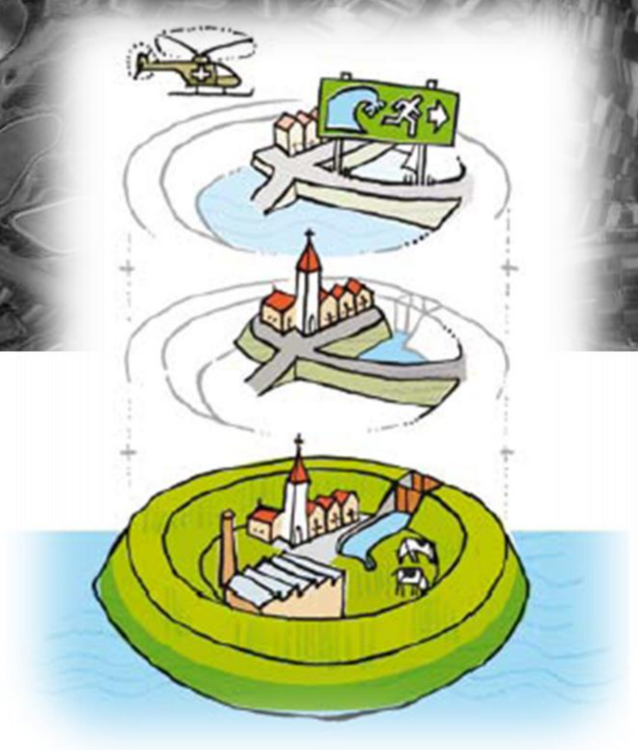
A comprehensive assessment of Multilayered Safety (*Meerlaagsveiligheid*) in flood risk management



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HKV LIJN IN WATER

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MSc thesis

A comprehensive assessment of Multilayered Safety *(Meerlaagsveiligheid)* in flood risk management

by

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This research has been done for the partial fulfillment of requirements for the Master of Science degree in Civil Engineering at the **Delft University of Technology**, Delft (NL).

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Preface

Deze scriptie markeert het eindpunt van mijn studie Civiele Techniek/Waterbouw aan de TU Delft. Mijn afstudeeronderzoek richt zich op Meerlaagsveiligheid in de beheersing van overstromingsrisico's; tegenwoordig een veel besproken onderwerp in de Nederlandse waterwereld. Ik hoop dat dit verslag een steentje aan de discussie zal bijdragen.

Mijn collega's bij HKV, alle betrokkenen bij Dordrecht en mijn afstudeercommissie wil ik langs deze weg bedanken. Ilhame en Ouiam, het is een prestatie dat jullie al mijn grillen hebben uitgehouden. Bedankt en veel succes met jullie Master! - Frauke

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Summary

Introduction

The ever-lasting struggle of the Dutch people to keep their land dry develops along the way. Centuries ago people settled on higher grounds such as river banks or built their houses on terps. When the population and the scale of agriculture increased, people started to build dikes to prevent floods. Over the generations dike rings became the core of the flood defense in the Netherlands. Until this day, the flood-prone parts of the country are protected by more than 50 dike rings. But major floods in the Zuiderzee in 1916 and Zeeland in 1953 gradually changed the understanding of flood protection. It was decided to shut out the sea water by (partially) closing the estuaries reaching deep into the country. Flood prevention thus again spread to a larger scale. The implementation of the latter of these two major projects, called the *Deltawerken*, was just nearing completion, when the big rivers (Rhine, Meuse, Waal) caused floods in 1993/95. This led to yet another step in the development of flood risk management. The realization grew that dikes and storm surge barriers are not the only way to prevent floods. This new strategy aimed at giving the rivers more space and was implemented in the project *Ruimte voor de Rivier*.

Multilayered Safety (*Meerlaagsveiligheid, MLS)* is the next step in this evolution of flood management. This concept originates from the discussion if there are alternatives to prevention. The flooding of New Orleans after Hurricane Katarina called into mind the severity of the impact if the flood prevention fails. Dutch history and examples from other countries show that there is an abundance of flood management measures that potentially might ease this impact of flooding. MLS divides those measures into three layers. The first layer is Prevention as was implemented in e.g. the *Deltawerken* and *Ruimte voor de Rivier.* Prevention, Layer 1, consists of all permanent measures that reduce the probability of a flood. The two other layers represent a possible extension of flood risk management. Layer 2 stands for all Spatial Solutions measures or put differently, all permanent measures taken to decrease the loss due to flooding. Crisis Management, Layer 3, is understood as all temporary measures to be taken if a flood is actually threatening.

Figure 0-1: Multilayered Safety as introduced in the Nationaal Waterplan 2009

Theoretical background

The theoretical basis of flood management is the risk approach. Risk is defined as the product of probability and the loss of an event. The overall flood risk is thus the sum of the risk of all possible events. Usually flood risk management is discussed in terms of probability and loss. Thus, measures are categorized by labeling them probability- or loss-reducing. The actual calculation of probability and loss, thus the risk, is based on a larger number of parameters. Those system parameters describe (undividable) physical characteristics:

- Hydraulic boundary conditions: Which water level WL occurs with what frequency [P(WL)]
- Exposure I: The number of exposed people resp. objects [n]
- Exposure II: The degree of exposure symbolized by the inundation depth. The inundation depth h is the difference between the ground level GL and the water level WL. Thus, the additional undividable system parameter is the ground level [GL]
- Vulnerability: The vulnerability of the affected people resp. objects, expressed as mortality resp. damage function (m resp. Dam).

There are a number of arguments to study MLS on the basis of those four system parameters above instead of probability and loss. First of all, flood risk management is about to be coordinated across all European countries (European Flood Directive). The aim of this study is to examine MLS in a way that the findings can be transferred to any flood-prone area. Those areas are characterized by unique combinations of values of the parameters listed above. To understand the effect of flood management measures in different areas it is thus necessary to find out which measures address which underlying system parameters. Secondly, implementing MLS would mean simultaneously using more than one type of flood management measures. Thus, it is important to understand the (in-) direct interaction of those measures. A sufficiently detailed analysis will have to be based on the system parameters. Thirdly, MLS is meant to ease the consequences of the failure the flood defense system. MLS might even have the potential to address the consequences of certain flooding scenarios resulting from a partial failure of the flood defenses. To accurately describe those consequences a greater level of detail than just "loss" is needed. Considering these arguments this thesis studies MLS as much as possible using the system parameters listed above instead of the less-detailed parameters probability and loss.

The study

This study analyzes the crucial properties of MLS – (side-) effects, interaction and failure – theoretically, occasionally supported by the case studies. The actual size of the effect and cost-efficiency of measures are examined using two case studies. The first case study is hypothetical. The second case study concerns the part of the City of Dordrecht lying inside Dike Ring 22. The abundance of flood management measures around the world makes it necessary to first come up with a theoretical framework that facilitates making a comprehensive choice of flood management measures to be modeled in the case studies. Given the theoretical background summarized earlier, it is necessary to find a framework that is based on the four system parameters introduced above.

A number of models for flood risk management and Safety Science as practiced in industry have been considered as potential foundations for a theoretical framework. The choice fell on Haddon's ten strategies because they comprehensively describe all possible manners of dealing with danger. Furthermore, those strategies support an analysis based on the five system parameters. Translating the strategies to flood risk management, it turned out that all flood risk measures can be divided into addressing the boundary conditions (P(WL)), the exposure (n, GL) and the vulnerability (m resp. Dam). It was found that MLS Layer 1, Prevention, mainly includes measures setting in on the boundary conditions and the exposure, whereas Layer 2 and 3 focus on exposure and vulnerability. The flood management measures have been clustered into categories distinguished by strategy as well as by MLS layer, see the table below.

Overview: Families of flood management measures MLS

Way of functioning theoretically	Way of functioning physically	Strategy No.	Prevention	Spatial Solutions	Crisis Management
Reduce hazard source	*Prevent extreme amounts of water in system*	3	-redistributing discharge over river arms -retaining run-off (i.e. forestation projects)		
	Relief extreme hydraulic situation	4	-Ease hydraulic land in waterways (i.e. Ruimte v/d Rivier) -Relief extreme situations with inundation polders etc		
Reduce exposure	*Prevent that objects/people are in the dangerous area*	5		-Reconsider location choices for i.e. building projects	-Preventive organized evacuation
	Reduce number of affected by erecting barrier between water masses and vulnerable people/objects	6	-Flood defenses	-Compartmentalization	-Temporary flood defenses
	Decrease degree by which objects are affected	7	-Flood defenses which allow controlling inflow Flood defenses resistant to overflow	-Elevate (terps etc.) -Change flood characteristics	
Reduce vulnerability	*Prevent damage from occurring among exposed*	8		-Flood-proofing of buildings	-Self-reliance -Temporary flood-proofing of buildings
	Reduce occurring damage among exposed	9			-Emergency relief -Rescuing

Results

The intended ***effect*** of the flood management measures is risk reduction. However, negative respectively unintended side-effects have been identified as a critical property when applying MLS successfully. By means of a parameter analysis, it was found that measures addressing the frequency of flooding (some of the strategies focusing on the boundary conditions and the exposure) have complex long-term side-effects on social developments such as the intensity and the vulnerability of the population. After all, more frequent floods determine if people choose to live in flood-prone areas and their capability to respond to flooding. Measures taken to reduce the exposure might change the flood characteristics and thus alter the performance of other flood management measures. However, the case studies showed that often those side-effects and their impact on the flood risk are small. Nonetheless, it should be strived to implement flood management measures in a way that does not change, especially worsen, the flood characteristics at another spot. Finally, measures aiming at the vulnerability show the least interaction with the system. Less vulnerability is a material value itself and thus leads to a larger maximal damage. As a consequence there is an optimum of vulnerability.

Interaction is another property important to MLS. It was shown that the cost-efficiency depends heavily on the initial flood risk. This is due to the fact that the any additional measure reduces the probability of an event causing a smaller loss or vice versa. Thus, every MLS measure that is added to an existing one is less cost-efficient. This type of interaction if flood management measures are combining, can be symbolized by 1<1+1<2. This interaction between the individual measures might make it more effective to turn to other measures instead of continuously intensifying the implementation of one measure.

MLS is based on the idea of adding more safety nets to the only existing one, namely Layer 1 – Prevention. In terms of ***failure*** flood safety turns out to be a parallel system. Thus having safety nets is an alternative to the traditional strategy of strengthening the strongest link (the dikes). Furthermore, it was found that most flood management measures resemble parallel systems. Only flood defenses in forms of barriers, such as dikes, are serial systems. It follows that the flood defense system as implemented today (only dikes) is a serial system. Introducing MLS would change this and make it a parallel system, see figure below. However, functioning safety nets are not necessarily desirable. In the case of MLS introducing safety nets might e.g. increase the transaction and administrative costs significantly.

Among the flood management measures, permanent measures, as found in Prevention and Spatial Solutions, have a higher reliability than the temporary measures of Crisis Management. Furthermore, it is noted that the failure of individual (types of) measures is probably highly correlated.

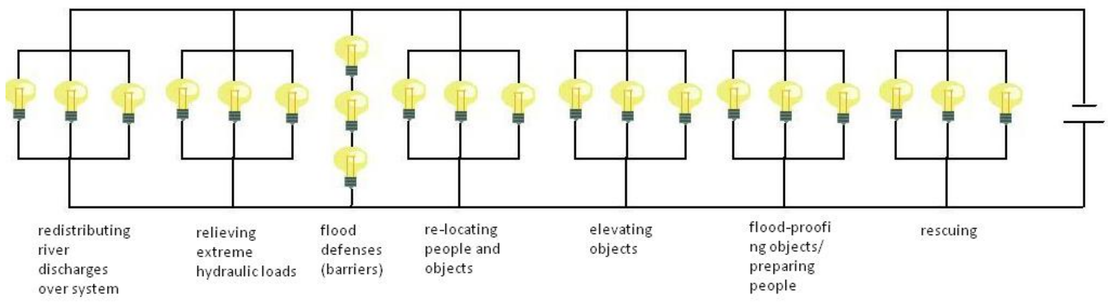


Figure 0-2: Failure behavior of different strategies in flood risk management. Flood defenses are the only strategy that fails like a serial system. It is assumed here that the system has failed if the loss equals the loss without any flood management measures.

The case studies showed that the ***cost-efficiency*** of flood management measures is highly dependent on the characteristics of the area and the initial safety level. It is thus impossible to do a general judgment on the cost-efficiency of MLS and the best way of implementing it. Nonetheless, it was found that flood management measures are most cost-efficient at the geographical scale they are applied at. E.g. Prevention is applied at a relatively large scale and thus cost-**in**efficient for a neighborhood. Flood-proofing is implemented per house or block of houses and therefore more suitable to increase the flood safety in a neighborhood only. Generally it can be said that the smaller the total flood risk, measures with a lower geographical scale of implementation should be chosen. Roughly, this comes down to choosing a lower strategy from the theoretical model. Extending this thought to the practice of Dutch flood risk management it is found that applying measures different than Prevention, as does MLS, is mainly appropriate to address deviations in local risk at the scale of neighborhoods. Spatial Solutions and Crisis Management are not found to be cost-efficient for scales larger than that (e.g. dike ring/delta).

For the ***case of Dordrecht*** it was found that it is most cost-efficient to improve the existing flood defense system by re-activating certain compartmentalization dikes and reinforcing the primary flood defenses by either heightening or making them overflow-resistant. It has been shown that a breach at *Kop van 't Land* in the East of the dike ring would be most devastating. Therefore, it is wise to prioritize reducing the contribution to the risk by this flooding scenario. Doing this makes reactivating certain parts of the compartmentalization dike so efficient.

Figure 0-3: Proposed reinforcement of compartmentalization in dike ring 22

It has been mentioned above that MLS is most efficient if used to customize flood risk management to local conditions. There are a number of ***neighborhoods in Dordrecht*** where the local risk is larger than in the surrounding areas. Those are opportunities to apply MLS in its full scope. It has been shown for the case of the *Wielwijk* that for smaller areas Spatial Solutions (MLS layer 2) are cost-efficient. Since the application of Spatial Solutions to existing buildings is extremely limited, Crisis Management (MLS Layer 3) is another, in the case of Dordrecht less cost-efficient, option. However, given the present national standards on flood safety, there is only a meager legal basis for implementing MLS. After all there are only standards on the exceedance probability of flooding, which does not leave space for choosing for any flood management measures adjusting the flood risk. A national standard limiting the actual flood risk would be necessary to systematically integrate MLS into national flood protection. Nonetheless, if the financial resources are available provincial and local governments have the opportunity to supplement nationwide flood protection for locations with a relatively larger flood risk. However, the range of possibilities differs for existing buildings and new housing development.

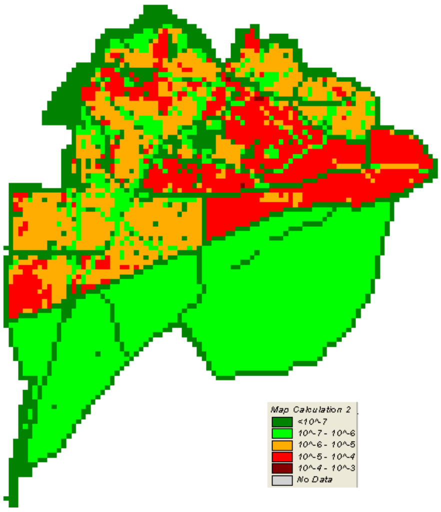


Figure 0-4: Individual Risk in Dike Ring 22. Small areas with relatively large flood risk (> 10^{-6} yr^{-1}) can be tackled most cost-efficient by implementing MLS.

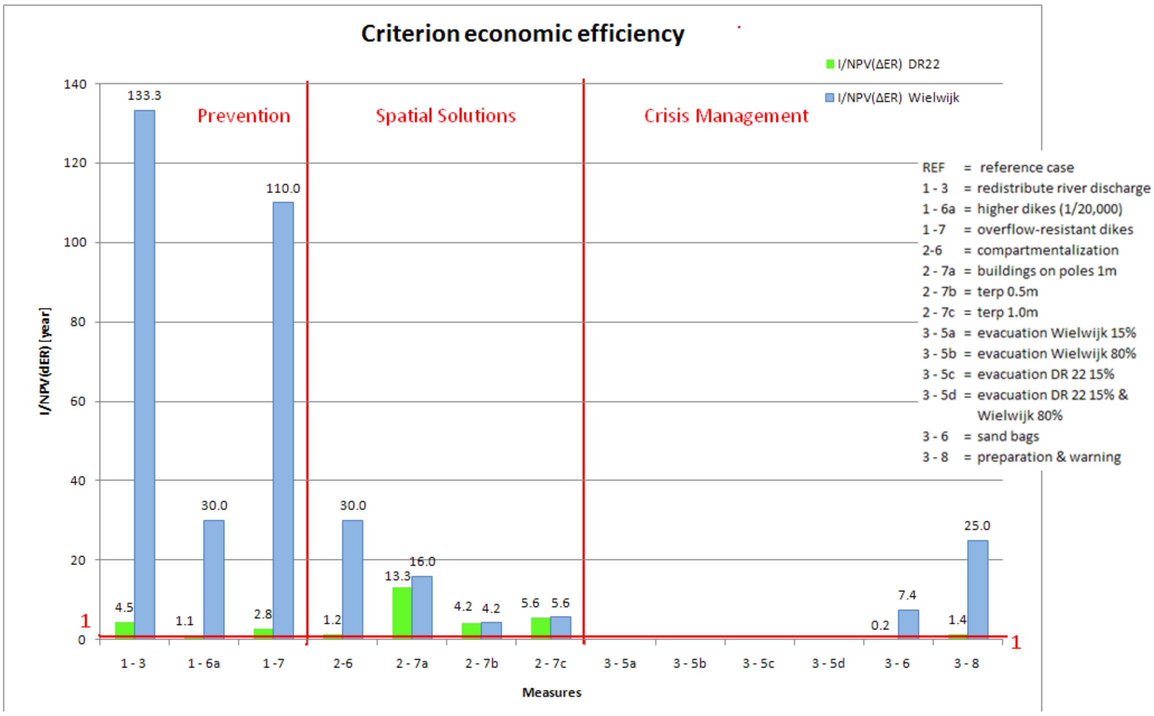


Figure 0-5: Cost-efficiency with regard to the expected number of fatalities per year. The lower the ratio between investment and saved statistical lives, the more cost-efficient a measure is. This diagram says nothing about the (monetary) value of a human live.

Conclusions

The main conclusions of this study are listed in the following:

- **A flood defense system heavily based on dike rings does not lend itself to implement MLS. There MLS is only cost-efficient to eliminated local differences in risk.**
- Introducing redundancy to flood safety by means of MLS is an alternative to only building flood defenses (strengthening the strongest link).
- The cost-efficiency of any flood management measure depends on the initial safety level. This interaction between the individual measures might make it more effective to turn to other measures instead of continuously intensifying the implementation of one measure.
- To implement MLS effectively it is necessary to know that different measures address different key parameters of risk and show different side-effects.
- Policy-making needs to be risk-based to make MLS relevant. Right now most flood management policies are based on Prevention and thus probability-oriented. To supplement those policies with loss-reducing measures, as MLS proposes, policy-makers need to be authorized to base their policies on the risk approach to flood management.

