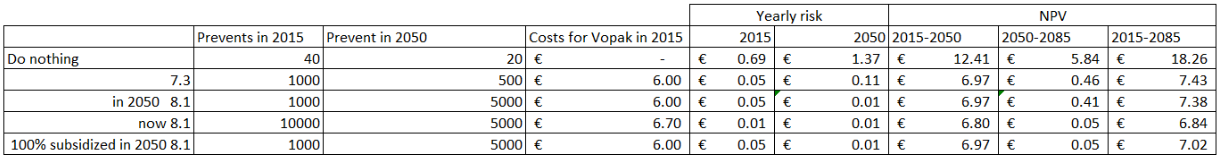
Figure 3 Damage values for an average of a meter inundation at terminal Neuhof, as used in 2015

Figure 4 Water inside the tank pit at Terminal Neuhof (water flowed through the tank dike)

Appendix C. Calculation of Neuhof optimum

This appendix provides foundation for the economic Cost-Benefit ratio that is used for the ALARP zone. It follows a practical approach CB ratio. The principle that a CB ratio of less than one signifies a beneficial measure is flawed. The economic CB ratio for flood reduction measures follows the ratio as is seen at the Vopak terminal in Hamburg.

Table 1 Risk Evaluation (flooding data based on Appendix B and (Hamburg Port Authority, 2016) (Vopak Terminal Hamburg, 2014)

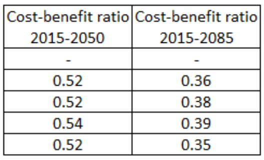


				Yearly risk		NPV		
	Prevents in 2015	Prevent in 2050	Costs for Vopak in 2015	2015	2050	2015-2050	2050-2085	2015-2085
Do nothing	40	20	€ -	€ 0.69	€ 1.37	€ 12.41	€ 5.84	€ 18.26
7.3	1000	500	€ 6.00	€ 0.05	€ 0.11	€ 6.97	€ 0.46	€ 7.43
in 2050 8.1	1000	5000	€ 6.00	€ 0.05	€ 0.01	€ 6.97	€ 0.41	€ 7.38
now 8.1	10000	5000	€ 6.70	€ 0.01	€ 0.01	€ 6.80	€ 0.05	€ 6.84
100% subsidized in 2050 8.1	1000	5000	€ 6.00	€ 0.05	€ 0.01	€ 6.97	€ 0.05	€ 7.02

For Vopak Hamburg there was the choice to protect to 7.3 meter, to protect up to 8.1 meter and protect to 8.1 meter in 2050. The different levels prevent inundation up to a flood event with a probability 1:1,000 and 1:10,000 a year respectively. The associated costs are shown in Table 1. For the different options the implementation costs are shown in 'costs for Vopak in 2015'. The annual risk is shown for each option; currently and in 2050 with the expected increase in sea level. The implementation costs in combination with the net present value of the risk of for three set of periods is shown.

In this thesis a design horizon is used of 35 years this information is used. For the period of 2015-2050 the table shown that protecting up to an inundation event of 8.1 meter has the lowest total costs but it is not executed. The measure has a lower CB ratio than protecting up to 7.3 meter. The different CB ratios are shown in Table 2 for the different flood prevention heights in Hamburg. The CB ratio of the 7.3 option is seen as the optimal cost-benefit ratio for measures since it slightly lower than the CB ratio of 8.1 meter which was not performed.

Table 2 Cost-benefit ratios Hamburg



Cost-benefit ratio 2015-2050	Cost-benefit ratio 2015-2085
-	-
0.52	0.36
0.52	0.38
0.54	0.39
0.52	0.35

The implementation costs were 52% compared to the benefits of the measure and even then the choice to implement had to be supported by additional benefits (the implementation was speeded by a flooding event).

It is assumed that the difference between the value for the CB ratio of 0.5 and expected value of 1 lies not into a sub optimization of the company's risk level but that it results from negative effects that are not covered in the implementation costs of the measures. Negative effects such as a hindrance during daily operations, possible unforeseen increase in other risks, or an increase in maintenance.

Appendix D. Discussion about: Recovery time

There are several causes of the length flood recovery which depends on the exact location. In general, there are four reasons for downtime due to a flooding. Repair of damages, repair or restart of external utility supply, personnel not present, rebooting time of installations (safety checks). These are explained in more detail in this appendix. Vopak has also a general guideline for business continuity, part of this appendix is based on the general information of that guideline (Royal Vopak, 2014).