- Given the assumptions of this case study, it is most cost-efficient in Dordrecht to (selectively) reinforce the existing system of primary and secondary dikes. it was found that probability-reducing measures are suitable for decreasing the overall risk but less fit for customizing flood risk management to local conditions (*maatwerk*). This implies that MLS brings forth the possibility to tailor flood risk management to local conditions and address hotspots.

Glossary

English (abbrev.)	Dutch	Definition
Boundary conditions	*Randvoorwaarden*	Hydraulic conditions in the supplying water body (river) at the border of the analyzed system. Usually presented as water level occurring with a certain probability.
Bow tie model	*Id.*	Model from Safety Science that aims to identify all possible ways of failure of a random system
Computational Model	*Rekenkundig model*	Mathematical model that studies behavior of a complex system, in this case a flood-prone area
Cost-effectiveness-analysis (CEA)	*Kosten-baten-analyse*	Analyzing the cost-efficiency of an investment by comparing its benefits with its costs.
Cost-efficiency	*Kostenefficientie*	Result of the Cost-effectiveness-analysis. Indicates the relation between costs and benefits of an investment.
Crisis	*Crisis*	The situation if an area is under immediate threat of flooding or is flooded.
Crisis Management (CM)	*Rampenbeheersing*	All organizational flood management measures to save lives and material value before and during a disaster. Those measures are organized beforehand and temporarily implemented during a crisis. Includes e.g. evacuation, sand bags, warning etc. CM is the third Layer of Multilayered Safety.
CSX	*Id.*	Costs of saving an extra statistical live. This is a computational measure to evaluate the cost-efficiency of live-saving flood management measures. NOTE: It says nothing about the value of a human live.
Damage function	*Schadefunctie*	Relation between flood characteristics and loss.
Deltaprogramma	*Id.*	The Deltaprogramma was drawn up by the Second Deltacommittee in 2009 to modernize Dutch flood risk management.
Dike Ring (DR)	*Dijkring*	Complete circle of *primary flood defenses* protecting the (material) values and lives inside it from a flood.
Dike Ring 22 (DR22)	*Dijkring 22*	Dike ring that protects the Eiland of Dordrecht, including most of the city of Dordrecht.
Dimension of risk	*Risicodimensie*	This study includes three dimensions of risk: Individual Risk, Societal Risk and Economic Risk. The first two quantify the risk for human lives, the third for economic values. The Individual Risk concerns a local risk whereas the other two concern an overall-risk for a certain area.
Economic Damage	*Economische Schade*	Direct and indirect loss of economic value. This can concern material losses but also e.g. loss of working hours and transportation delays.
Economic Risk (ER)	*Economisch Risico*	Risk that economic values run. See also Economic Damage.
Effectiveness	*Effectiviteit*	Degree with which a flood management measure decreases the risk.
Eiland van Dordrecht	*Id.*	Subject of the second case study in this study. Includes the City of Dordrecht and is surrounded by the Dike Ring 22.
Exposure	*Blootstelling*	Number and degree to which valuable objects and people are affected by a flood.
Failure	*Falen*	The (partial) loss of intended function respectively capacity due to one or more failure mechanisms.
Failure mechanism	*Faalmechanisme*	(Un-)expected way of failing. Each piece of infrastructure can fail in a number of ways. Those types of failure are often correlated.
Family of measures	*Familie van maatregelen*	Groups of flood management measures that physically function in the same way. Derived for the schematization of Multilayered Safety using Haddon's strategies.
Fatality	*Slachtoffers*	Lost human lives as a direct consequence of a flood. Not to be confused with the number of people affected by a flood.
Fault tree	*Id.*	Model to analyze the necessary and sufficient conditions that lead to total failure of a system.
Fleuve	*Id.*	Name of the river in the first (hypothetical) case study of *Mouillé*.

Flood	*Overstroming*	The situation if land is temporarily covered by water that is normally not covered by water and loss is caused. In this study only floods from supplying bodies of water are considered, excluding e.g. floods from sewage systems.
Flood characteristics	*Overstromingskarakteristieken*	The flood characteristics quantify a flood and are represented by the inundation depth (h), the flow velocity (v), the rise rate (r) and the duration of flooding (t).
Flood management measure	*Maatregel tegen overstromingen*	All structural and organizational measures taken to prevent flooding or ease the impact of floods.
Flood Risk	*Overstromingsrisico*	The flood risk can be expressed in several dimensions. It indicates the expected number of fatalities resp. the amount of economic damage per year. The risk is the product of the probability of an event and its impact.
Flood risk management	*Overstromingsrisicobeheer*	Process to reach a certain level of (flood) safety cost-efficiently and effectively.
Geographical scale of implementation	*Geografische schaal van toepassing*	Flood management measures can be implemented at four geographical scales: Delta, dike ring/polder, Neighborhood, Individual.
Ground Level (Z)	*Bodemhoogte*	Height of ground in reference to NAP.
Ground Use (GU)	*Bodemgebruik*	Way in which ground is used, e.g. industry, housing, agriculture
Haddon's strategies	*Haddons strategieen*	Model from Safety Science used to derive a schematization for Multilayered Safety. It lists all possible strategies to prevent a hazard harming a target. Each strategy has a different way of physical functioning.
Hazard	*Gevaar*	A level of threat respectively amount of energy that has the potential of harming somebody or something (target).
Hazard-Barrier-Target Model (HBT-model)	*Id.*	Model from Safety Science that indicates how different types of barriers might protect the target from the hazard.
HIS-SSM	*Id.*	Software that calculates the fatalities and economic damage depending on flood characteristics (input).
Impact	*Gevolg*	Consequence of a flood, also called loss.
Individual Risk (IR)	*Plaatsgebonden risico*	Quantifies the probability of losing one's live for every location. Often indicated in zones.
Interaction	*Interactie*	In this study interaction is defined as the (in-)direct effect of flood management measures on each other's effectiveness in risk reduction.
Inundation depth (h)	*Waterdiepte*	The difference between water level and ground level at the same location.
Investment (I)	*Investering*	Financial investment in flood management measures, only considering the direct (material) costs.
Location characteristics	*Eigenschappen van de locatie*	Properties of a location, such as ground level, ground use etc.
Loss (D) resp.	*Schade*	Loss due to a flood, in terms of fatalities and economic damage.
Mortality (M)	*Mortaliteit*	Relation between flood characteristics and fatalities.
Mouillé	*Id.*	Name of the dike ring and the city in it that are subject to the first (hypothetical) case study in this study.
Multilayered-Safety (MLS)	*Meerlaagsveiligheid*	Concept first introduced by the National Waterplan to modernize flood risk management in the Netherlands. MLS is the main subject of this study.
National Standard	*Nationale normen*	The government issues standards that infrastructure has to live up to guarantee among others sufficient safety. In the Netherlands there is currently only a national standard on the probability of flooding of a dike ring.
National Waterplan	*Nationaal Waterplan*	The National Waterplan, published in 2009 by the Dutch government, describes all the water-related measures that have to be taken in 2009-2015 to keep the Netherlands save and prospering for the generations to come. It introduced Multilayered Safety.
Neighborhood	*Buurt*	A gathering of houses as part of larger human settlement. The size can vary widely. This term is rather used to indicate relative geographical scales at which flood management measures are

		taken. A neighborhood is the scale between the individual and a dike ring resp. polder.
Net Present Value (NPV)	*Netto Constante Waarde*	The net constant value is the value of e.g. investments to be done in the future expressed in the currency value nowadays. For an endless time horizon the amount of money has to be divided by the interest rate gives the net present value of that amount of money.
Object characteristics	*Objekteigenschappen*	Characteristics of individual objects, such as mortality or damage function.
Parallel System	*Paralleel Systeem*	In a parallel system all components must fail to make the whole system fail.
Parameter	*Parameter*	The smallest undividable physical unit that is needed to calculate e.g. the risk.
Prevention	*Preventie*	Prevention means to prevent a flood from occurring. These permanent flood management measures are the first layer of Multilayered Safety. NOTE: When analyzing a dike ring, prevention means to prevent a dike breach. In this study this terms has been defined wider though.
Primary flood defense	*Primaire waterkering*	The most outward line of flood defenses.
Probability (P)	*Kans*	This study mostly talks about the probability of flooding, but also about the probability of failure. So please check which one is meant.
Public Good	*Publiek goed*	"A commodity is a public good if its consumption by any one person does not reduce the amount available to others. Putting it another way, providing a public good to *anyone* makes it possible, without additional cost, to provide it to everyone." (Hirshleifer *et al.* 2005: 518)
Redundancy	*Redundantie/Meervoudigheid*	"In engineering, redundancy is the duplication of critical components of a system with the intention of increasing reliability of the system." (Wikipedia 2010)
Safety Chain	*Veiligheidsketen*	The safety chain is an older concept in safety science and flood risk management. It never broke through in the latter field of application though.
Safety Net	*Vangnet*	A large net for catching one that falls or jumps, used as a metaphor in this study. It describes successive safety mechanisms that provide security resp. safety.
Safety Science	*Veiligheidskunde*	Safety science is a research area that aims to improve safety mainly in industry.
Scenario	*Scenario*	A scenario is an event occurring with a certain probability. A scenario describes the conditions at hand, including e.g. the water level, location of dike breach, success of evacuation.
Schematization	*Schematisatie*	A schematization is a simplification of a complex system reducing it to its main properties. Schematizations are used as the basis for computational models.
Secondary flood defense	*Secondaire waterkering*	A secondary flood defense is located behind a primary flood defense. Compartmentalization dikes are secondary flood defenses.
Serial System	*Serie Systeem*	In a serial system only one component has to fail to make the whole system fail.
Sobek	*Id.*	Software that is used to calculate flood characteristics, both 1D and 2D.
Societal Risk (SR)	*Groeprisico*	The Societal Risk is one of the dimensions of risk. It concerns the question of the number of fatalities at once. This dimension was introduced to account for the potential turmoil a flood can cause in society.
Spatial Solutions (SS)	*Ruimtelijke Ordening*	Spatial Solutions are permanent flood management measures, including e.g. re-locating, terps, flood-proofing. This is the third layer of Multilayered Safety.
Strategy	*Strategie*	See Haddon's strategies.
Supplying water body	*Toevoerend water lichaam*	Rivers, lakes, the sea etc. can be supplying bodies of water. In this study those are seen as the only potential cause of a flood.
Swiss Cheese Model	*Id.*	A model from Safety Science that describes the process of hazards

		doing harm to targets.
Target	*Doelwit*	A target can be human lives or valuable objects such as buildings. It is vulnerable to the impact of a *hazard*.
Vulnerability	*Kwetsbaarheid*	The vulnerability determines how much harm an object of person suffers due to certain conditions, in this case flood characteristics. It is quantified by the mortality and damage function.
Water level (WL)	*Waterlevel*	The water level is indicated relative to NAP.
Wielwijk	*Id.*	The Wielwijk is a neighborhood in Dordrecht and subject to the second case study in this study.

1 Introduction

1.1 Floods- Yesterday's, today's and tomorrow's policies

The Netherlands are the delta of the rivers Rhine, Meuse and Waal. Landscape, economy, politics and culture are heavily characterized by living with the rivers and the sea. Floods are a problem the Netherlands had to deal with from the very beginning of human settlement there. Alongside land reclamation efforts, the scale of flood prevention has increased gradually. With it the accompanying policy became highly centralized. Safety against floods has become a national priority since two thirds of the country is flood-prone. Needless to say, the economical, social and societal stakes are high.

Deltaprogramma:

The *Deltaprogramma* is the direct result of the Deltacommittee which issued its advice in 2008. The program consists of nine sub-programs. One of them is *Safety.* That is what multilayer safety is part of via the project *Waterveiligheid 21e eeuw (WV21).*

The new standards again fall under the first layer of multilayer safety: Prevention.

Figure 1-1: Box about Deltaprogramma

Since large parts of the Netherlands' territory are artificially created and developed by humans, the Dutch are convinced that the land can be managed and engineered as a whole. The land and its water are seen as an interconnected system that first and foremost serves its people. This attitude can be noticed in a tradition of huge engineering projects that change the nature of the system like the *Afsluitdijk* that made a North Sea bay a freshwater lake or the *Deltawerken* that closed of a number of estuaries along the Dutch coast. These projects often come forth after major catastrophes have set pressure for change. The Deltawerken implemented the vision of the so-called First Deltacommittee, suggesting that the water should be shut out from the respective areas and controlled as much as possible. That major project was the direct consequence of a disastrous flood in 1953 and continued an approach practiced for centuries, to prevent water from coming in by flood defenses such as dikes and dams.

In 2008 a Second Deltacommittee delivered a report with a new vision on dealing with the danger of floods (see Figure 1-1). Luckily, this time it was not a flood in the Netherlands itself that created momentum for a new approach to flood policy. The recent topic of climate change and a devastating flood in New Orleans due to hurricane Katrina made shockingly clear that the achievements are not yet sufficient. In the last decade the realization came about that flood protection might never be fully achieved since the external conditions due to for example climate (e.g. sea level rise or higher river discharges). At the same time the internal values, such as the desired standard of protection, are subject to continuous change. Additionally, the environmental consequences of the traditional flood policy have attracted increasingly more attention and criticism. It thus became intolerable to assume that floods could be made impossible (Ontwerp-Beleidsnota 2009: 8). So, little by little, the thinking changed from "shutting the water out" - and in a way the nature with it – towards trying to live side by side with the water.

With the country-wide project "Ruimte voor de Rivier" (literally translated: Room for the river) the new flood policy was put into practice. Instead of putting all stakes on prevention by flood defenses the river beds were now widened in an attempt of pro-action to prevent critical hydraulic loads all together. The aim and the way to of that new approach were set by the central government. But the implementation was left to the local authorities "Ruimte voor de Rivier" which also meant a change in determining local policy.

The National Waterplan (Nationaal Waterplan) of 2009 continues to go down this path with innovative flood management. With "Ruimte voor de Rivier" it was anticipated that flood defenses are not the only way to prevent floods. While this project nears the completion of its implementation, the following step is already being set: acknowledging that flood management can do more than *preventing* floods: It can also reduce the impact of floods. *Meerlaagsveiligheid* (literally translated multilayered safety [MLS]) has been introduced by the National Waterplan to give this additional expansion of flood management the necessary momentum. The idea behind MLS is to supplement prevention (layer 1) with Spatial Solutions (layer 2) and Crisis Management (layer 3) (Ontwerp-Beleidsnota Waterveiligheid 2009: 9). A short introduction to MLS is given in Chapter 1.2.

The City of Dordrecht seems fit to demonstrate the potential a concept as MLS might have. Dordrecht illustrates the limits and consequences of concentrating on flood prevention. The biggest part of the city lies inside the small dike ring 22 called Eiland van Dordrecht. Former research has shown that this dike ring runs a relatively high flood risk in terms of fatalities as well as economic damage (Asselman *et al.* 2008: 119). The historical city center lies partly outside, partly on top of the dike ring itself and even its houses itself function as primary flood defense. It is a much discussed problem that Dordrecht's original prevention strategy neglects dwellings outside the dikes. But Dordrecht's major problem is that the location of the city center makes it extremely difficult to keep the height of primary flood defense up to the legal standard, therefore endangering the entire dike ring. Nevertheless, the dike ring deluded the population's perception of flood safety resulting in an ever extending city at a geographical position with a comparatively high flood risk. This has led to severe consequences. Housing development and perceived safety inside the dike ring meant that some compartmentalization dikes have been perforated by traffic infrastructure, having unknown effects on flood safety. For these reasons the City of Dordrecht constitutes an ideal case study for MultiLayer Safety. The Dutch Ministry of Transport, Public Works and Water Management shares this opinion and made Dordrecht a pilot project for MLS (Dutch: gebiedspilot meerlaagsveiligheid).

This study will examine the value of a MLS approach to flood safety in Dordrecht. This is done on request of the Waterschap Hollandse Delta, which has the responsibility for Dordrecht's flood safety. Furthermore, the thesis seeks to find out if MLS is an alternative for other flood-prone areas in the Netherlands as well as abroad. Therefore, the work was done in cooperation with the European Interreg Project *Mare* and contributes to the ministry's pilot project mentioned above.

1.2 Short introduction to MLS

Multilayered Safety will be introduced in length in Chapter 3.2. Here only a short introduction is given to provide sufficient background knowledge for further reading. The idea behind Multilayered Safety is to not rely on one safety night when it comes to flood protection. In the Netherlands so far, the only (official) safety net is Prevention in the form of dikes etc. Prevention is thus the first layer of MLS. The second and third layers are Spatial Solutions and Crisis Management. There are different interpretations. Spatial Solutions are measures such as elevating or flood-proofing houses, re-locating houses. Crisis Management involves more organizational measures such as evacuation, training, flood forecasting, warning but also physical measures like sand bags.

Figure 1-2: Mulitlayered Safety

MLS was first introduced in the National Waterplan 2009. As it is described there the two new layers of MLS are meant to supplement the traditional (and heavily implemented) layer of Prevention. Put differently, the Spatial Solutions and Crisis Management are meant as back-ups in the case that the primary flood defenses fail. This thought is reflected in the risk perspective (see Chapter 2.1). According to the risk-based approach Prevention reduces the probability of flooding whereas Spatial Solutions and Crisis Management limit the impact of a flood. This study aims to give an idea of the performance of MLS in areas where flood safety is not dominated by dikes. After all, in those areas Spatial Solutions and Crisis Management might not just be supplementary layers.

MLS consists of a number of individual measures. Before MLS can be understood and applied as a comprehensive approach, it has to be studied first what the effect of each individual measure is. This is important to predict the actual effect and the risk reduction of a measure. Additionally, for the performance of MLS it has to be found out if any measures have (negative) side-effects.

Putting MLS into practice equals implementing a package of two or more flood management measures. Those flood management measures will interact. They might reinforce each other, so that interaction is beneficial. But some measures might have negative side-effects on the surroundings and other implemented measures. To evaluate the potential of MLS, it is thus crucial to study the interaction between different flood management measures.

It was explained above that the idea behind MLS is having a back-up in the case that the primary flood defenses (Prevention) fail. The two supplementary layers are thus experienced as a form of safety nets. Understanding MLS requires examining if the three MLS layers indeed do work like safety nets. Since one safety net only comes into action if the net above him fails, a good understanding of the nets' failure is needed. Next to interaction and (side-) effects of measures, failure is thus a third property of MLS that has to be studied careful. (Side-) Effects, interaction and failure will be discussed in Chapter 4.

1.3 Problem analysis

It is generally accepted that the flood management should be based on a risk approach. The flood risk is defined as the probability of flooding multiplied by the impact of the flood (CUR 1997: 3-2). The National Waterplan does emphasize that the flood management policy will continue to focus on prevention. But at the same time few people question that there will always remain a chance that a flood occurs, no matter how small that probability might be. Therefore it seems only logical to try to improve the cost-efficiency of flood protection by to not only limiting the probability of flooding but also to reducing the impact of a possible flood. This is what MLS aims at. The concept of MLS sparks plenty of visions and ideas of how to adapt our surroundings so that floods would have a less harmful effect on human settlements. The gap between the idea of MLS and an actual application is still rather big though.

The layers of MLS have been named but those labels trigger different pictures with different people. There is an abundance of studies suggesting flood management measures but those possible measures haven't been inventoried yet from a MLS perspective. As a consequence it is vague what effects the MLS layers actually have on the flood risk. Put differently, MLS provides an opportunity to study the effect of flood management measures when applied in combination. What is more, MLS intervenes in many aspects of life making it difficult to oversee what the (side-) effects of different layers may be. Different measures potentially change flood characteristics, causing different effects at different locations. The interaction of MLS layers among each other and with the surroundings is complex and therefore difficult to anticipate. In sum, it remains unclear if MLS would reduce the overall flood risk and what a balanced strategy would be given the circumstances and boundary conditions. As a consequence it is thus far also unknown if MLS is fit for Dordrecht.