Repair of damages

The repair of damages has to occur before a full return to service is possible. However, depending on the kind of the damages a partial return to service is very well possible. When the flooding of the terminal is limited a likely scenario is that reparations can take place while a large part of the terminal is in operation. Parts of the essential infrastructure like the command centre or integral safety systems are crucial for every part of the operations. These need to be repaired to provide any function. Other parts such as equipment for a single tank (pit) or mooring facility, can be repaired while there is partial functionality.

The repairs after a flooding event will take (extensively) longer than normal maintenance because of the following reasons:

- High demand on contractors from multiple customers who experienced flood damages
- Limited availability of components
- Access to the terminal might be limited
- A lot of different contractors working simultaneously
- Access at the terminal might be limited if pumping out of water gives environmental issues.
- Planning has to be made on the fly instead of in front of execution to safe time.

The risk to Vopak increases due to having outsourced the construction and the maintenance. The influence on the repair order would be larger with having this in house. Also the availability of components is coming from external supply. The supply is likely insufficient for multiply large orders.

Damage to external utility supply.

The terminals are dependent on external sources of utilities and the access to those can be impaired by a flooding. Utilities can be temporarily shut down to prevent damage and/or it can have sustained damage. A restart of the system can take place quickly but a (temporary) repair will take more time. Depending on the kind of utility this poses certain problems which will prevent full continuation of business. Especially electricity and access will be crucial for a quick return to operations. Other repairs or reboots are dependent on a power supply.

The problem with external utilities is that Vopak has no direct influence on the repairs. Even if it decided that it is in Vopak’s best interest to fund and execute the repair of its utilities by repairing a transformer station of Stedin this is not allowed

The access to the Vopak installations is limited during the storm and in the aftermath of a flooding situation. This is due to closing of roads when high winds speeds are present and due to damage to roads afterwards. However, during extreme storms closing off roads is not a high priority and considering the importance of having access to the harbor area a fully closed A15 is very unlikely. Even with water flowing over the A15 it is expected that the road is still open for certain vehicles. The tunnels won’t be functional but the bridges are still accessible.

Lack of personnel, internal and external

Additional personnel could compensate for having decreased automated control and overview. Also to regulate a high amount of repairs and coordinate them efficiently additional personnel will be required. However, this will be difficult to achieve. Vopak operating personnel often lives in the areas around the Rotterdam harbor. With their homes and families in danger the terminals will have lower priority when an extreme storm situation occurs. For downtime this means that after such a flood it might be difficult to assemble a full crew, let alone to assemble additional personnel. Hiring external contractors to obtain the needed manpower is common practice in a normal situation. However, it is stressed that Vopak is not a sole bidder in this market and the supply of external contractors is limited. Any solutions that highly depend on a large amount of personnel should be considered with this in mind.

Rebooting time of installations

When a plant was shut down due to extreme weather situation checks have to be performed before operations can safely continue. The checks and time needed for this depend on the severity of the shutdown. If only transferring operations have to be ceased the rebooting time is limited. If part of the electrical system has failed some of the checks that normally occur in the CCR have to be conducted manually.

Checks that should be conducted depending on the amount of damage are

- Visual inspection of the site
- Check on the water level in tank pits and pump pits
- Inspection on electrical systems
- Check on fire safety since higher than average fire hazard at restarting after a flooding
- Contaminations of product
- Checks on suppliers and receivers of products

Two examples of repair speed that are present for the repair speed are the flooding of Calgary in 2013 where 51% of the infrastructure is repaired after 18 months (Arthurs, 2015) and the flooding of New Orleans (2005) where electrical plants needed around 3 months of repair before functioning again. The information from these cases is limited or less applicable for the Rotterdam harbor. For the Calgary case no differentiation for different kinds of infrastructure is made. For New Orleans, the flooding area and inundation levels are larger compared to the Rotterdam harbor area.

Appendix E. Description of objects of the system

In this appendix it is described why objects are in the system from 4.1.3. It is also stated in what detail a part of the system is considered.