Most flood management policy is based on a Social Cost-effectiveness-analysis. Many flood management measures have been analyzed but they have not been compared on a wide basis like MLS yet. Nonetheless such an analysis is needed to be able to implement MLS economically.

The challenge is to fill the concept of MLS with tangible measures to be taken per layer. Additionally it needs to be understood what the effect those measures have on the flood risk. As applying MLS means taking measures in all three layers it is necessary to know if and how the layers are complementary to each other. To round off the picture, the effort and investment needed to reduce the flood risk by MLS have to be investigated.

1.4 Objectives

The main objective of this study is to investigate if MLS is an effective and cost-efficient way of reducing the flood risk. This objective split up in sub-questions:

Definition and functioning of MLS (Chapter 3)

- What is the definition of each MLS layer and which actual measure correspond to each? (Chapter 3.2)
- How can MLS be schematized? (Chapter 3.5)

Important properties of MLS (Chapter 4)

- Which properties do individual flood management measures (and thus the MLS layers) have; how do they function? What (unintended) side-effects do individual flood management measures have? (Chapter 4.2)
- What is the interaction between MLS layers? (Chapter 4.3)
- Do the MLS layers work like safety nets? How does MLS behave with regard to the failure of the flood protection? (Chapter 4.4)

Implementation of MLS a.o. in Dordrecht (Chapter 5, 6)

- Under which conditions does MLS lead to the reduction of the flood risk? Is MLS fit for Dordrecht?
- Is MLS cost-effective in Dordrecht?

1.5 Method of working

The study consists of two parts, a general and a case-specific one. In the general part theoretical knowledge is gathered and applied. The case-specific part includes two case studies in which MLS is actually tested.

1.5.1 General part

So far there is no clear definition of MLS. It has not been defined yet which MLS layer includes which flood management measures. Furthermore, there is an abundance of potential flood management measures. It is impossible to include all of these measures in this study; a schematization of MLS is needed. Additionally, the two case studies only examine MLS in two specific areas respectively dike rings. The cases themselves are not instructive about the potential of MLS in any other flood-prone area. To tackle these three problems the core of the general part is finding a theoretical framework for MLS. The theoretical framework thus serves a number of purposes. First of all it has to provide the foundation of the schematization of Multilayered Safety. The schematization is needed to try out MLS in the two cases. To find a theoretical framework a number of models from flood risk management and safety science are looked at. The most suitable one is chosen and subsequently the schematization is based on it. At the same time this exercise will clarify which flood management measures each MLS layers consists of. Furthermore, insight will be gained which measures and thus MLS layers function in which way.

The general part will also include a discussion of the most important properties of MLS: (side-) effects, interaction and failure. These three properties have been identified to be crucial to the performance of MLS (Chapter 1.2). The theoretical framework of MLS derived earlier will facilitate understanding (side-) effects, interaction and failure in depth.

1.5.2 Case-specific part

The case-specific part consists of two case studies. The first one is the hypothetical case of the dike ring *Mouillé.* This case is entirely fictive. For the case studies the schematization of MLS derived in the general part will be used. This schematization will be translated into the computational model commonly being used. This first case is meant to overcome difficulties when making the step from the schematization to the computational model. Furthermore, ways have to be found to visualize the outcome. Nonetheless, *Mouillé* will of course provide a first preview on MLS.

The second case study tests MLS in a real flood-prone area. MLS will be applied to a neighborhood called *Wielwijk* in the City of Dordrecht. This case study makes use of the schematization derived in the general part and the experiences gained in the first case study. This second case study thus actually evaluates the potential MLS has in Dordrecht but also provides a reality check for the findings from the theoretical parts of the study.

1.5.3 Reader's guide

The general part of the study consists of Chapter 2 and 3. The study starts off with a chapter on background knowledge. This includes the risk-based approach, ways of calculating risk and today's practice of handling flood risk (Chapter 2). The theoretical framework will be derived in Chapter 3. The important properties (side-) effects, interaction and failure (compare Chapter 1.2) will be treated in Chapter 4. The case-specific part consists of two chapters as well; one for each case study. Chapter 5 covers the hypothetical case study and Chapter 6 the study on Dordrecht. The report ends with by bringing the findings from both the general and case-specific part together in the concluding Chapter 7.

2 Basics of Flood Risk Management

The objective of this chapter is to give the reader background knowledge in flood risk management. This knowledge is important to understand the expectations for and the actual performance of Multilayered Safety (MLS).

First the risk-based approach as it is used in flood safety nowadays will be introduced. It will be explained how risk is measured and calculated. Furthermore, it is described how investment decisions are based on the risk approach. Following that the Dutch national standards for flood risk are introduced. The chapter closes with a discussion of the suitability of the risk-based approach to schematize and evaluate MLS.

2.1 Risk-based approach

Flood management in the Netherlands is based on a risk approach. Therefore this approach will be explained in general and more specifically how it is used in the practice of Dutch flood management. Figure 2-1 shows the different parts of the risk analysis. The chapter will close with clarifying how the risk is actually computed in national projects as, for example, *Veiligheid Nederland in Kaart* (VNK, English: Flood Risk and Safety in the Netherlands [FLORIS]).

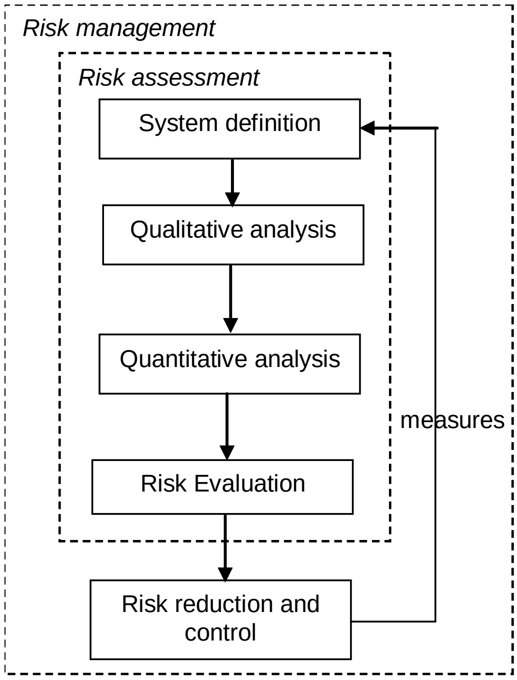


Figure 2-1: Steps of risk analysis (Source: S.N. Jonkman)

2.1.1 Risk

Already after the big flood in 1953 the Dutch government, and more specifically the First Delta Committee, based their flood management policy on a risk inventory. With the knowledge available back then, the Committee considered the possible consequences of a major flood (Ontwerp-Beleidsnota Waterveiligheid: 13). According to the potential damage, excluding human lives, five categories of probabilities of flooding were introduced. Each dike ring was assigned to one category. As examples, dike ring 14 (Central Holland) was awarded a probability of 1/10000 years and dike ring 22 1/2000 years. As a last step the probabilities of flooding were translated to a water level occurring with that probability. This water level was then used as the main design criteria for dikes.

Nowadays it is generally accepted that the risk R is defined as the probability P of an event occurring multiplied with the loss L that this event would cause. Since a number of scenarios n are thinkable, the risk is calculated for each scenario and subsequently those risks are added up to an overall risk.

In flood risk management and other sectors of industry risk is measured on three dimensions: the societal risk, the individual (local) risk and the economic risk. These dimensions are introduced in Chapter 2.2.

2.1.2 Probability

Probability as it is understood in the Netherlands consists of two parts: The probability of a certain hydraulic load to occur and the probability that primary flood defenses fail. It is thus a probability of exposure to floods.

This approach has grown on the assumption that the failure of a dike is directly dependent on the water level outside the dike. The first delta committee assumed that the water level equals the design water level of the dike, the dike will fail with a probability of 0.1. (Weijers, Tonneijck: 28ff.). Probability of flooding was equal to the probability of a certain water level reduced with an educated guess on the failure of primary flood defenses.

One of the lessons of the disaster in 1953 was that a dike can fail due to other reasons than a too low crest level. Examples are piping, micro- and macro-stability of the slopes. Thus, not only the crest height of the flood defense matters but also for the width among others.

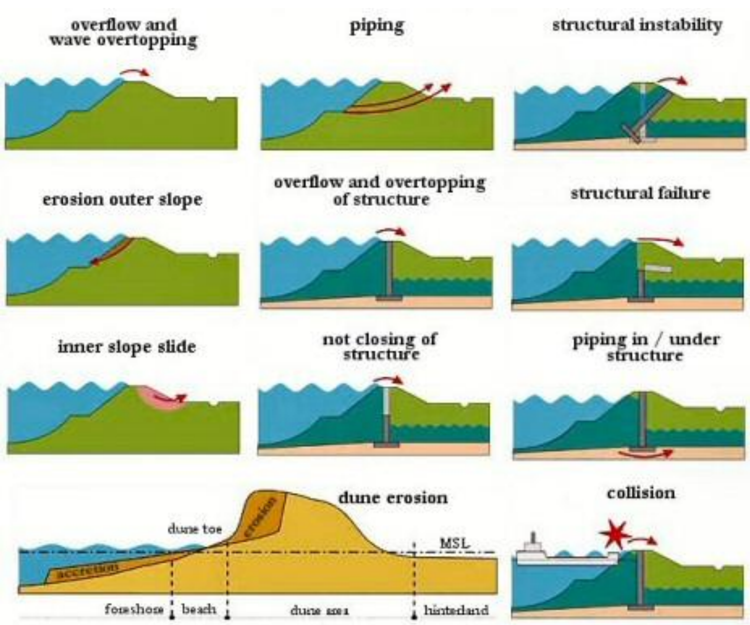


Figure 2-2: Failure mechanisms of flood defenses (Source: www.safecoast.org; July 24th, 2010)

For this reason the probability of flooding is now understood to consist of two parts: The probability of a certain hydraulic load and the probability of failure of the primary flood defenses. Thus the strength (resistance) of the primary flood defenses, including all the possible failure mechanisms shown in Figure 2-2, is approached probabilistic as well (V&W 2007: 30ff.).

In other countries and areas (that are not characterized by dike rings) the probability of flooding is generally the frequency of occurrence of a certain water level relative to the ground level of the area in question.

2.1.3 Loss

There are different forms of damage or called differently loss. Loss is defined as lost human lives and economic damage. Damage is understood to be only relevant to objects. The kinds of impact as identified by the Dutch Ministry of Transport, Public Works and Water Management are listed in the table (Table 2-1) below (V&W 2007: 33).

Table 2-1: Overview of different kinds of loss

	Immaterial loss	Material loss
Loss in the inundated area due to damage	fatalities, damage to eco-systems, damage to cultural objects, loss of personal belongings such as photo's	Damage to capital goods (e.g. Houses, factories, fields, roads, cars) and repairing costs of flood defenses
Damage in inundated areas due to interruption of company activity	Social disruption	Loss of income of shops, hotels etc.; production loss of companies
Loss of income of shops, hotels etc.; production loss of companies	Stress and distress of other people than the inhabitants	Loss of production outside the inundated area due to shortage of material, lack of consuming market, loss of infrastructure
Social disruption	Evacuation stress	Emergency relief, evacuation

For calculating the risk, in the Netherlands the focus lies on two forms of impact: human lives and material damage. The flood management policy as introduced by the National Waterplan of 2008 uses three dimensions to anticipate the loss suffered in terms of human lives and material damage: Individual Risk (IR) and Societal Risk (SR) to account for lost lives and Economic Risk (ER) to capture material damage. These will be introduced in the following.

2.2 Dimensions of risk

As of 2010 the Dutch government is busy inventorying the actual flood risk in the Netherlands. For this project, *Veiligheid Nederland in Kaart (VNK, English: Flood Risk and Safety in the Netherlands [FLORIS])*, the approach of how to calculated risk has been modernized and updated. The output is the calculated risk split up into three dimensions: Individual Risk (IR), Societal Risk (SR) and Economic Risk (ER). These types of risk will be introduced in the following.

Please see Chapter 2.3 to find out how those dimensions of risk are calculated.

2.2.1 Individual risk

Along with others, Jongejan *et al.* describes the individual risk "as the probability of death of an average, unprotected person that is constantly present at a certain location". This risk has to be in a reasonable proportion to other risks which modern humans are exposed to in, for example, traffic or hospitals (Jongejan *et al* 2009: 2). When using the Dutch safety standards as applied in industry the IR should be below 10^{-6} per year. Sometimes a distinction is made for existing situations and 10^{-5} per year is tolerated. From the perspective

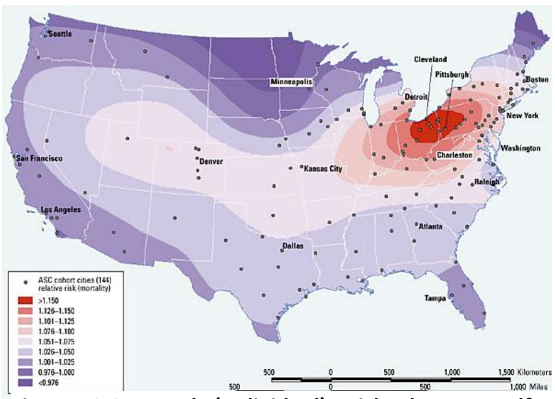


Figure 2-3: Local (Individual) Risk due to sulfate concentrations in the USA. (Source: http://ehp.niehs.nih.gov/members/2001/suppl-3/375-380burnett/burnett-full.html)

of life expectancy a risk criterion of 10^{-6} per year would decrease the life expectancy by one day (CUR 1997: 4-17). The Individual Risk is usually shown on maps as the one in Figure 2-3.

2.2.2 Societal risk

Even though the individual risk is low, a disaster might kill a lot of people in once and therefore cause social unrest. To appreciate this, societal risk has been introduced with the rule of thumb that a disaster with ten times as much fatalities has to be a 100 times less likely. Again for floods this risk has to be coherent to risks resulting from, for example, industry (Jongejan *et al* 2009: 2).

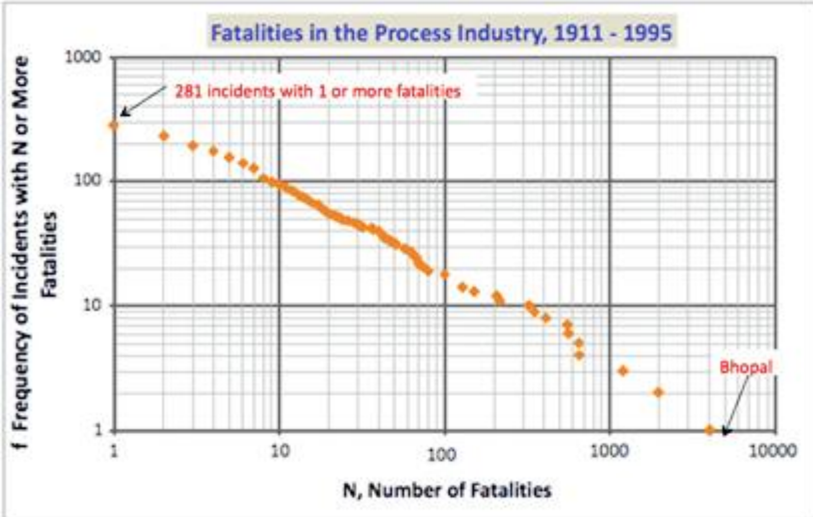


Figure 2-4: FN-curve in process-industry (Source: www.risk-safety.com)

The Societal Risk is visualized in a so-called FN-curve. For different scenarios, notably not necessarily all flooding scenarios, the probability and impact are determined. Those two parameters are plotted on a probability axis and an axis indicating the number of fatalities. An example of an FN-curve in industry is shown in Figure 2-4.

In the Netherlands the safety standard also used in industry is mathematically represented by (CUR 1997: 4-17ff.):

$$1 - F_{N_{dj}}(n) < \frac{10^{-3}}{n^2} \qquad \text{(for all } n \geq 0\text{)}$$

with

$1\text{-}F_{Ndij}(n)$ – frequency of exceeding of the number of fatalities in a year as a result of a activity i location j;

n - realization of N_{dij};

N_{dij} - number of dead at location j as a result of activity i .

This so-called FN-criterion is visualized in the FN-curve as a downward sloping line. Therefore according to this standard the risk is low enough if the FN-curve stays below the FN-criterion.

2.2.3 Economic risk

The Economic Risk (ER) indicates the expected material, direct or indirect damage caused by a flood expressed in Euro's per year. For the Dutch project FLORIS the following types of damage are accounted for (Wouters 2005: 10):

- Direct damage - material: Reparation costs for immovables such as real estate and means of production, damage of household effects, damage or loss of movables such as commodities, resources and products (inclusive damage on the harvest).
- Direct damage – due to interruption of company productivity
- Indirect damage – e.g. loss for companies outside the inundated area and increases in travel-time.

There is no general standard below which the Economic Risk should lay. Usually a Social Cost-benefit Analysis (SCEA) is used to investigate what level of investment in safety measures is economical given the values to be protected.

The ER is visualized in a similar way like the Individual and Societal Risk. Instead of a FN-curve the Economic Risk is shown in a FS-curve. There are some cases when also the local Economic Risk is visualized. This is only possible though for objects with the same damage function.

2.2.4 Investment decisions

For the case studies later on it is important to know which criteria determine if an investment is worth it. That question will be treated in this paragraph.

Material values

Decisions on the investment in the flood protection system are an optimization problem. According to van Dantzig's theory, the total costs in a system have to be minimized. The total costs are the investment in safety measures plus the net present value of the expected value of damage per year (equal to economic risk as introduced in Chapter 2.2.3).

$$\min(C_{tot}) = \min\left(I + E(D)\right)$$

with C_{tot} = total costs in system [€]
I = investment [€]
E(D) = expected damage (Net present value) [€]

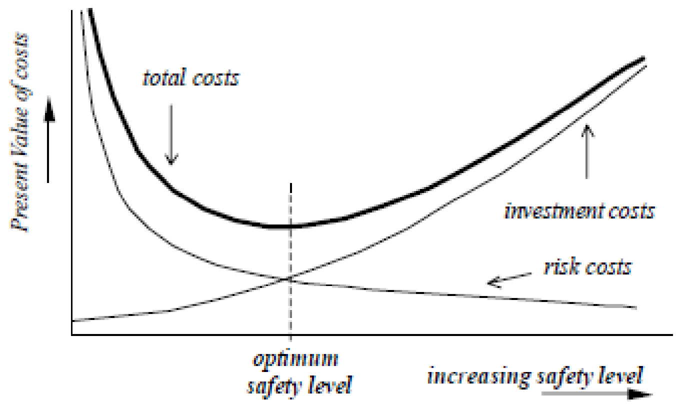


Figure 2-5: Economic risk optimisation van Dantzig

This optimization problem is shown in Figure 2-5 (Arends *et al.* 2003: 220).