The electrical stations are important because of the fact that without electricity the terminal will not be able to function. Although tanks will keep the product contained, without electricity the visual or digital measurement of the product height in the tank will be difficult and heating of the product will cease. Because electricity is so vital for Vopak a relative high level of detail is used in assessment of this object group compared to the other objects.

The electrical grid is considered from main transformer stations in the embanked areas to the electrical substations stations on Vopak's terminals. Failure of small electrical equipment like lighting is integrated as a factor added to the value of the distribution stations.

The embanked area as limit for the grid considered is chosen for two reasons. The first reason is that embanked areas are considered to be adequately safe and second being that it geographically outside of the considered area. On the other end of the electrical infrastructure sub substations are chosen as last level at which it is applicable to individually consider objects. This is chosen with respect to the impact size of failure and the effort required. Cable failures are not considered individually since no soil deformations are expected. Without soil deformations electricity is expected to fail only at interconnections.

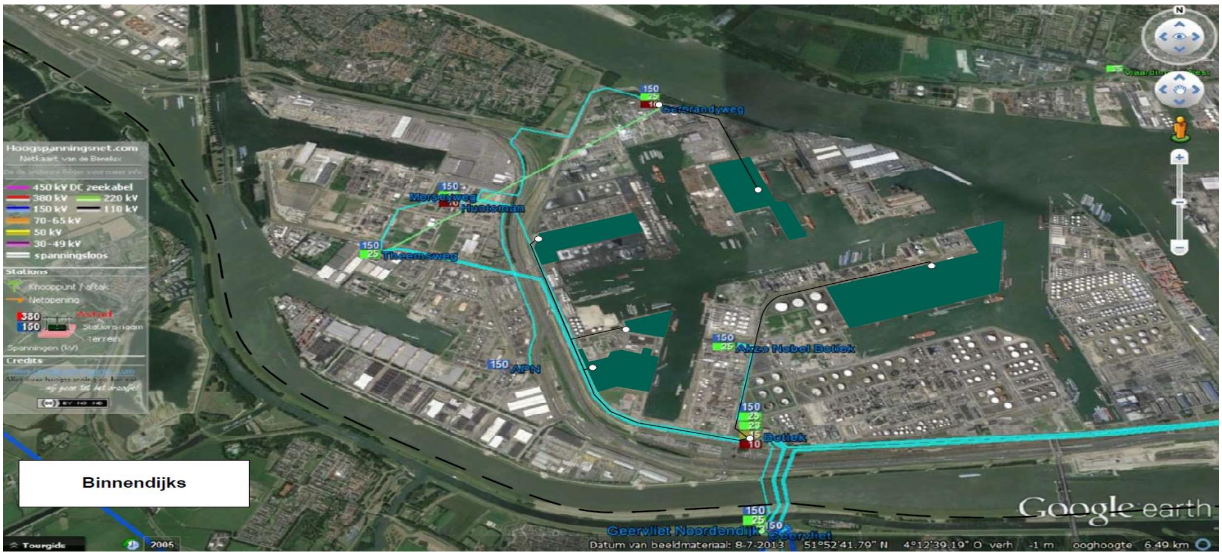


Figure 5 Electrical infrastructure.

The intermediate ring infrastructure of Stedin is placed in a circle and therefore more robust against the failure of one node. However, a flooding event is likely to affect multiple nodes. In the assessment this serial ring structure is not taken into account. A connection from the Botlek station directly to a Vopak terminal is assumed.

In the Central Control Room there is an overview by cameras and from sensors. For the Rotterdam terminals the control of the pumps is partially automated from the CCR. Two of the Botlek terminals are recently sharing one CCR, whereby the former separate control rooms can still be used. The central control room is connected through the two local CCR's which makes the local CCR still crucial for functioning.

Automation takes into account the cameras, the sensors and the digital control of valves and pumps. This object considers everything of the automation except for the central control room since this is considered as an individual object. Most pumps can also be controlled locally however not all monitoring equipment has a manual backup. The more expensive automation parts are located inside the electrical stations.

Water treatment is present onsite and offsite. The onsite water treatment is often only a partial treatment plant after which the still contaminated water is transported to an offsite water treatment plant. When needed it can also directly be pumped to the offsite plant. The offsite plant is considered as one (large) object with one set of object data.