In terms of Economic Risk an investment is thus justified if the capital involved is less than the net present value of the risk reduction. Calculating the net present value means calculating transforming the risk per year to the value of this risk at one point in time. For an endless time horizon the formula is as follows:

$$NPV = \frac{\Delta ER}{r}$$

With NPV = Net present value [€]
ΔER = reduction in economic risk [€/yr]
r = rate of interest [1/yr]

Thus an investment I should meet the following rule to be economically justified:

$$\frac{I}{\Delta ER/_{r}} \leq 1$$

Fatalities

Such a rule cannot be given for the Individual Risk (IR) and the Societal Risk (SR) because this would require attaching a (financial) value to each live. There are a number of ways to approach the cost-efficiency with regard to saving lives. Examples are the Willingness to pay (WTP), the value of a statistical life (VSL), the human capital approach (HCA) or the cost of saving an extra statistical life (CSX) (Arends 2005: 220-221). In this study the CSX is used to evaluate investments into flood safety because it based on the least normative assumptions. Most notably, a life does not have to be expressed in a monetary value. This needs to be done if using the VSL, HCA and WTP. With other words, the CSX compares measures by how much it costs to have one fatality less per year. This is calculated as follows:

$$CSX = I/\Delta E(N)$$

With CSX = costs of saving an extra life per year [€/#/year]
I = investment [€]
E(N) = expected number of fatalities [#/yr]

It is only possible to rank flood management measures according to their CSX score. To determine which amount one is ready to pay for an extra saved life is a political and societal decision. A study of 587 live-saving interventions across different sectors such as Health Care, Residential, Transportation, Occupational etc. has been done. Figure 2-6 shows the result of that study. The median cost of each life-year saved for fatal injury reduction across all sectors and prevention stages is $ 48,000 (1993) (Tengs *et al.* 1994: 371). With a life expectancy of approximately 80 years in Europe, the median costs of an extra saved life (CSX) are thus in the range of 2.5-3 million Euros. But this varies so greatly throughout all sectors of industry, that the CSX is by no means suitable to determine

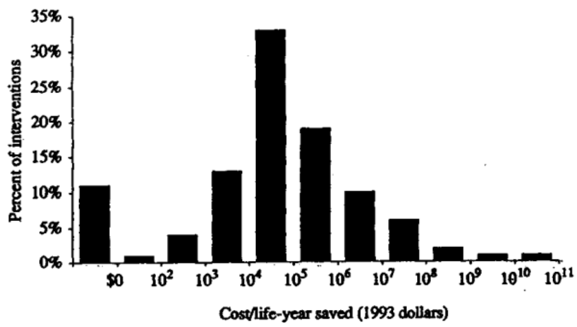


Figure 2-6: Distribution of cost/life-year saving estimates across all sectors of society and all types of safety interventions (n=587). Source: Tengs *et al.* 1994: 371)

the cost of a life. E.g. the average CSX for reducing the number of fatalities by toxin control is $ 2.8 million. Thus, saving an extra life in that way would cost about 60 times as much as by fatal injury reduction.

Naturally, the CSX is being discounted for a value decrease of the years. This is based on the normative assumption that inflation etc. does not apply to lives.

Risk = Σ Probability · Loss

2.3 Calculating the risk

As discussed above the risk is mainly based on two measures, namely the probability of a flood and the loss suffered as consequence of that flood. The loss is split into fatalities and material damage. It is important to understand that the scenarios used determine the flood characteristics and subsequently the impact. The loss calculation translates the flood characteristics to loss using vulnerability as transformation function (see Chapter 3.4.2).

All undividable parameters such as the ground level, the water level and its probability of occurrence, the number of vulnerable objects/people and their probability are the variables that determine the risk profile of an area. By altering one or more of these four variables, the risk profile of the area in question can be tuned to the safety needs of the inhabitants.

In the following paragraphs the calculation approaches for probability of flooding, the number of fatalities and the economic damage are explained. Furthermore, the computational models most commonly used in the Netherlands as of 2010 are described. Last, the relevant parameters for risk calculation are summarized.

2.3.1 Probability of flooding

The probability of flooding of a dike ring can be split up in two parts. First of all the probability of a certain hydraulic load to occur is looked at. The water levels are constantly registered, including their frequency of occurrence. Extrapolating those data allows estimating the probability of occurrence of any water level. Knowing the probability of occurrence of water levels in is sufficient to compute the probability of flooding for areas outside the dike ring.

For areas inside the dike ring the resistance of the flood defenses alters the probability of flooding. The resistance of the flood defenses is approached probabilistically as well. The overall probability of an inundated dike ring is represented by the overlapping tails of the normal probability distribution of load and strength, see Figure 2-7 (Weijers, Tonneijck: 28ff.).

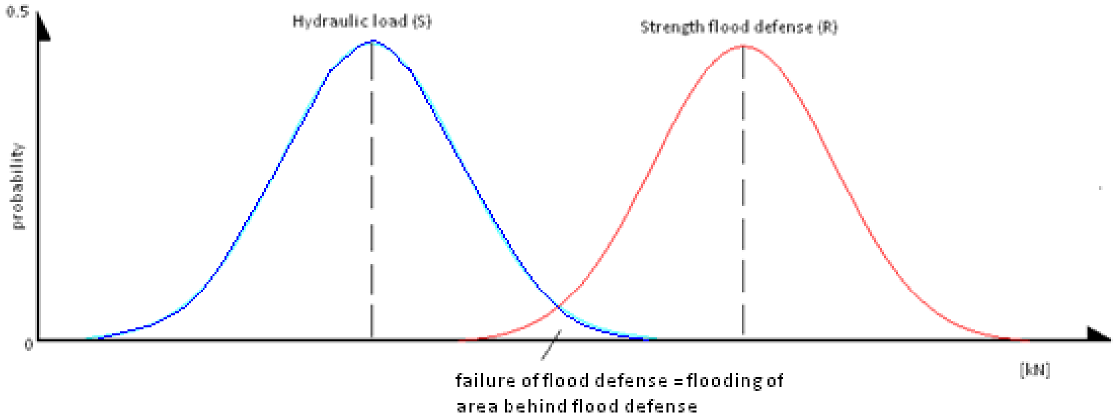


Figure 2-7: Probability density function of a dike ring being flooded

Since different hydraulic loads will cause different effects in- and outside a dike ring scenarios are used as a basis of risk calculation. There are different scenarios for boundary conditions. An example of a set of scenarios would be a high river discharge, high sea levels and a combination of both. But scenarios can also involve the failure of engineering structures such as storm surge barriers and dikes. It follows that each scenario has another probability of occurrence (see also Chapter 2.1.2).

For the case-specific part of the study the probabilities of flooding as established by the Dutch government per dike ring will be used. The calculation will be based on the dike breach scenarios that are used in the FLORIS project. Each scenario concerns another breach location. Since it is beyond the scope of the present study to determine the state of the flood defenses in dike ring 22, a simplified approach will be taken: The probability of each dike breach scenario will be the norm valid today (1/2000 per year) divided by the number of dike breach scenarios.

2.3.2 Calculation of Fatalities

The individual and the societal risks are based on the mortality due to a flood. If people die, and how many, depends mainly on the flooding characteristics such as the inundation depth, the rise rate and the flow velocity. Based on floods in the past, mortality functions using those three parameters have been derived by Jonkman (Jonkman 2007).

For these mortality functions three zones are defined: a breach zone (1), a zone with rapidly rising water levels (2) and the remaining space with more moderate flood characteristics (3). Generally the mortality function is a normal probability distribution:

$$F_D = \Phi\left(\frac{\ln(h) - \mu}{\sigma}\right)$$

with $F_D(h)$ – flood mortality [-]
h – inundation depth [m]

Table 2-2 sums up the conditions that define a zone and the corresponding parameters for the normal probability distribution. (Flood characteristics: r – rise rate [m/hr], h – inundation depth [m], v – flow velocity [m/s]).

Table 2-2: Probabilistic mortality functions (Maaskant, Jonkman, Kok 2009: 4-43ff)

Zone	Conditions	Parameters probability distribution
1 Breach Zone	$h \cdot v \geq 7 m^2/s$, $v \geq 2$ m/s	$F_{D,B}(h) = 1$
2 Zone quickly rising water	($h \geq 2.1$m and $w \geq 4$m/hr) and ($hv < 7\ m^2/s$ or $v < 2$ m/s)	($F_{D,S}$) $\mu=1.46$, $\sigma=0.28$
3 transition zone	($h \geq 2.1$ m and $0{,}5\text{m/hr} \leq w < 4$ m/hr) and ($hv < 7\ m^2/s$ of $v < 2$ m/s)	$F_{D,T}= F_{D,O} + (w-0.5) * (F_{D,S} – F_{D,O})/3.5$
4 remaining zone	[$w < 0.5$ m/hr of ($w \geq 0.5$ m/hr and $h < 2.1$ m)] and ($hv < 7\ m^2/s$ of $v < 2$ m/s)	($F_{D,O}$) $\mu=7.6$, $\sigma=2.75$

The probability of death is then defined as the probability that a flooding scenario results in particular values for the above mentioned flood characteristics multiplied by the probability of dying under those circumstances.

$$P_d(x,y) = \sum_{i=1}^{n} p_d(h,v,r) \cdot p_i(h,v,r,x,y)$$

with $P_d(x,y)$ – probability at location (x,y) [yr^{-1}]

$p_d(h,v,r)$ – probability of death in case of inundation depth h [yr^{-1}]

$p_i(h,v,r,x,y)$ – probability that flooding scenario i causing particular values of h,v, r at location (x,y) [yr^{-1}]

n – number of flooding scenarios [-]

The Individual Risk expresses the risk at every location in the examined area. It is equal to the probability of dying as a result of the flood characteristics h, v and r for that location.

Knowing the population density or with other words the number of people present in the area, the probability density function of the number of fatalities can be estimated by integrating the above probability density function (Jongejan *et al.* 2009: 3-4). This results in the Societal Risk of the examined area.

2.3.3 Material damage calculation

When it comes to the material damage, the damage is classified by the sort of land use. Furthermore there is a distinction between direct material damage, direct damage due to production standstill of companies and indirect damage. Direct material damage is defined as recovery costs for real estate, means of production such as machines, household effects, products and raw material including the harvest. Indirect damage consists of increased travel-times or the exposure on companies outside the inundation area (compare Chapter 2.2.3).

For each category of land use i a damage factor α_i depending on the flood characteristics inundation depth h, rise rate r and flow velocity v can be calculated. The material damage D is then defined as follows (Jonkman *et al.* 2008: 82):

$$D = \sum_i^m \sum_l^n \alpha_i(h_l, v_l, r_l) \cdot n_{i,l} \cdot D_{max;i}$$

with D – damage
l - location in flooded area [-]
i – damage or land use category
m – number of damage category
i – number of locations in flooded area
D_{max} – maximum damage
h, v, r – hydraulic characteristics (see Chapter 2.3.2)

Generally the damage can be expressed in whatever unit is chosen. It should be noted that the material damage calculation is computed in a deterministic way per scenario.

The damage factor comes from a damage function defined for each damage class. Examples of damage classes are houses, agriculture, traffic and communication infrastructure and so on. The damage function indicates the percentage of the total possible damage occurring depending on the inundation depth.

2.4 Computational Model

Risk and its dimensions have been introduced in the above. Chapter 2.3 gives the mathematical details of calculating risk. The following paragraphs will give an introduction to the practice of calculating risk as it is done for projects like *Veiligheid Nederland in Kaart* (VNK/FLORIS).

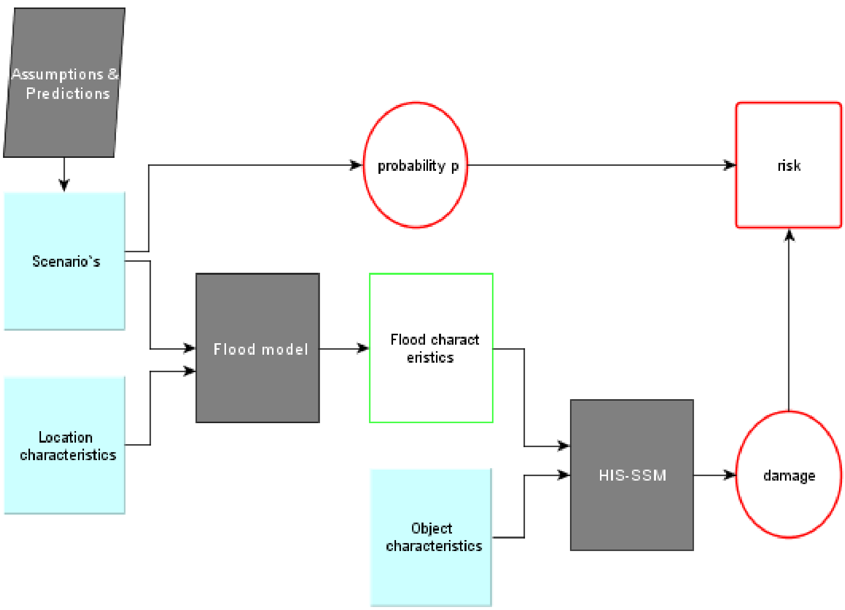


Figure 2-8: Schematization of computational process at parameter level. Damage includes material loss and loss of life.

2.4.1 Calculation scheme

The computational process is schematized in the graph below. As this study uses a Dutch computational model, it is based on a dike ring. Thus the scenarios represent different dike breaches. This means that the model as described here is not suitable for none-dike ring areas.

The computation process starts with the flood model. It calculates the flood characteristics based on the location characteristics and the scenarios given as input. The scenarios include among others different hydraulic situations and different breach locations. Location characteristics are e.g. the ground level. The strength of the flood defenses is inherent to the probability of the scenarios. Only the flood characteristics inside the dike ring are calculated.

Knowing the flood characteristics and the object characteristics of the exposed objects (e.g. number of objects, vulnerability) the loss can be derived. Finally multiplication of the probability of the scenario with the loss indicates the risk. Addition of the risk for all the scenarios results in the overall risk. The process just described is schematized in Figure 2-8.

2.4.2 Flood model in Sobek 1D2D

In the Netherlands, there is a one-dimensional model of the lower rivers Maas, Rhine and Waal available. It calculates the discharge and the water level in those and some side rivers for different boundary conditions. The storm surge barriers along the coast and several weirs in the rivers are included as well. This model is the basis for all the calculations done for *Veiligheid Nederland in Kaart* (VNK, English: Flood Risk and Safety in the Netherlands [FLORIS]). To compute inundation depths in the dike rings along the river a 2D model is available. Underlying this model is a ground level grid by 100x100m^2.

The 1D and 2D model are connected as follows. The dikes separate the flood-prone area from the rivers. If a dike breach occurring with a probability of 1/2000 per year is to be modeled the water levels occurring at that dike ring with the same probability are chosen as boundary conditions. After all a dike breach is assumed to happen if the water level exceeds it crest height. Thus there is a direct relation between the water levels and the probability of failure of the dikes. In some cases, like the Island of Dordrecht, the decisive water levels might be dependen on the boundary conditions of the rivers and the sea.

In the computational model it is disclosed on what day and at what time the dike will breach and how fast the breach will grow. The entering water is the input for the 2D part of the model. A similar mechanism is used for all line-shaped obstacles in the modeled dike ring, e.g. compartmentalization dikes. If the water level in front of a compartmentalization dike reaches its crest height the secondary dike is assumed to break. For this purpose the 2D model includes pre-defined breaches in those dikes (see Figure 2-10).

The flood model is available in Sobek software. The outputs are grids with the Water Level, the inundation depth, rise rate and flow velocity of the water inside the dike ring. Furthermore discharge and water level curves for the water bodies are available.

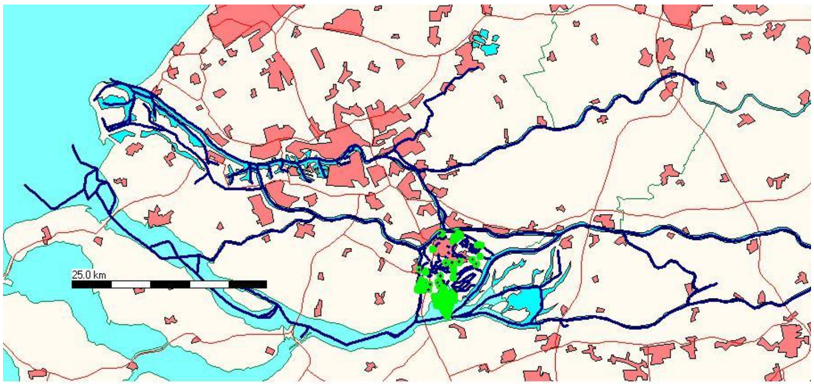


Figure 2-9: Sobek 1D model of the lower rivers in the Netherlands

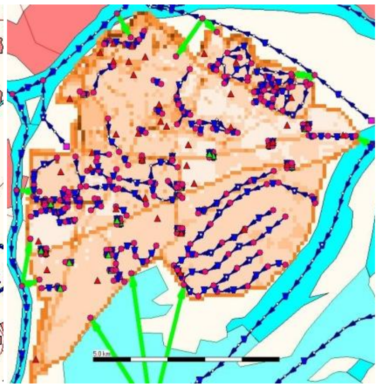


Figure 2-10: Sobek 2D model of Dike Ring 22 - Island of Dordrecht

2.4.3 Damage Calculation in HIS-SSM

FLORIS uses HIS-SSM (Hoogwater Informatie Systeem Schade- en Slachtoffer Module, Flood Information System Loss and fatalities Module) to numerically calculate the loss due to floods. First the flooding scenario and its flood characteristics have to be determined using the flood model. Then the land use has to be classified using pre-defined categories. Knowing these parameters the correct damage and mortality functions are chosen and the damage is being calculated with the formula's given above (Chapter 2.3). The computations are done using a grid calculating the damage for every grid point. Damages to environment, landscape and cultures are not included in this model (Wouters 2005: 37ff.)

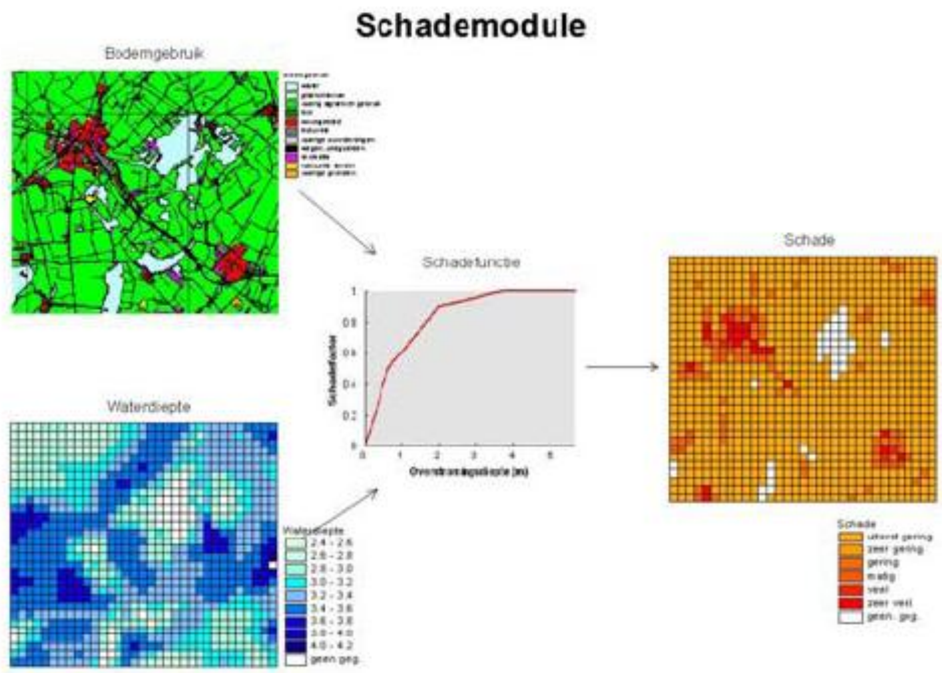


Figure 2-11: Set-up of HIS-SSM, material damage part

2.5 National Standards

Nowadays the flood risk management policy is dominated by aiming to reduce the probability flooding rather than the loss of a flood. These national standards enforce this approach. In the following those standards and possible alternatives are introduced. This clarifies what the legal background is for applying Multilayered Safety (MLS).

2.5.1 History

After a wake-up call in 1953 new national standards regarding flood safety were issued by the first Delta Committee. Back then only the Economic Risk was examined. The conclusion was for the most flood-prone area a probability of flooding of 1/125,000 (1/year) would be an economical optimum of protection (see Figure 2-12). It was assumed that a the probability that a dike breaches, if the water level exceeds its crest height, is equal to 10% the probability of that water level occurring. Ten percent of 1/125,000 is ca. 1/10,000 (1/year). So the latter was made the norm for the most populated areas like Central-Holland. Other dike rings were given a standard of 1/ 2,000 or 1/ 4,000 (1/year) (Weijers, Tonneijck: 28ff.).

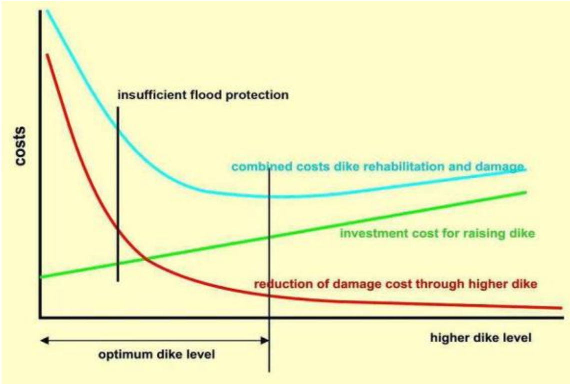


Figure 2-12: Economic optimum for flood defense (Source: Weijers, Tonneijck: 28)

2.5.2 New Standards

Since the population and the economical value have increased significantly since the fifties of the last century, the government is now working on new national standards. The expectation is that they will be implemented starting from 2015. The following changes to the national standards are being discussed.

- Besides planning to decrease the probability of flooding as mentioned in the standards, a couple of other changes are being discussed. Since the knowledge about failure mechanisms of flood defenses, e.g. piping, has been extended tremendously it is considered to sophisticate the definition of probability of flooding. Since a dike is considered as failed if the water level exceeds its crest height, the standards expressed in a probability are now directly translated to a crest height. Now possibilities are sought for to express the strength of a dike with more parameters than the crest height. In this way the resistance against piping etc. could be accounted for as well.
- The last standards were only based on an analysis of Economic Risk. This is going to be extended to an analysis of the number of fatalities as well.
- During the time between two revisions of the national standards or two rounds of maintenance of the flood defenses the risk continuously increases due to e.g. economic growth respectively deterioration of the flood defenses. It is discussed to make the

standards a bit more conservative to anticipate this mechanism of flood management policy and its implementation lagging behind the facts.

2.5.3 Types of standards

The discussion about new national standards gives the opportunity to recall which different types of standards based on the risk approach are thinkable. They will be discussed in the following.

- *Prevention-based standards:* The standards used today exclusively standardize the probability of flooding. The damage that a flood would cause is only considered in the Cost-effectiveness-analysis when determining which probability of flooding is most economic (see Figure 2-12).

  A disadvantage of this type of standard is that the potential damage changes due to economic growth and population fluctuations. Therefore the standard has to be revised approximately every 50 years. Furthermore prevention-based standards do not account for (differences in) local risk.

  The only way to live up to the standards on probability of flooding is changing the boundary conditions (discharge etc.) or building flood defenses. All other flood management measures have no legal basis in this approach. Since the two of the MLS layers aim at loss-reduction, they have thus no legal support.

Definition Flood: According to the Flood Directive of the European Union a flood „means the temporary covering by water of land not normally covered by water“ excluding only floods from sewerage systems (Flood Directive Art.2.1). In this study a flood is defined as the situation when extreme hydraulic conditions in a supplying body of water cause damage. High water levels not causing damage will be called nuisance.

Figure 2-13: Definition of Flood

- *Damage-based standards:* Another thinkable type of national standards is a standard on the maximal damage. The maximum can be defined as an absolute value (x million Euros) or relatively (x% of the GDP). This kind of standard allows the choice between probability- and loss-reducing measures. In terms of fatality this is rather an impractical approach since it would have to be determined how many fatalities are tolerated. Furthermore, a damage-based standardize does not limit the frequency with which an area is flooded. This type of standard does not account for local risk either.

- *Risk-based standards:* This type of standard combines the two types described earlier and makes full use of the risk approach to flood safety. It is possible to set standards for overall-risk (e.g. of a dike ring), for local risk or societal risk. The advantage of this approach is that it includes the frequency as well as the impact of flooding. A standard for the local risk accounts for local differences and ensures that everybody is equally safe. The societal risk ensures that the total impact on the society is bounded. The advantage of these two risk dimensions is that they do not have to be adapted if the protected value grows. If the Economic Risk is expressed as a percentage of the GDP, this standard would not have to be revised due to changes in the country either. If the perception of safety changes in the society, flood standards will have to be updated nonetheless.

A risk-based standard opens up the opportunity to use other flood management measures besides Prevention. Standards on local and societal risk have a positive side-effect on the standards on prevention: At the time of the next revision the potential damage of a flood will have grown less, thus requiring a smaller increase of the prevention standards.

- *Combinations:* Combinations of the types of standards described above are thinkable as well. They can be used as a definite standard or as interim when switching between two different kinds of standards. An example would be supplementing a Prevention-based standard with a standard on local risk. Such an approach provides equality in terms of safety for everybody. Additionally it creates a legal basis for implementing concepts such as Multilayered Safety. These supplementary standards do not necessarily have to be issued by the national government but possibly also by other authorities.

The previous shows that there is no legal basis for any flood safety concept going further than Prevention in the Netherlands right now, including MLS. Encouragements to reduce the local and societal risk will have to be (financially) carried by other public institutions or by the private sector.

2.6 Discussion

This chapter introduced the risk-based approach and its use in the practice of flood risk management. The aim of this study is to evaluate the performance of Multilayered Safety (MLS). The following will discuss if the risk-based approach is suitable to study MLS in depth.

By definition, applying MLS equals implementing a package of different flood management measures. To evaluate MLS it is thus crucial to study the physical interactions of those measures. Indirectly, this is possible with the risk-based approach. But this approach is not detailed enough to understand how the flood management measures actually interact. After all, the risk is based on a number of parameters like the ground level, the water level, the number of vulnerable of object, their vulnerability etc. Flood management measures interact at this level of detail. For example increasing the ground level at one spot might lead to higher water levels at another spot. Higher dikes might result in a larger inundation depth if they fail. These interactions influence the performance of other measures taken, e.g. behind the dike. It is thus essential to study at one level of detail deeper than just the distinction between probability- and loss-reduction.

Another aim of this study was to be able to extend the findings of this study to other areas than the cases. This study is meant to make possible to give a good estimate of the performance of MLS anywhere. The risk-based approach as based in the Netherlands does not entirely allow this. A prerequisite to extend the findings of the studies to other areas is a theoretical framework that works anywhere. The following examples show why this is not the case for the risk-based approach:

- Dikes are generally seen as reducing the probability of flooding. It could just as well be said that they limit the number of affected objects and are thus loss-reducing (see Figure 2-14).
- Generally all measures inside a dike ring are seen as loss-reducing. Thus a compartmentalization dike is labeled as the loss-reducing. Nonetheless it physically functions exactly in the same way as a primary flood defense, which is understood to be probability-reducing.
- The measure of elevating houses is seen as loss-reducing inside a dike ring but is rather probability-reducing outside a dike ring (see Figure 2-14).
- It is unclear if relocating vulnerable objects is probability- or loss-reducing. If they are re-located inside the dike ring it is seen as loss-reducing. But what if they are moved from outside the dike ring to inside the dike ring?
- Heightening a dike is considered to reduce the probability. But is widening the dike to prevent total failure of the dike probability- or loss-reducing.

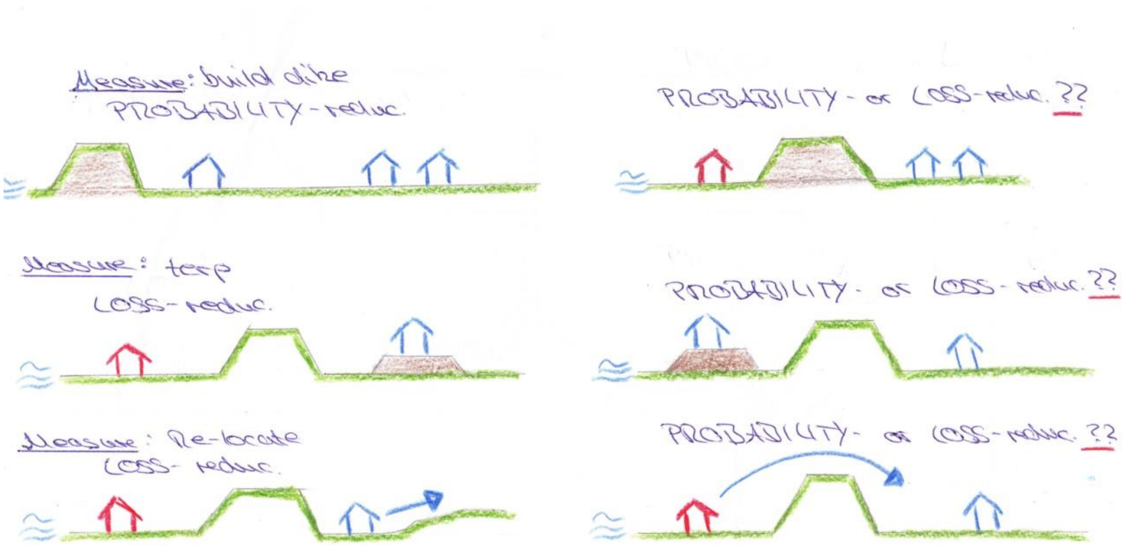


Figure 2-14: Problems if using the risk-based approach to describe all flood management measures. See red house indicates a house outside the dike ring, not having benefited by any measure.

Due to the conventions it is better to evaluate MLS in the currency of probability and loss. But to study two essential properties of MLS, interaction and failure (compare Chapter 1.2), it is better to look for a theoretical framework that is consistent for all areas and provides the necessary level of detail. This is done in the following chapter.

3 Theoretical Framework

To schematize and examine MLS it is necessary to have a theoretical model. The chapter describes first why such a model is necessary and which expectations it has to meet (Chapter 3.1). Then a number of models from flood risk management, including MLS itself, and Safety Science are introduced. The potential of each introduced model to be the foundation of a theoretical framework will be discussed along the way. The descriptions of MLS and other flood risk models have a double information load. On the one hand itself they might be potential model that a theoretical framework could be based on. On the other hand they give a better understanding of MLS itself. After having introduced the flood risk and safety science models, in Chapter 3.5 a choice is made for one of those models. Using the chosen model a schematization of MLS will be derived.

3.1 Objectives theoretical model

To examine the benefits of MLS it is necessary to schematize it. In the practice of flood risk management there are a few dozens of measures that can be taken to increase the safety. Since it is impossible to include all these measures in the schematization of MLS, a limited number of them have to be selected. **(Objective 1:)** The aim is to come to a balanced and comprehensive choice of measures. Those measures have to represent MLS well and cover the array of available measures as much as possible. The chosen theoretical model has to facilitate and legitimate the choice of those measures.

The success of MLS depends on a number of properties, namely interaction between different flood management measures and their failure. After all, applying MLS by definition equals combining a number of measures. Furthermore, the idea of safety layers arises from the wish to come up with an integrated strategy of flood risk management that does not only rely on prevention. **(Objective 2:)** To be able to look into those properties it is preferred that the theoretical model to be chosen is based on the way the measures work.

Recent developments, like the assimilation of flood risk management across all European countries (European Flood Directive) and the discussion of climate change, make it necessary to look beyond the *Dutch* flood risk *today*. Therefore, the theoretical model is supposed to make it possible to extend the findings of this study to all kinds of flood-prone areas and anticipate changes in the environment such as climate change or population growth. Usually flood management measures are looked at as probability- and loss-reducing. Flood-prone areas and changes like climate change, cannot be captured accurately with those two parameters (probability and loss). **(Objective 3:)** Therefore it is desired to find a framework providing a greater level of detail. Ideally it would be based on the smallest possible parameters, namely quantifying undividable units, such as the number of people and the water level.

3.2 MLS as in the National Waterplan

The government has first introduced MLS in the National Waterplan 2009. The National Waterplan describes all water-related measures to be taken to ensure that the Netherlands stay safe and prospering for the generations to come. There are a number of different interpretations of MLS (for example the one from the Dienst Ruimtelijke Ordening Amsterdam). In the following it shall be referred to MLS described in the National Waterplan.

3.2.1 Description MLS

Multilayer safety (MLS) aims at realizing flood protection not only by Prevention (layer 1) but also by Spatial Solutions (layer 2) and Crisis Management (layer 3) (Nationaal Waterplan 2009: p. 6). Later on a number of other concepts that present a similar approach such as the *safety chain* in the Netherlands (veiligheidsketen, [ten Brinke 2008, Gilding 2008]) or *Multiple Lines of Defense* (Jongejan *et al.* 2008, Lopez 2009) in the USA will be discussed.

Figure 3-1: Multilayered Safety in the National Waterplan 2009

Prevention reduces the chance of a flood happening whereas Spatial Solutions and Crisis Management try to limit the amount of loss caused by a flood. On first sight MLS adds mainly loss reduction to the traditional policy of only prevention. Prevention thus reduces the probability of water entering the dike ring, while Spatial Development and Crisis Management reduce the consequences of a flood. For each layer many different measures are thinkable. An overview of all those measures will be given in Chapter 3.5.3 below. At this point first the three layers of MLS will be clearly defined:

Prevention is layer 1 of the concept MLS*.* Prevention can be defined as preventing river or seawater from inundating areas that are usually dry. When talking about a dike ring, this refers to preventing water from entering the dike ring. In this case examples for prevention are building flood defenses such as dikes or preventing high river discharges. Against the general perception, Prevention thus does not automatically mean building dikes. This is especially the case in areas along rivers where many alternatives to building a dike are available.

Spatial Solutions, layer 2, deals with using spatial planning and adaption of buildings that pro-actively counter floods. Potential measures are building at less flood-prone locations, having more water storage, living on the first floor, raising the ground level and scores of other possibilities.

Crisis management, which constitutes the layer 3, pays attention to disaster plans, risk maps, early-warning systems, evacuation, temporary physical measures such as sand bags, medical help and so on. It has to be mentioned that in this study looks at the preparation for Crisis Management rather than at Crisis Management itself. This can cause some confusion when looking at MLS from the safety chain perspective since disaster management itself is a response to a disaster.

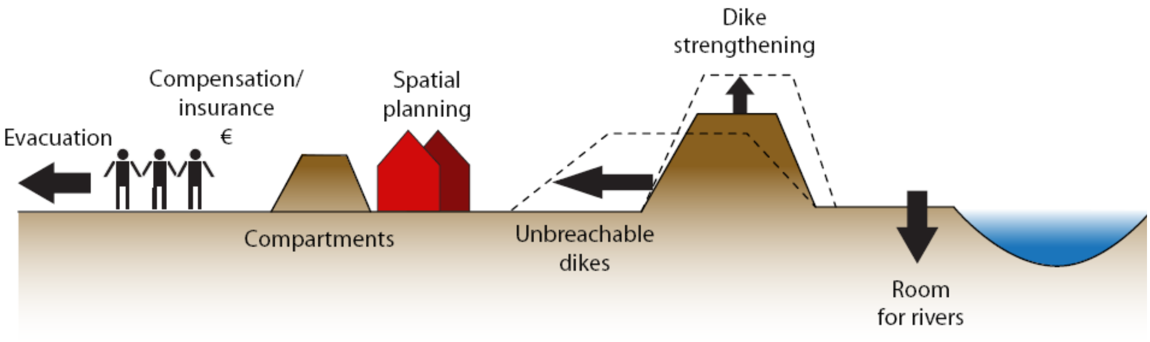


Figure 3-2: Measures for prevention, constraint and disaster control of floods (source: S.N.Jonkman)

3.2.2 MLS: Objectives and Expectations

In general it can be assumed that flood management strives to reduce the risk to below target values for different dimension of risk, such as individual risk, societal risk and Economic Risk (see Chapter 2.2). Subordinate to this are some additional expectations attached to MLS, listed below. It is part of this study to indicate to which degree and at what costs MLS can fulfill (some) of these expectations.

- *Alternative*: Spatial Solutions and Crisis Management as alternative where options for Prevention are limited.
- *Diversification:* Flood risk management deals with a lot of uncertainties. The rate of return of investments in flood protection measures is thus uncertain as well. Modern portfolio theory states that a combination of investments should be chosen that has the highest possible expected return given the uncertain developments (Aerts *et al.* 2008: 41ff.). Put differently, MLS gives the chance to spread financial risk over a number of different investments.
- *Multi-functionality*: Letting flood protection measures serve more than one goal, e.g. enhance a sustainable and water-rich living environment, possibly resulting in financial advantages.
- *Sustainability*: Interruption of the risk spiral of increased safety due to flood defenses resulting in more construction of e.g. housing and more housing again requiring more flood defenses (Seo 2006: 43).
- *Efficiency*: Synergy between the layers resulting in a better rate of return of investments in flood safety.
- *Acceptability*: Enhanced public and political support for an innovative and dynamic concept.
- *Financing*: Spreading of the costs of flood safety to private parties (Layer 2) and costs

made only if a flood occurs (Layer 3), possibly triggering a market mechanism to consider flood safety when making investments in e.g. real estate.

- *Uncertainty*: possibility to anticipate rapid and/or unexpected changes due to climate changes, societal developments etc.
- *Loss*: attention for loss-reduction since floods can never be fully excluded.
- *Redundancy*: More than one "layer" of safety measures, as proposed in MLS, is felt to minimize the chance of failure and thus loss due to flooding

3.2.3 Discussion

This paragraph examines if MLS meets the objectives for choosing a theoretical model given in Chapter 3.1 .

Naturally MLS itself meets the aim of choosing measures that represent MLS. The model is also based on the way the measures work. When departing from a dike ring perspective, it is agreed that Prevention is probability-reducing and the other two MLS layers are impact-reducing.

But MLS is less suited to extend the study to other areas and landscapes than the dike ring. From any other perspective than the dike ring probability- and impact-reduction only become labels that say little about what a measure actually does and its interaction with other measures (compare Chapter 2.6). Furthermore the risk approach does not make it immediately apparent how fluctuations in the environment such as population growth influence the performance of MLS. For an in-depth discussion of the conceptual weaknesses of MLS, please see Chapter 3.3.2 where MLS is compared to the safety chain approach.

3.3 Other models in flood risk management

As discussed in the previous subchapter, the model of MLS itself is not sufficient for the scope of this study. The following chapters review a number of other models. This is partly done to learn which characteristics make a good model. The main objective is to find a suitable theoretical framework for this study though (see Chapter 3.1).