Firefighting is considered on-site and off-site. The onsite part consists of the firefighting pumps and their ability to function during a flood. These pumps are located -4m compared to surface level (at water level) and will experience a large inundation level if the area around the pump facility is inundated with only a limited level. The offsite parts consist of the collective fire brigade. While the fire station will be inundated, the equipment is expected to be temporarily relocated. It is assumed that when access to the harbor is restored, the fire brigade will be in working order without repairs.

Steam is often produced offsite but can always be locally produced. A failure in this supply will lead to partial shutdown of the terminal.

The pump pits are located below surface level and are prone to significant flooding if a limited inundation level is present at surface level. The pump pits have systems to drain them from water, the amount is however not adequate for flooding. It is designed for rainfall. The contents of the pump pits are mostly water-resistant. Flooding by rainwater did occur with minimal damage. However, salt water is expected to cause a larger amount of damage to the electrical equipment present in the pump pits.

Tank pits
The floor level of a tank pit is often several meters below the outside surface level and has a tank dike or sheet pile wall surrounding the pit as containment wall. It is designed to prevent product from spreading out (and not from water flowing in).

Pipelines are present in different sizes and shapes. Those depend on the type and amount of product transported. Mostly the pipelines are located slightly below surface level.

The nitrogen supply is needed for the operation of many parts of the terminal. It is supplied from an external source located in the Botlek to all of Vopak's terminals by pipelines. The damage to the nitrogen supply is assessed by taking the production plant as a single object with one damage factor.

The general area that gets inundated experiences damage from water. This object group covers leftover parts such as tracing, valves, insulation, washed out streets, cleaning of contamination, cleaning of debris.

Appendix F. Damage functions electrical

For the damage function the basis is that for every inundation level a certain percentage of the maximum damage is present. The maximum damage is defined as value.

The damage function of the Standard Method of the Dutch department of publics works is considered the most usable. In this appendix it is, with some assumptions, compared to the values Vopak used in Hamburg and the estimates by Stedin. For Stedin it is assumed that the value for which failure occurs is 31% damages and for a total failure this is 98%. The maximum amount of damage is 100% of the replacement value.

Table 3 Damage factors relative to inundation level

flood depth	Standard Method 2004 RWS damage factor	Stedin >25KV	Stedin 25KV-1k	Stedin <1KV	Stedin AVG1	Vopak Hamburg estimate
0.0	**0.00**	0.00	0.00	0.00	0.00	0.00
0.1	**0.08**	0.00	0.08	0.12	0.07	0.07
0.2	**0.16**	0.01	0.16	0.24	0.14	0.11
0.25	**0.20**	0.01	0.18	**0.31**	0.17	0.13
0.3	**0.24**	0.01	0.20	0.38	0.20	0.16
0.4	**0.29**	0.02	0.25	0.53	0.27	0.23
0.5	**0.32**	0.04	**0.31**	0.68	0.34	0.31
0.6	**0.35**	0.07	0.37	0.80	0.41	0.40
0.7	**0.39**	0.11	0.43	0.89	0.48	0.50
0.8	**0.42**	0.16	0.50	0.95	0.54	0.60
0.9	**0.46**	0.23	0.57	0.98	0.59	0.69
1.0	**0.49**	**0.31**	0.63	**0.99**	0.64	**0.77**
1.1	**0.52**	0.40	0.69	1.00	0.70	**0.84**
1.2	**0.56**	0.50	0.75	1.00	0.75	0.89
1.3	**0.59**	0.60	0.80	1.00	0.80	0.93
1.4	**0.63**	0.69	0.84	1.00	0.84	0.96
1.5	**0.66**	0.77	0.88	1.00	0.88	0.98
1.6	**0.69**	0.84	0.91	1.00	0.92	0.99
1.7	**0.73**	0.89	0.93	1.00	0.94	0.99
1.8	**0.76**	0.93	0.95	1.00	0.96	1.00
1.9	**0.80**	0.96	0.97	1.00	0.98	1.00
2.0	**0.83**	**0.98**	**0.98**	1.00	0.98	1.00
2.1	**0.86**	0.99	0.98	1.00	0.99	1.00
2.2	**0.90**	0.99	0.99	1.00	0.99	1.00
2.3	**0.93**	1.00	0.99	1.00	1.00	1.00
2.4	**0.97**	1.00	1.00	1.00	1.00	1.00
2.5	**1.00**	1.00	1.00	1.00	1.00	1.00
2.6	**1.00**	1.00	1.00	1.00	1.00	1.00
2.7	**1.00**	1.00	1.00	1.00	1.00	1.00