3.3.1 Overview of other approaches

Whereas the Netherlands traditionally relies mainly on prevention, in other countries limiting impact is more influential. Often this has resulted in other chain- or layer-based concepts similar to MLS. But also in the Netherlands itself there are other chain-like safety concepts and even different version of MLS itself. At this point it is important to note that (slightly) different concepts often carry the same name. Table 3-1 gives an overview of the different approaches being used.

Multi-layered flood management							
NL (floods)	NL (floods)	NL/industry	NL (NWP)	D (TU Hamburg-Harburg)	USA	JAP	F – IT sector
Multi-layered safety (Meerlaagsveiligheid)	**Multi-layered safety** (Meerlaagsveiligheid)	**safety chain** (Veiligheidsketen)	**safety chain** (Veiligheidsketen)	**Before, during, after**	**Multiple lines of defense (see** Figure 3-3**)**	**From River to Basin**	**Security against intrusion (IT) ***
1 Prevention: flood defenses	**1 Prevention:** flood defenses	**2 Prevention:** flood defenses (category A and B), hydraulic measures such as „Room for Rivers“	**2 Prevention:** flood defenses (reinforcement, maintenance)		**1 Offshore shelf** **2 Barrier Islands** **3 Sound** **4 Marsh land bridge** **5 Natural Ridge** **6 Highways** **7 Flood gates** **8 Levees**		**1 prevention**
2 Spatial Development: *(inside the dike ring?)* spatial planning, adaptation of buildings	**2 Impact reduction** (spatial measures)	**1 Pro-action:** spatial planning, adaptation of buildings	**1 Pro-action:** adaptation of buildings, protection of vital infrastructure	**2 Avoidance** (land use control): Spatial Planning, Building regulations	**9 Pumping Station** **10 Elevated Building**	**1 Pre-flood preparedness**	**2 reduction**
3 Crisis management	**3 Crisis management** (social impact reduction)	**3 Preparation:** crisis management plans, equipment, adaptations, regulation, communication	**3 Preparation:** early-warning systems, monitoring water levels, planning, training, risk maps, evacuations	**3 Alleviation** (preparedness): Flood resistant building, cascading flood compartment **1 Awareness** (Capacity building of human resources): Information, Education, Communication	**11 Evacuation Route** ****focus used to be on evacuation and individual measures***	**2 Operational flood management:** forecasting, warning, emergency rescue, strengthening defenses, operate retardation ponds.	**3 deception** **4 detection** **5 reaction** **6 correction**

		4 Response: implementing plans: temporary physical measures, disaster relief, communication, coordination, decision-making	**4 Response:** alarm, coordination, decision-making, physical measures, providing information, communication, disaster relief	**4 Assistance** (contingency measures) Financial preparedness, emergency response, Emergency infrastructure, Recovery			**5 reaction** **6 correction**
		5 aftercare, rehabilitation: (resilience) compensation of damage, rebuilding	**5 aftercare, rehabilitation:** (resilience) compensation of damage, rebuilding, evaluation, psycho-social aftercare, accountability			**3 Post-flood response:** Relief, Reconstruction, recovery/regeneration, review	**7 evaluation**
Ontwerp-Beleidsnota Waterveiligheid 2008	Dienst Ruimtelijke Ordening. Note that here it is already in the definition that Layer 3 does not save material value.	Own interpretation	Interpretation in Ontwerp-Beleidsnota Waterveiligheid 2008	Pasche *et al.* 2007: slide 14.	Lopez J.A. 2009.	Kundzewicz, Z., W. and K. Takeuchi, 1999.	Coolen R., Luijf H.A.M. 2002.

Table 3-1: Overview chain-like safety approaches

Figure 3-3: Multiple Lines of Defense as used in the USA. (Source: Lopez 2009: 190)

3.3.2 Discussion of the models in flood risk management

To facilitate giving MLS a theoretical basis, a couple of the approaches mentioned in Table 3-1 will now be examined for their conceptual strengths and weakness. Since the safety chain and MLS are the most relevant approaches in the Dutch flood safety discussion these days, in the following these two will be discussed in more detail.

Safety Chain

The Safety Chain and MLS differ fundamentally. The first functions like a series system and the latter like a parallel system. Nonetheless, a few lessons can be learned from the safety chain to find a water-proof definition of MLS. The Safety Chain shows some imprecision in definitions. Such imprecision should be avoided when defining MLS. Therefore, the definition problems of the Safety Chain are discussed in the following.

When defining the safety chain (Pro-action, prevention, preparation, response, aftercare) authors disagree on the question where the line between preparation and repression should be drawn; after all disaster management (repression) has to be prepared as well as to be implemented at times of crisis. The draft policy memorandum on water safety by the Dutch government defines preparation as early-warning systems, monitoring of water levels, planning, trainings, risk maps, flood warnings and evacuation. The repression (or by others called the response phase) includes alarm, coordination, decision-making, implementation of physical measures, provision of information, communication and medical aid (Ontwerp-Beleidsnota Waterveiligheid 2009: 17). Especially with regard to physical measures such as sand bags and medical aid one could point out that those have to be prepared beforehand, with certain costs attached.

Evacuation is another measure that is difficult to place because in case of floods evacuation starts before the disaster actually happens but continues as a repression measure. Then it may also be called self-reliance though. Gilding faced the same definition problems in his thesis and decided to use the measures evacuation and sand bags for both preparation as well as repression (Gilding 2008: 3-16). It can be said that the safety chain approach was introduced to flood risk management to *prepare* against disaster striking. Therefore it is rather curious that preparation has been made a chain link itself.

Another definition problem occurs when using the safety chain in a dike ring approach inherent to flood risk management in the Netherlands. As an example, pro-action is usually defined as spatial planning, adaption of buildings and protection of vital infrastructures (Ontwerp-Beleidsnota Waterveiligheid 2009: 17). When dealing with a dike ring, these measures can be used inside and outside the dike ring. Pro-action is mainly meant to reduce the loss caused by inundation but outside the dike ring pro-action has another very crucial effect: it prevents critical hydraulic loads on the dikes etc. by giving the rivers space to discharge (measures in the prevention link). It therefore reduces the probability of flooding. So the definition of pro-action is vague and it is not clear if this is a purely loss-reducing measure. Pro-action furthermore only purely facilitates the idea of a safety *chain.* When understanding an inundation as a chain of events, pro-action sets in at different points in the chain. If reducing the flood risk is seen as a chain of actions pro-action is not clearly different from prevention.

Multilayer Safety

The concept of Multilayer Safety (MLS) solves some of these imperfections but introduces others. Preparation itself is not part of the concept anymore but a prerequisite. Therefore, for drawing up a national policy for flood safety MLS seems more suitable than the conventional safety chain. Speaking of different layers implies the notion of safety nets, implying several lines of defense. Prevention indeed is often implemented as one or more lines of defense. If different lines of flood defense are applied, all have to fail to cause a flood. The other two MLS layers do not work like a line of defense. Additionally the two layers do not work like two lines of defense placed behind each other. They both come into effect simultaneously once an area floods. It is not the case that Crisis management only comes into effect if the Spatial Solutions fail. If one fails that does not mean the worst possible damage will occur. These notes are fundamental when modeling MLS systematically. See Chapter 4.4 for an in-depth discussion on the failure of flood management measures (serial and parallel systems).

Another discussion revolves around the question which layers are probability- or loss-reducing. The Dienst Ruimtelijke Ordening of the City of Amsterdam (DRO) handles a different definition being Prevention as layer 1, impact-limiting as layer 2 and crisis management as layer 3. Semantically this implies that Crisis Management would not be impact-limitation since impact-limiting itself is defined as Layer 2. In the view of the DRO this is not the case since they see layer 2 as technical measures for loss reduction whereas layer 3 consists of organizational measures mainly reducing the social impact. Another argument would be that Crisis Management indeed is mostly organizational involving little equipment. Usually the equipment needed for Crisis Management is hired from private companies with the costs being an issue to be discussed after the crisis has taken place. These costs, and therefore partly Crisis Management as well, could therefore be seen as part of the economical damage. On the other hand there is no arguing about the fact that the very goal of Crisis Management is impact-reduction. Since measures as e.g. reinforcing the flood defenses with sand bags is also part of Crisis Management it is questionable if this third layer really only reduces social impact, as the DRO assumes. The dispute in this paragraph is by-product of the conceptual weaknesses of the risk-based approach to flood safety (see Chapter 2.6).

In general the definition of Crisis Management raises difficulties. To pick up the example of the sand bags again, one could also state that dikes reinforced with sand bags have a lower probability of breaking. This would introduce an overlap with prevention measures. This issue shows that defining flood and failure of protection matters considerably.

The framework for MLS that will be elaborated later on in this study thus has to solve the difficulties mentioned above. The objectives for finding a theoretical framework are elaborated in Chapter 3.1.

To prevent misunderstandings it should be stressed here that all MLS measures are preventive in a way. Layer 1 – called prevention – indeed prevents a flood. But once water floods an area the remaining two layers try to prevent people/objects to be exposed and loss to occur.

3.3.3 Implementation world-wide

Ideally the framework of MLS to be developed in this study will be applicable to as many cases as possible. Therefore it is important to find out what the situation in other countries is and which approaches to flood risk management are used there.

Of all these approaches the safety chain (Dutch: veiligheidsketen) is probably the most well-known one as it is also applied in other safety problems apart from floods. Therefore this concept is a logical choice when comparing the flood policies of different countries. In the following a short overview will be given of which links of the safety chain other European countries, the USA and Japan concentrate on.

Germany mainly puts its stakes on spatial planning and awareness of the public to minimize loss due to flooding.

Belgium's policy does not differ much from the Dutch even though they pay slightly more attention to private insurances and spatial planning.

In the *United Kingdom* there is a striking emphasis on private insurances and the personal responsibility of people. Due to the much smaller flood-prone areas it is possible there to invest little into prevention. Flood risk management is much more dealt with by the local than by the central government. It should be noted that the UK is not dealing with a delta challenge as the Netherlands is.

In *France* the nature of floods is much different than in the Netherlands since co-called flash floods constitute a greater problem. While there is little effort put on prevention, a start has been made to use more spatial planning to reduce risks.

Floods are seen as a given in the *USA,* so that all resources are used to limit the loss. While this is interesting for the Dutch progress in loss reduction, a heavy focus on accountability makes the American approach only partly applicable.

While *Japan* is densely populated it is also exposed to frequent floods. As the Netherlands Japan has been concentrating on Pro-action and Prevention but is now trying out multi-functionality of spatial planning and structures. Like the UK Japan does not have to deal with a whole delta but with smaller catchments having independent floods.

The following Figure 3-4 gives an overview of all countries described (ten Brinke 2008: 97ff.).

	Pro-action	Prevention	Preparation	Response	Recovery
Japan	Strong	Very strong	Strong	Strong	Little
Germany	Very strong	Strong	Strong	Very strong	Little
The Netherlands	Strong	Very strong	Strong	Strong	Average
Belgium	Strong	Strong	Strong	Strong	Average
UK	Strong	Average	Very strong	Very strong	Strong
France	Average–strong	Average	Very strong	Very strong	Strong
USA	Little	Little	Very strong	Very strong	Strong

Table 2. The relative efforts put on safety chain links for flood risk management in several countries. The countries are placed in order such that the emphasis shifts from the left-hand side of the chain (top of the table) to the right (bottom of table)

Figure 3-4: Overview of application of the safety chain in flood management in different countries (ten Brinke 2008: 97ff.)

3.4 Safety Science

In the above theoretical models used in flood risk management have been introduced. None entirely met the objectives for the theoretical model given in Chapter 3.1. Therefore the search for a suitable theoretical model is continued in the world of Safety Science.

Safety Science originates from industry. Therefore this subchapter starts off with discussing the parallels of flood risk management and safety science (Chapter 3.4.1). Following that some basics notions from safety science are introduced and applied to flood risk management (Chapter 3.4.2, 3.4.3). This is necessary to understand the theoretical models from a flood risk perspective. Only then the theoretical models offered by Safety Science are introduced (Chapter 3.4.4).

Definition Safety:

The condition of being safe from undergoing or causing hurt, injury or loss. (Merriam-Webster)

Definition of Safety Science:

- Predicting the relations in a technological system which threaten either people or the environment or long term damage (models)

- Developing assessment methods, criteria, and standards about the acceptability of the risks which arise during the functioning of the system (methods & criteria)

- Operationalising and applying existing knowledge and insights into the technical, human and organisational solutions to problems in (re)design, construction, use, maintenance and disposal phases of the system (application)

(Guldenmund 2009: slide 18, 23)

Figure 3-5: Definitions of Safety and Safety Science

3.4.1 Parallels with flood risk management

Along with aviation and industry safety science has developed to a science in its own right. Similar to the historical developments in flood safety mechanical engineers first and foremost relied on prevention for more safety. As early as the end of the nineteenth century engineers had started to include safety in their designs by “simply trying to add it [safety, FH] on it the form of guards” (Leveson 1995: 132). These developments correspond remarkably well to flood safety in the Netherlands. As described in the introduction (Chapter 1.1) the Dutch focus on preventing flood safety by adding guards in form of flood defenses such as dikes. Just like the machines remained the same, only with guards added to them, so far what is protected by the dikes, cities etc., has been adapted rather as a side-effect and on a minimal scale. MLS is an approach that would change this by requiring an adaption of the flood-prone areas.

Additionally in industry it was anticipated early that safety could be left to the market forces since a higher degree of safety meant more production (Leveson 1995: 132ff.). This was also the case for flood safety in its early days. Groups of individuals set up the first water boards (*waterschappen*) to organize protection against floods so that they could make a living undisturbed behind the dikes. These days flood safety is a national issue with private parties playing only a side role, the awareness of flood risk in public is generally low. This is one of the reasons for the spiraling risk often mentioned in the context of flood management. People build houses in potentially dangerous areas because the national government provides safety. This leads to a vicious cycle because more houses require again a higher level of safety (Seo 2006: 43). Again MLS could cause this to change since some measures as adaptation of buildings would possibly be paid by private parties. Since this market mechanism according to Leveson worked well in some sectors of industry it is an interesting aspect to consider when studying MLS. Among other aspects such a development would imply that safety is not necessarily purely a public good. After all, private parties can invest in safety in a way that nobody else benefits from it as well. Safety achieved by e.g. dike rings, however, will always stay a public good.

Definition Public Good
" A commodity is a public good if its consumption by any one person does not reduce the amount available to others. Putting it another way, providing a public good to *anyone* makes it possible, without additional cost, to provide it to everyone."
(Hirshleifer *et al.* 2005: 518)

Figure 3-6: Definition Public Good

3.4.2 System approach of safety science

The theoretical basis of Safety Science is Systems Theory. When doing research about Multilayer Safety it can be fruitful to approach the flood-prone area as a system. Leveson states the following on Systems Engineering:

> "The objective is to integrate the subsystems into the most effective system possible to achieve the overall objectives. Complicating matters is the fact that a system may have multiple objectives and some of these may conflict with other objectives such as ease of operation and maintenance or low initial costs. A goal of systems engineering is to optimize the system operation according to prioritized design criteria." (Leveson 1995: 141).

This quote is highly relevant to flood safety when considering that a flood-prone area has to provide space for living, working and recreation under conditions as accessibility, clean environment, (flood) safety and many more. The fact that flood risk is a hotly discussed issue in the public, demonstrates that flood safety by far does not always have the priority among all the demands an area of settlement has to fulfill.

Prevention traditionally added flood safety to an area by building flood defenses. MLS layers like Spatial Solutions and Crisis Management go a step further and try to adapt the areas and objects at risk themselves to make them saver. Put differently, Multilayered Safety is meant to step away by from just adding flood safety to an area but to make an area or city save to floods itself. Thus, flood safety indeed becomes an emergent property if MLS is applied.

Leveson adds that system safety also captures tradeoffs and conflicts within a system. These are welcome tools when examining MLS. After all, tradeoff between layers in terms of for example funds, attention and space are expected. The aim of studying MLS as a concept is not only looking at the effectiveness of each layer separately but in interaction with each other. When assuming a flood-prone area to be a system with safety as an emergent property, any framework excluding interaction would fall short. The real potential of MLS might lay in letting those layers work together so that studying them as a system becomes necessary. A system approach with safety being an emergent property would indicate how the layers of MLS would work together since it is impossible to implement those layers independent of each other. Furthermore a system approach could indicate criteria that facilitate a positive interaction of MLS layers.

It is wise to adapt a system approach for MLS like it is done in safety science. Only like that can flood safety as an emergent property be evaluated properly. A system approach means taking all characteristics of a flood-prone area into account. This facilitates another objective of this study, namely finding a framework for MLS that is applicable to any random flood-prone area. The differences between those areas are differences in the same characteristics that the emergent property of safety depends on.

3.4.3 Basics of safety science translated to flood risk management

Safety science approach to flood management

Exceptionally high water levels do not by definition result in loss. There are a number of stages before a high water level becomes a flood that costs lives and damages valuable objects. This is also an important notion for flood management because different measures – also in MLS - set in at different stages between the every-day situation and loss occurring due to flooding. The notions *hazard, exposure* and *vulnerability* describe those stages from a theoretical perspective. Furthermore most safety concepts in Safety Science are based on the two notions *hazard* and *target.* These four terms are crucial for a developing a framework for MLS and are thus introduced in the following from a flood management perspective.

- *Hazard*

In the normal situation a *hazard* might arise. In flood management this would be high water levels at sea or in the supplying waters such as rivers, thus the boundary conditions. The existence of a hazard does not mean at all that any calamity will occur. A hazard can cause damage if there is a vulnerable target exposed to it.

- *Target*

A *target* can be human lives or valuable objects such as buildings. Furthermore, a target coming into contact with water does not necessarily have to suffer damage.

Safety Science has developed a number of models that concern separating the hazard from the target. Examples are the Hazard-Barrier-Target Model, the Swiss-Cheese-Model, the Bow Tie and Haddon's ten strategies (see Chapter 3.4.4).

- *Exposure*

Hazards, such as high water levels, do not always pose the same threat. A dike ring is a very particular case of the flood risk problem. While in most rivers in the world en the areas outside the dikes the water level rises gradually, large parts of the area in the dike ring would flood very quickly with a large inundation depth. The same hazard threatens areas inside a dike ring very differently than areas outside a dike ring. Thus an area is characterized by its *exposure* indicating how many vulnerable objects are at risk and to what degree.

- *Vulnerability*

The *vulnerability* of a target determines how much damage a target suffers when coming in contact with water. Not every kind of object will experience equally much loss under the same flood circumstances. Agricultural companies might suffer more or less loss than a paper factory for example. Furthermore the same kind of objects can differ in the severity of flood damage. An example would be that two different houses, neighboring each other, might need very different amounts of reparation after a flood. These differences are quantified in the notion of vulnerability.

The vulnerability is the link between flood exposure and the loss coming forth from the exposure. The vulnerability functions transform the flood characteristics to the loss suffered. If an object (target) is not vulnerable the exposure to a flood will stay a hindrance whereas exposure will be turned into a loss in case of vulnerability.

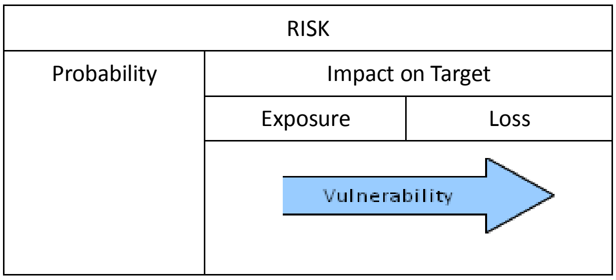


Figure 3-7: Definition of Risk, Probability and Impact

3.4.4 Models

Naturally many different models to provide safety have come forth from Safety Science. In this study five of these models will be introduced: the Domino Model, the Swiss Cheese Model, the Hazard-Barrier-Target Model, the Bow Tie Model and Haddon’s ten strategies. Each model points to other features of safety and safety management. For the sake of length only the model that is most relevant to the further study, namely Haddon’s ten strategies, is described here in length. For the other four models please see Appendix 9.1.

For better understanding it should be noted that all of these models are based on the following notion: It is assumed that the hazard harms the target by uncontrolled release of energy or by disturbing the normal level of energy (Leveson 1995: 186). In the case of flood safety this energy would have the form of kinetic energy due to flow velocity and other kinds of energy such as the temperature of the water. This is does not cover the entire load of harm done by water. But it does describe the way of thinking in safety science.

Haddon's Ten Strategies and similar approaches

Some authors actually name the barriers that are only indicated in the models described above. An overview is given in Table 3-2. Among these authors Haddon introduces the most comprehensive classification of strategies. He defines a logical sequence of strategies to prevent human and economic losses. Each strategy corresponds to one step that a calamity passes through before it reaches its full consequence.

It is important to note that Haddon did not mean to rank the strategies by the effectiveness when putting them into a sequence. As an example he uses tea cups, which could considered as hazarded when being moved around. This hazard can be prevented by simply not moving them. As this is not very practical, they are being wrapped with paper, which decreases their vulnerability. This strategy is lower in the sequence than preventing the hazard altogether by not moving the cups, but still more desirable. Other hazards as e.g. hurricanes cannot be prevented at all (Haddon 1976: 324). Furthermore Haddon notices that some damage done might be irreversible limiting the scope of available actions to his strategies 8-10. Thus, attention has to be paid to the fact that this classification of strategies is not meant to quantify the effectiveness or efficiency of the strategies. It exclusively looks at the strategies' way of functioning.

Nonetheless, the ranking of the strategies does facilitate choosing an appropriate strategy. Haddon states that the larger the amount of energy related to the resistance of the target, the earlier the used strategy or strategies should lie in the sequence (Haddon 1976: 325).

Attention has to be paid to the fact that this classification only considers the type of effect of the different strategies but not the effect itself, it`s side-effects and costs. In other words, neither the effectiveness is indicated nor the efficiency. After all, in most cases more desirable strategies are often far more costly than the ones less preferred, due to the scale at which is being intervened.

Last but not least it is mentioned that Haddon's strategies can not only understood as physical measures. In flood safety other factors as organization, safety culture or latent conditions, as introduced by the other safety models, remain relevant.

Table 3-2: General chain-like approaches to safety (Guldenmund 2009: slides 31-33)

	Haddon	Different version of Haddon	Sozial- en Preventivmedizin 1981
1	Eliminate hazard source		Banish hazard
2	Lower, diminish, reduce hazard source	Prevent buildup energy	
		modify characteristics of energy	
		limit amount of energy	
3	Prevent release of hazard	Prevent uncontrolled release of energy	
4	Modify rate of release of hazard source	Modify rate and concentration of released energy	
5	Separate in space and time hazard source and object	Separate source of energy and target in time and space	Removal of person (target)
6	Use a barrier between the hazard and the objects	Separate with physical barriers	Contain hazard
			Protection of person (target)
7	Modify contact surface of hazard source		
8	Strengthen objects against hazard	Improve the target's ability to endure an energy flow	
9	Mitigation (Abschwächung)	Limit the development of injury or loss	
10	Reparative strategies/stabilization	Stabilize, repair, rehabilitate	

3.5 Schematization

In the following one of the models introduced above will be chosen. It will be translated to flood risk management first. Then the available flood management measures will be ordered according to that model. Finally a schematization for Multilayered Safety will be derived.

3.5.1 Choice

In Chapter 3.4.4 Haddon's ten strategies have been introduced. First of all, from all the models studied, Haddon covers the range of possibilities to deal with danger most comprehensively (Objective 1). Furthermore, it complies best with the objectives for the theoretical framework given in Chapter 3.1.

It is very convenient that Haddon explicitly names the strategies and their way of functioning. That makes it very easy to picture what is actually happening. Usually flood risk measures are looked using two parameters: probability and loss. But, as Chapter 2.3, has shown, those two parameters are calculated using other parameters. Those parameters describe undividable units such as the number of people or the ground level and therefore provide a greater level of detail.

With Haddon's ten strategies it is possible to exactly point out, which of those parameters or relations between those parameters a measures targets. This opens up the way to study MLS at the level of detail that is needed to e.g. understand the interaction between flood management measures (Objective 2). Additionally, it becomes possibly to transfer the findings to any flood-prone area. After all, each of those areas is a unique combination of values of those parameters mentioned above (Objective 3).

In consideration of those arguments Haddon's model is chosen to serve as a basis for a theoretical framework for MLS.

3.5.2 Translation to flood management

In the first column of Table 3-3 Haddon's ten strategies are translated to flood risk management. Some of the strategies are not realistic for flood risk management since it is impossible to eliminate the reason for a surplus of river discharge as this would mean preventing rain or melting of ice. Thus strategy 1 and 2 are not applicable for flood risk management. Furthermore, Strategy 10, repairing occurred damage, is not relevant for Multilayered Safety. That strategy deals with resilience that is not included in the notion of MLS as introduced in Chapter 3.2.

The second column of Table 3-3 indicates which parameters underlying the risk calculation are affected by this measure. This shows which buttons each strategy turns to tune the risk profile. Possible buttons are all parameters that are needed to calculate the risk (see Chapter 2.3). Here it is visible that Haddon provides the opportunity to distinguish flood management measures at the desired level of detail (compare Chapter 3.1).

Interestingly the notions hazard, exposure and vulnerability introduced in Chapter 3.4.2 emerge from Haddon's strategies as well. This is shown in the last column of Table 3-3. Analysis shows that strategies 1-4 limit the hazard source; strategies 5-7 limit the exposure and strategies 8-10 limit the vulnerability. In the case of flood risk management the hazard source has to be understood as the hydraulic load expressed in the boundary conditions.

Table 3-3: Strategies in Flood Risk Management

	Haddon	Strategies in Flood Risk management	Parameter affected	Effect on basic safety notions
1	Eliminate hazard source	NA	NA	
2	Lower, diminish, reduce hazard source	NA	NA	Reduce hazard source
3	Prevent release of hazard	Prevent extreme amounts of water in system	Probability of hydraulic load P_{load}	
4	Modify rate of release of hazard source	Relief/Alter extreme hydraulic situation	Water level WL	
5	Separate in space and time hazard source and object	Prevent that objects/people are in the dangerous area	Number of exposed n	
6	Erect a barrier between the hazard and the objects	Erect a barrier between water masses and object/people	Probability of exposure P_{exp} resp. number of exposed n	Reduce exposure
7	Modify contact surface of hazard source	Decrease the degree by which the objects are effected	Inundation depth h	
8	Strengthen objects against hazard	Prevent damage from occurring among exposed	Vulnerability Dam/ Mortality m	
9	Mitigation (Abschwächung)	Reduce occurring damage among exposed	Vulnerability Dam/ Mortality m	Reduce vulnerability
10	Reparative strategies/stabilization	NA	NA	

3.5.3 Deriving the schematization

The theoretical framework is meant to facilitate schematizing Multilayered Safety. Schematizing MLS means choosing a limited number of flood management measures that represent MLS comprehensively. Now that a framework has been derived, it is possible to sort all available measures into the framework. This has been done in Table 3-4 - Table 3-6 for each of the three layers of MLS. The measures have also been arranged by geographical scale of application: delta, polder, neighborhood and individual object.

The last step to come to a schematization is to choose representative measures from all the available flood management measures summed up in Table 3-4 - Table 3-6. For a comprehensive schematization it is best to choose one measure for each strategy respectively each layer. Then the schematization covers all the different ways of functioning for all MLS layers. Of course it has to be possible to model the chosen measures in the existing computational model. Furthermore, attention has to be paid that the chosen measures allow transferring the findings about them to the measures not-chosen. Thus, the chosen measures should not be too specialized. In example including flood-proofing buildings in the schematization is better than choosing for floating buildings, since that is only one form of flood-proofing.

Figure 3-8 shows the measures chosen for the schematization.

Table 3-4: Flood management measures in Prevention Layer ordered by way of functioning and scale of application

Layer 1:PREVENTION							
	Haddon	Physical way of functioning	Family	Geographical of application			
				Delta	Polder	Neighborhood	Object
1	Eliminate hazard source	Prevent storm and rain					
2	Lower, diminish, reduce hazard source	Reduce storm and rain					
3	Prevent release of hazard	Prevent extreme amounts of water in system	-Retain run-off	- Forestation	- Retention basins - Vegetation/Forestation		
			Redistribute water mass over waterways	- re-distribute discharge over existing rivers/canals - add rivers/channels	- add a flood channel		
4	Modify rate of release of hazard source	Relief extreme hydraulic situation	Capacity increase of water system	- widen river-foreland - deepen summer bed of river - remove obstacles from river-foreland - natural water buffer - artificial water buffer			
			Relief extreme situations	- inundation polders - pumping out trapped water			
5	Separate in space and time hazard source and object	Reduce number of objects in flood-prone area	NA				
6	Use a barrier between the hazard and the objects	Barrier: Prevent that objects are being reached by the water, thus reduce number of effected	Flood defenses	- (Adjusting) storm surge barriers - Compartmentalizing supplying big waters	- Natural flood defenses (dunes) - Dike (traditional, unbreachable, etc.) - Dam - Flood gates (need operation) - cascading dikes - super dike - climate dike - electronic monitoring - artificial sand nourishment	- Retaining wall	- Riverside wall - Building as flood defense
7	Modify contact surface of hazard source	Decrease degree with which objects are being reached by water, thus reduce severity with which objects are effected	Control entering water		- controllable inlets - controlled dike breach		- controlled flooding of buildings/basements
			flood defenses resistant to overflow		- flood defenses resistant to overflow		
8	Strengthen objects against hazard	Prevent that effected objects suffer damage	NA				
9	Mitigation	Reduce occurring damage among effected	NA				
10	*Reparative strategies/stabilization*	*Stabilize, repair, rehabilitate*	NA				

Table 3-5: Flood management measures in Spatial Solutions Layer ordered by way of functioning and scale of application

Layer 2: SPATIAL DEVELOPMENT							
	Haddon	Physical way of functioning	Family	Geographical of application			
				Delta	Polder	Neighborhood	Object
1	Eliminate hazard source	Prevent storm and rain	NA				
2	Lower, diminish, reduce hazard source	Reduce storm and rain	NA				
3	Prevent release of hazard	Prevent extreme amounts of water in system	NA				
4	Modify rate of release of hazard source	Relief extreme hydraulic situation	NA				
5	Separate in space and time hazard source and object	Reduce number of objects in flood-prone area	Spatial Planning		- zoning/ land use/ function change - reserving locations/ protection zones (for flood defenses) - improved obligatory water test (*watertoets*) - awareness (risk maps)	- building at physically more favorable locations	
6	Use a barrier between the hazard and the objects	Barrier: Prevent that objects are being reached by the water, thus reduce number of effected	Compartmentalization		- Double wall strategy - partition strategy	- value protection strategy	
7	Modify contact surface of hazard source	Decrease degree with which objects are being reached by water, thus reduce severity with which objects are effected	Elevate vulnerable objects		- naturally high grounds	- big terps, artificial islands - cascading flood compartments - elevating ward	- building on stilts - no housing on ground level
			Change flood characteristics		- Retention basin/ open water - artificial/natural water buffers - more pumping capacity - instrumentalization of existing compartmentalization dikes	- diverting water from vulnerable areas (hedges, noise barriers etc.) - reduction of paved surfaces - improved run-off	- vegetated roofs - vertical water buffers
8	Strengthen objects against hazard	Prevent that effected objects suffer damage	Flood-proofing				*Flexible buildings* - floating buildings - amphibian buildings - boats - pontoons - removable buildings
							water-resistant buildings - dry-proof buildings (water doesn't enter) - wet-proof buildings (water doesn't damage building): choice/processing of materials, furnishing, (- database damages through flooding)
9	Mitigation	Reduce occurring damage among effected	NA				
10	*Reparative strategies/stabilization*	*Stabilize, repair, rehabilitate*	NA				
				Delta	Polder	Neighborhood	Object
	Haddon	Physical way of functioning	Family	Geographical scale of application			

Table 3-6: Flood management measures in the Crisis Management Layer ordered by way of functioning and scale of application

Layer 3: CRISIS MANAGEMENT							
	Haddon	Physical way of functioning	Family	Geographical of application			
				Delta	Polder	Neighborhood	Object
1	Eliminate hazard source	Prevent storm and rain	NA				
2	Lower, diminish, reduce hazard source	Reduce storm and rain	NA				
3	Prevent release of hazard	Prevent extreme amounts of water in system	NA				
4	Modify rate of release of hazard source	Relief extreme hydraulic situation	NA				
5	Separate in space and time hazard source and object	Relief extreme hydraulic situation	Preventive Evacuation		- flood-resistant communication system - flood-resistant traffic infrastructure (heightening, marking) - flood-resistant electricity network - equipment (boats etc.) - evacuation plans	- refuge shelter/evacuation terps	- instructions through education - escape routes
6	Use a barrier between the hazard and the objects	Barrier: Prevent that objects are being reached by the water, thus reduce number of effected	Temporary flood defenses		- temporary reinforcement flood defenses (sandbags, water-proof covers for dikes)	- temporary flood defenses (sandbags or innovative systems)	
7	Modify contact surface of hazard source	Decrease degree with which objects are being reached by water, thus reduce severity with which objects are effected	NA				
8	Strengthen objects against hazard	Prevent that effected objects suffer damage	Self-reliance		- Early warning-systems - Alarm		- Training - storage of equipment/supplies - generators - drinking water tank - basic supplies storage - awareness
			Temporary flood-proofing				- panels/sand bags to close doors/windows
9	Mitigation	Reduce occurring damage among effected	Disaster Relief	*Technical:* - generators - drinking water tank - basic supplies storage - awareness - training	*Technical:* - Emergency pumps - ...	*Technical* - Construction material to fix leakages etc. - ...	
				Humanitarian: - Food supply - Accommodation - Medical help - information -			
			Rescuing				
10	*Reparative strategies/stabilization*	*Stabilize, repair, rehabilitate*	NA				

Overview: Families of flood management measures MLS

Way of functioning theoretically	Way of functioning physically	Strategy No.	Prevention 	Spatial Solutions 	Crisis Management 
Reduce hazard source	*Prevent extreme amounts of water in system*	3	-redistributing discharge over river arms -retaining run-off (i.e. forestation projects)		
	Relief extreme hydraulic situation	4	-Ease hydraulic land in waterways (i.e. Ruimte v/d Rivier) -Relief extreme situations with inundation polders etc		
Reduce exposure	*Prevent that objects/people are in the dangerous area*	5		-Reconsider location choices for i.e. building projects	-Preventive organized evacuation
	Reduce number of affected by erecting barrier between water masses and vulnerable people/objects	6	-Flood defenses	-Compartmentalization	-Temporary flood defenses
	Decrease degree by which objects are affected	7	-Flood defenses which allow controlling inflow Flood defenses resistant to overflow	-Elevate (terps etc.) -Change flood characteristics	
Reduce vulnerability	*Prevent damage from occurring among exposed*	8		-Flood-proofing of buildings	-Self-reliance -Temporary flood-proofing of buildings
	Reduce occurring damage among exposed	9			-Emergency relief -Rescuing

Figure 3-8: Schematization

3.5.4 Discussion flood management measures

After having sorted all the available flood management measures into the framework a few things can be noted already. These are discussed in the following. When choosing the measures for the schematization in Chapter 3.5.3 care has to be taken that they show the properties discussed below. This is necessary to assure their representativeness.

Way of functioning

Generally the MLS layer Prevention – layer 1 – lies slightly higher in the sequence of strategies. It decreases the hydraulic load and the exposure. **The function of MLS layer 2 and 3 – Spatial Solutions and Crisis Management – is to decrease the exposure and vulnerability**. Further it can be noted that all Prevention measures are based on strategies that reduce the probability side of the risk. With the exception of strategy 6, temporary flood defenses and compartmentalization, Layer 2 and 3 are based on loss-reducing strategies.

Another important observation is the fact that **the MLS layer says little about the way of functioning of a measure**. Indeed, Layer 1 Prevention is labeled to be probability-reducing and the other two MLS layers to be loss-reducing. But as was mentioned in Chapters 3.2.3/2.6 this says nothing about the way those measures actually tune the risk profile. As the schematization in Figure 3-8 shows each layer at least promotes four ways of functioning.

Geographical scale of application

Furthermore it can be observed that **families of measures ranking higher in the sequence of strategies are applicable to larger geographical scales compared to families ranking lower in the sequence**. It is impossible to identify any clear lines as to which families apply to what geographical scales. Other properties of the flood-prone area, such as available space and resources, make the difference when choosing the scale of application.

Cost-benefit relation

All layers of MLS are affected by the Law of Diminishing Returns, but it strikes Layer 3 – Crisis Management – disproportionally strongly. Except the temporary flood defenses all Crisis Management measures suffer from this economic law. This finding justifies saying that MLS Layer 3 is characterized by the Law of Diminishing Returns.

As a consequence of the Law of Diminishing Returns it depends very much on the present safety level if an investment into safety is economic.

Efficiency

There are two main resources that the implementation of flood risk management measures needs: financial funds and space. In the Netherlands both are subject to a relatively high level of scarcity. As a first indication it can be observed that **measures ranking high in Haddon's sequence need more space than the ones ranking lower**. For financial funds the opposite is true in most cases: **the lower ranking measures tend to be more capital intensive than the higher**

ranking ones. But this is extremely dependent on the unit of analysis. For a delta or polder it might be cheaper to build a dike instead of flood-proofing all houses, whereas this is not the case for a neighborhood or building.

Be aware that this sequence of strategies only expresses a preference of strategies concerning safety facing a hazard of a certain magnitude. Flood safety is only one of many properties a region has to be able to offer. The scarcity of resources, in the Netherlands especially space and funds – usually dominates any decision in flood risk management.

Miscellaneous

Additionally, it should further be noted that Layer 1 and 2 consist of permanent measures while Layer 3 – Crisis Management – only includes temporary measures. Nonetheless, these temporary measures have to remain in a state of preparation permanently.

Another important fact is the impossibility to apply most Spatial Solutions (measures of Layer 2) to existing cities, neighborhoods and buildings.

3.5.5 Link to risk approach

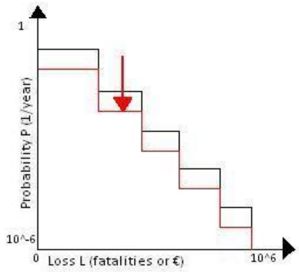
In Chapter 2.6 it was mentioned that it is better to evaluate the performance of the flood management measures and MLS in terms of probability- and loss-reducing. It was discussed in that chapter that the label probability- and loss-reducing does not have necessarily say anything about the actual functioning of a measure. Thus, even though the schematization for the case studies was done based on the theoretical framework derived above, in the case studies the performance of MLS will be discussed in terms of probability- and loss-reduction. Please see Appendix 9.1 to find out about the theoretical link between the framework just derived and the risk-based approach as introduced in Chapter 2.1.