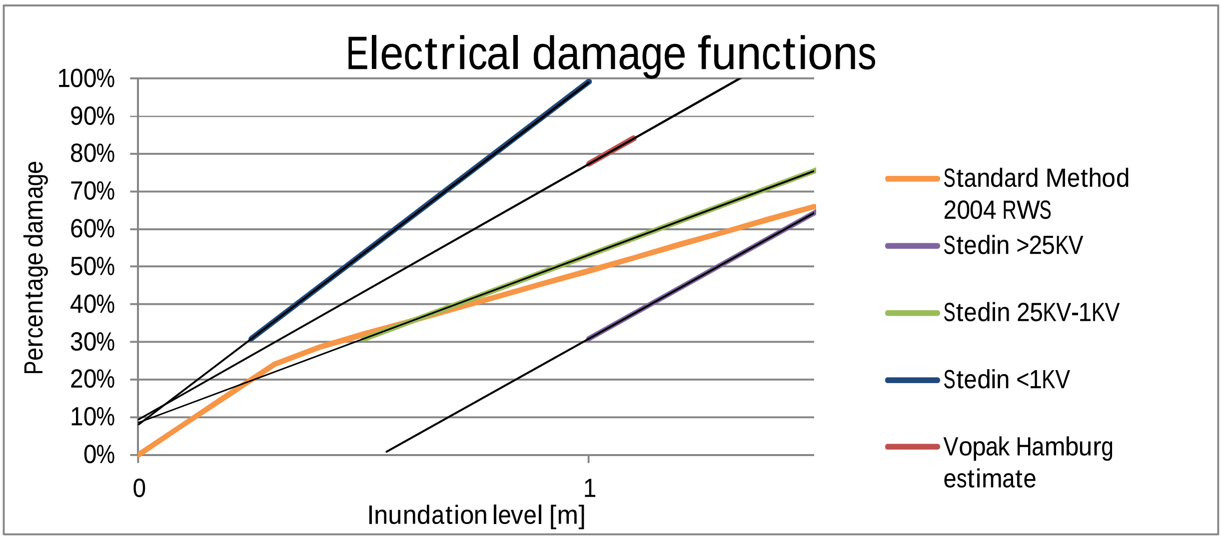


Figure 9 Comparison between electrical damage functions

In Figure 9 the linear extrapolation between the Stedin and Vopak point values are shown, extended with trend lines, next to the damage function from the standard method. Especially for the middle voltage stations, which is similar to the substations at Vopak, the values of Stedin correlate well with the standard method. This supports the use in this thesis of the damage function. However, for inundations in the range of 1 meter Vopak's estimated is extensively higher.

The assumed value of 31% damage for the level of failure of an electrical station is influencing the comparison very highly. Therefor the use of the comparison is limited.

Appendix G. Relation between dike height and pit depth

Failure of the tank dike type of containment wall occurs through one of the three failure mechanisms; sliding, overtopping and seepage. The value results in the level for which exceedance results in a failure of the tank dike. In Figure the inundation level for which there is failure of the tank dike is shown for different tank dike heights.

In this graph it is assumed that from a certain dike height higher tanks dikes are combined with deeper tank pits, with the assumed relation as shown in Figure 7. This relation is visually assumed. It can be seen that two values in this graph are above the assumed relation. This are pits with a high depth compared to the tank dikes and those require extra attention.

With the ‘conservative boundary’ as depth/height relation the failure inundation level function holds for most tank dikes as is shown in figure 8. For deep tank pits (a depth/height ratio of more than 1) it does not hold.

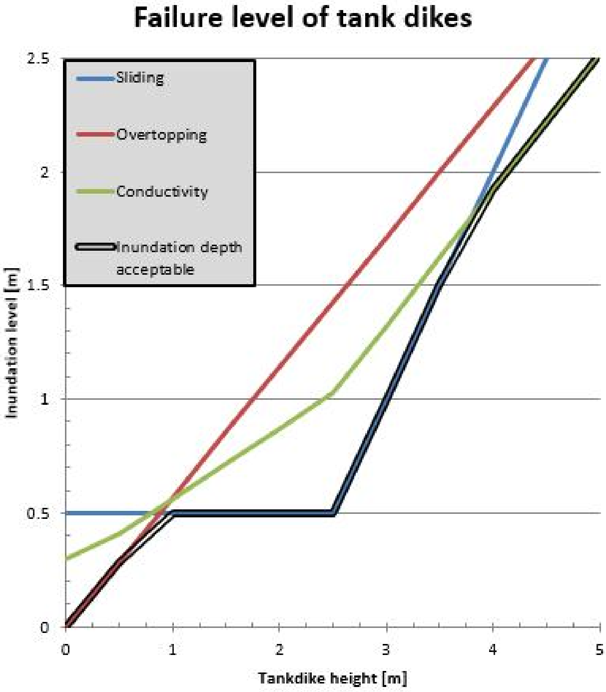


Figure 6 Failure level of tank dikes

The practice values in both graphs results from tank pits located on VTC (TP9, TP8, TP6, TP4, TP1), VTE (TP030, TP090, TP100, TP101, TP103, TP104, TP107, TP140) and VTL (TP1, TP2). The tanks are picked around the possible inundated areas.

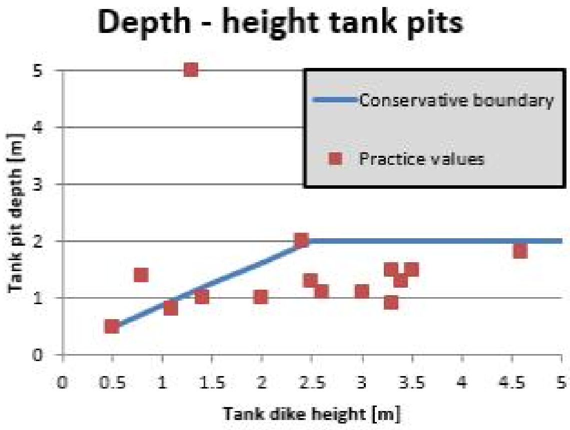


Figure 7 Tank dike height versus tank pit depth

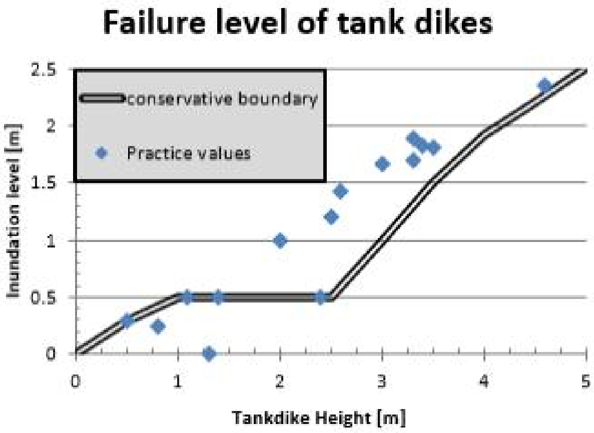


Figure 8 Difference between boundary and practical values

Appendix H. Terminal data

To assess possible temporary fall-back options for electricity and nitrogen outage, the current usage is considered. For electricity the average value of the month with the highest electricity usage from the last three years is used. For example, if the month with the highest use is January, then the average of the value from January 2014, 2015 and 2016 is taken. It is checked if this month is in the storm season; if it is not, another month is used. This is since a inundation event is expected to take place in the storm season. For nitrogen usage the same method is used as for electricity. The result is presented in Table 3

Table 3 Nitrogen and electricity use (Vopak Data)

Terminal	Nitrogen usage		Electricity usage	
	m^3 in gas / year	m^3 in liquid / day	Monthly (kWh)	Peak (kW)
Botlek	1,927,791	7.82	929,708	3,821
Chemiehaven	1,960,560	7.69	587,381	2,414
TTR	4,441,570	17.71	322,808	1,327
Total	6,407,411	33.22	1,839,897	7,652

For the amount of available electrical power that is needed for a terminal it is assumed that the peak use is three times the average use of the terminal.

For the nitrogen use no peak use is considered. An average daily use of liquid cubic meters is calculated to consider how many trucks are needed to supply such demand. The conversion of liquid to gas form has the ratio of 1:694 (Air Products and Chemicals, Inc,, 2015).