For Table 3-7 the notions that Prevention (MLS layer 1) is probability-reducing and Spatial Solutions and Crisis Management (MLS layer 2 and 3) are loss-reducing have been followed. In particular Table 9-2 and Chapter 9.2.5 of the appendix discuss the link between the theoretical framework and Table 3-7.

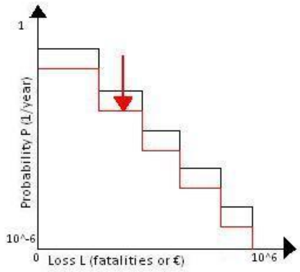
The flood defenses (strategy 6) also differ on another aspect with the other flood management measures. The barriers do not shift the entire FN-/FS-curve like all other strategies but rather cuts a part of the curve off (see Table 3-7). For an in-depth discussion of this observation, please see Chapter 4.4.4.

Table 3-7: Visualization of risk reduction

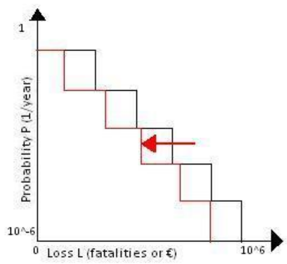
<table>
<tr><th></th><th>Practical way of functioning</th><th>Dimension effected</th><th>MLS layer 1: Prevention (probability-reducing)</th><th>MLS layer 2: Spatial Solutions (loss-reducing)</th><th>MLS layer 3: Crisis Management (loss-reducing)</th></tr>
<tr><td>3</td><td>Prevent extreme amounts of water in system</td><td rowspan="2">Boundary conditions</td><td>Re-distributing discharge of river arms; Retaining run-off



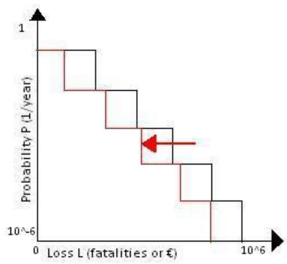
</td><td></td><td></td></tr>
<tr><td>4</td><td>Relief extreme hydraulic situation</td><td>Relief extreme hydraulic load



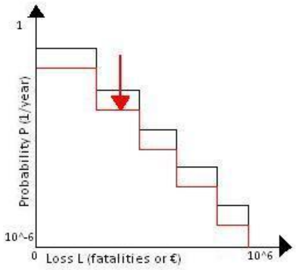
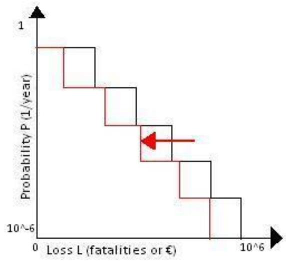
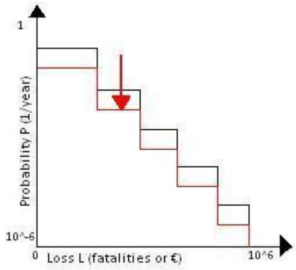
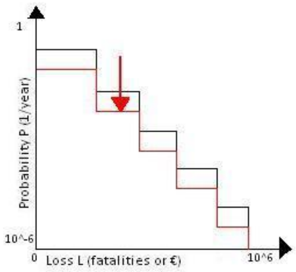
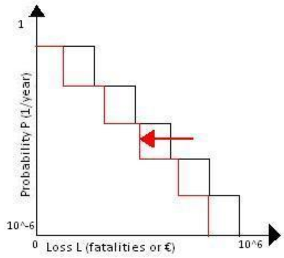
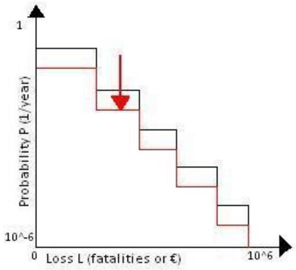
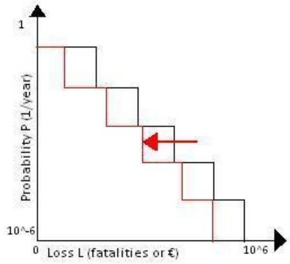
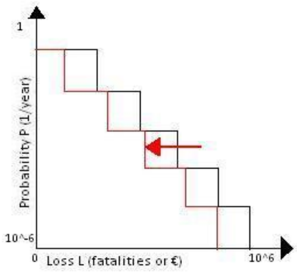
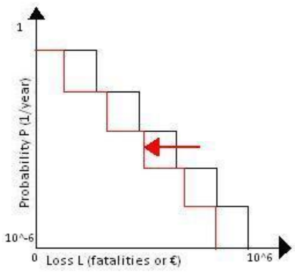
</td><td></td><td></td></tr>
<tr><td>5</td><td>Reduce number of objects in flood-prone area</td><td>Exposure</td><td></td><td>Re-locating



</td><td>Evacuation



</td></tr>
</table>

6	Erect barrier betwee n water masses and objects/ people		Primary flood defenses 	Compartmentalization dikes 	Temporary flood defenses  It very much depends if temporary flood defenses are used in front, on or behind primary dikes if they are considered probability- or loss-reducing. In the definition of MLS Crisis Management was defined as loss-reducing. But in the case study the temporary flood defenses have been modeled as reinforcing the primary dike. Therefore, temporary flood defenses are considered to be probability-reducing in this study.
7	Decreas e degree by which objects are effected		Flood defenses resistant to over-flow/ with controlled inflow 	Elevation of buildings 	
8	Prevent that effected objects suffer damage	Vulnera -bility		Flood-proofing of buildings 	Increasing self-reliance/ temporary flood proofing 
9	Reduce occurrin g damage among effected				Emergency relief/rescueing 

4 Effects, Interaction and Failure

In the introduction of this study Multilayered Safety was presented shortly (Chapter 1.2). As mentioned in that chapter MLS and its performance can only be thoroughly understood if three of its properties are examined in depth. Those three properties are failure and side-effects of and interaction between flood management measures respectively the MLS layers. The theoretical framework derived in Chapter 3.5 will be used to study failure and interaction.

4.1 Objectives

In terms of ***failure*** the main objective is to find out if MLS indeed does work like three safety nets and if it does so in any case. Furthermore, it is interesting to know if the flood management measures that MLS consists of, differ in the failure behavior. In this way a package of measures can be chosen to achieve optimal failure behavior when implementing MLS.

MLS consists of individual flood management measures. To choose an optimal package of measures it is important to know how each measure works. Even more crucial for a maximal performance of MLS is the knowledge about (negative) ***side-effects*** of the individual flood management measures. After all, the effect of MLS might turn out to be less than expected if those side-effects have not been accounted for.

By definition, applying MLS equals implementing a package of measures. If all three layers of MLS are supposed to be used at least three flood management measures have to be taken at the same time. Those flood management measures might interact. If they reinforce each other it is an advantage, but the opposite can happen as well. For an optimal implementation of MLS the ***interaction***s between its measures have to be well-known and used wisely. Only in this way the measures can live up to their maximum and no bad surprises will occur.

4.2 Effects of measures

The following will discuss how flood management measures affect the safety level. In the case studies the effects of the flood management measures are studied at a higher level of abstraction: It was assumed that MLS layer 1 is probability-reducing and MLS layer 2 and 3 are loss-reducing. The FN- and FS-curves included in the chapters about the case studies visualize the effect and the size of that effect (Chapter 5.6 and 6.4). In the present chapter the effects of the measures will be analyzed in greater detail. Furthermore, side-effects that the computational models and thus the case studies overlook will be identified.

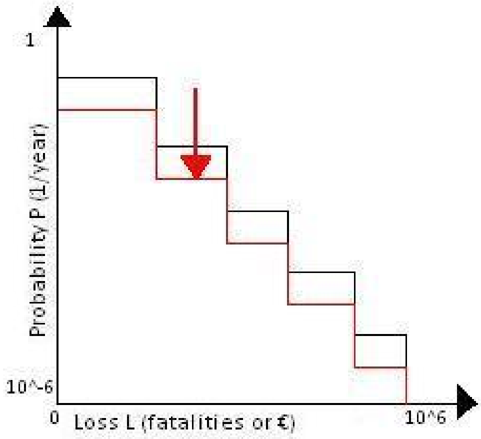


Figure 4-1: Effect of probability-reducing measure at a high level of abstraction

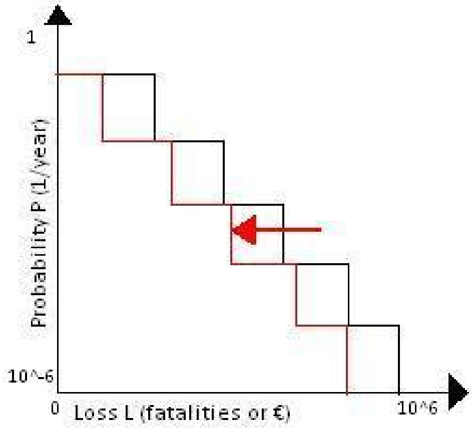


Figure 4-2: Effect of loss-reducing measure at a high level of abstraction

Studying the effects of the flood management measures in detail will be done based on a parameter analysis. First it will be reviewed which parameters are needed to calculate risk (compare Chapter 2.3) and how they are related. Secondly, it will be analyzed at which parameters and relations the flood management strategies aim. It is then possible to analyze the effect of measure respectively strategy. Special attention will be given to unintended negative side-effects of flood management measures. The theoretical framework from Chapter 3.5.3 provides the foundation for this exercise.

4.2.1 Parameter analysis

Risk is calculated using a number of parameters. Those parameters describe basic properties of a (flood-prone) system. That means that those parameters cannot be split up again into more parameters. A number of parameters or characteristics have been reviewed when discussing how to calculate risk with the existing computational models in Chapter 2.3 and 2.4. The scheme of the computational model given in Chapter 2.4.1 already indicated different classes of parameters. That graph is repeated in a simplified version here (Figure 4-3).

Appendix 9.3 provides an in-depth analysis and discussion of the parameters and the way they are related. Here, only the interaction of the measures will be discussed. That will happen based on the scheme given in Figure 4-3. That scheme has been made more detailed to include the individual parameters during the parameter analysis (Figure 9-10). That detailed scheme will be used to study the interaction of measures (see Figure 4-4).

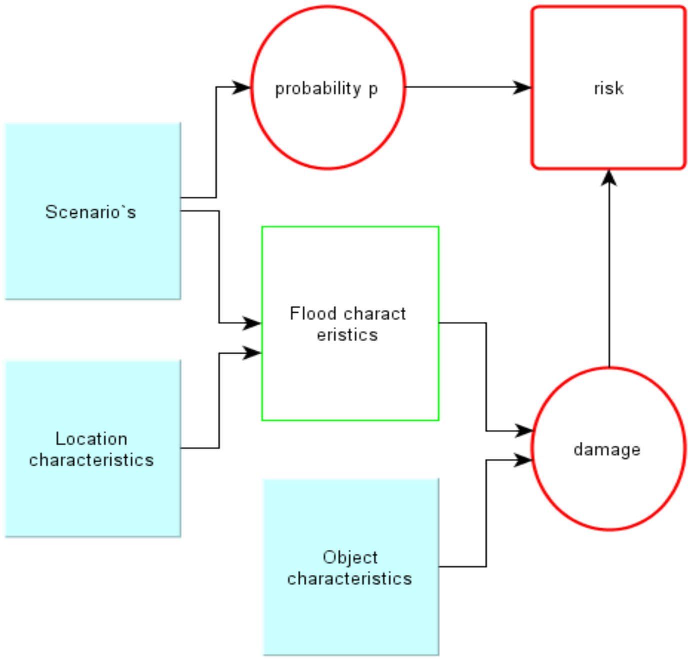


Figure 4-3: Schematization of parameters in computational process

4.2.2 Effects of measures

The objective of the analysis is to understand the (side-) effect each measure has. Flood management measures reduce the risk by changing the fundamental parameters of the system such as the boundary conditions, the exposure and the vulnerability. The exposure is quantified by flood, location and object characteristics, excluding the vulnerability parameters. The scenarios represent the boundary conditions and the vulnerability parameters (part of object characteristics) describe the vulnerability.

Using the flow chart from the parameter analysis (Figure 9-10), the (side-) effects of different flood management measures will now be analyzed. To visualize what is discussed below, Figure 4-4 shows Figure 9-10 with the strategies from the theoretical framework in Chapter 3.5.3 added to it. It is indicated with arrows which parameter the strategies set in on. In the schematization in Figure 4-4 the arrows point to the parameters that depend on the parameter from which the arrow is departing. The red arrows represent the interdependencies which the computational model is based on. The black arrows indicate any further interdependencies. Since those dependencies are not accounted for in the computational model they might indicate unintended side-effects.

At this point, the only thing that is to going to be said about the effect of the measures is the fact that the strategies 3 and 4 indeed change the boundary conditions, strategies 5-7 the exposure and 8-9 the vulnerability. This is according to what was found in Chapter 3.5.3. For more a detailed description of the effect of flood management measures, please see Chapter 9.2.4 and especially Table 9-2. The analysis following here concentrates on the unintended negative side-effects as those might jeopardize the intended risk reduction.

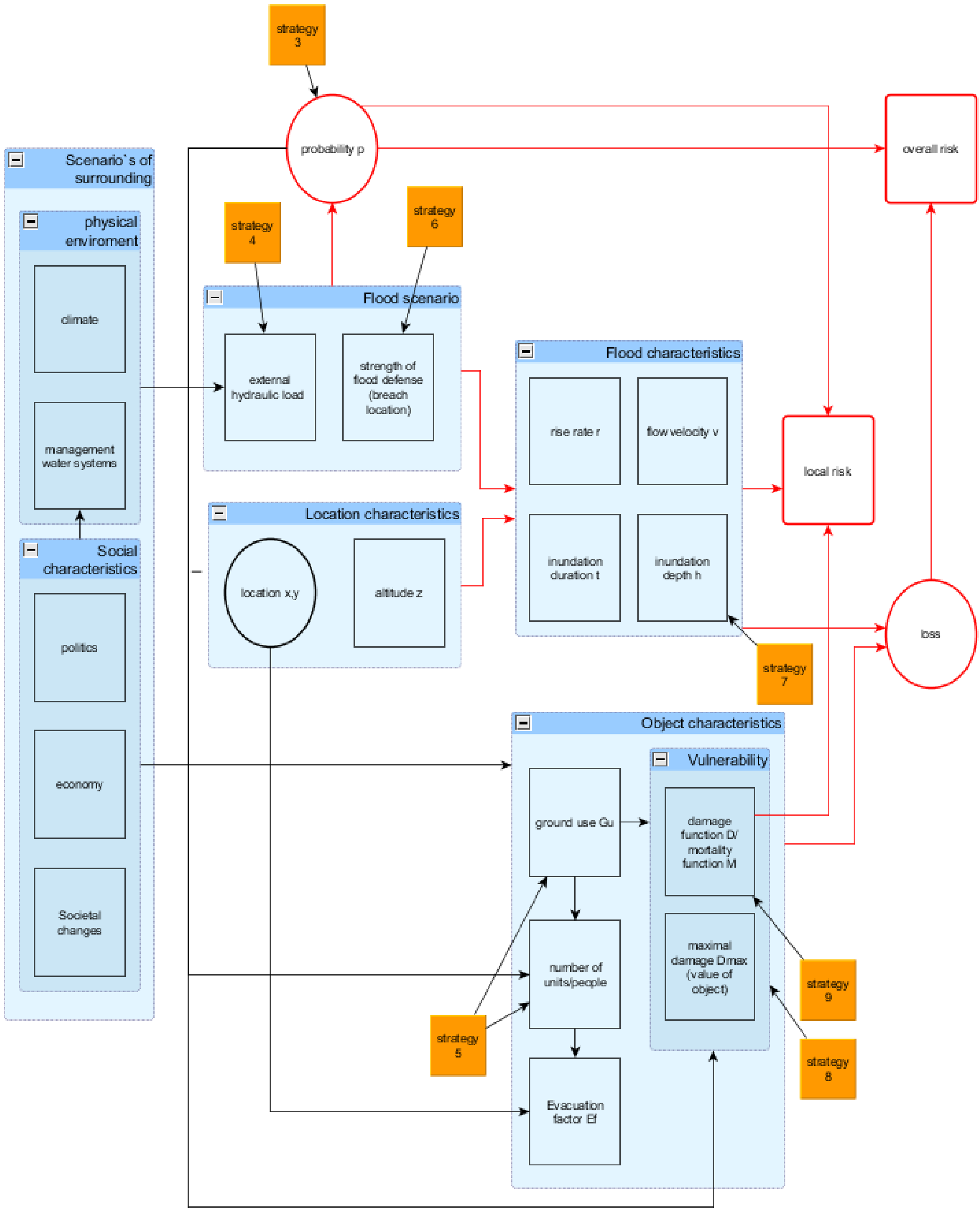


Figure 4-4: Effect of the strategies in flood risk management. The red arrows show the relations used in the computational model. The black arrows indicate other relations that might lead to unintended side-effects.

Side-effects of measures aiming at the boundary conditions

Measures aiming at the boundary conditions have the most side-effects that are not captured by the computational model (compare Chapter Figure 9-10). E.g. the frequency of flooding determines how many people live in a flood-prone area (exposure) and how well they are prepared for floods (vulnerability). Those are (long-term) side-effects the current computational models do not account for. The measures aiming at the boundary conditions are represented by the strategies 3, 4 and 6 (compare Chapter 3.5.2). Thus, it is difficult to anticipate the long-term effects of these measures and their interaction with measures setting in on exposure and vulnerability.

Nonetheless, the complex long-term side-effects of measures setting in on the boundary conditions should also be understood as chance. If handled skillfully, probability-reducing measures might affect exposure and vulnerability advantageously (see paragraph on national standards Chapter 2.5).

Side-effects of measures aiming at the exposure

Strategy 5 and 7 (to some extent strategy 6 as well) are meant to reduce the exposure to floods (compare Chapter 3.5.2). It was reasoned in the parameter analysis that this is done best without changing the location characteristics since this might have disadvantageous effects on the flood characteristics. Thus, **when implementing measures it is smart to do so without increasing the inundation depth somewhere else**. As an example, it is wiser to elevate houses using poles instead of terps, especially in small dike rings. Both the degree with which measures change flood characteristics and the potential to prevent this differ widely for the different measures.

In Case Study 2 it will be tested how severe some measures interact with the flood characteristics. It will be examined if large terps inside dike ring 22 would worsen the flood characteristics for the area around. To find out about the results, please see page 147.

Side-effects of measures aiming at the vulnerability/objects characteristics

Strategy 8 and 9 serve to decrease the vulnerability. By reducing the number of affected Strategy 5 also sets in on the Object characteristics defined in the parameter analysis. From the parameter analysis it follows that **changing the object characteristics is the best way to lower flood risk without triggering side-effects that are difficult to predict**. There is one disadvantage to changing the objects characteristics. Lowering the vulnerability means investing in the object at risk. This investment will increase the value of the object and thus the maximal damage. **There is thus an optimum for the vulnerability of an object**.

4.2.3 Summary Side-Effects

The parameter analysis showed that tuning the boundary conditions of flooding triggers complex dynamic interactions with e.g. the population density or the awareness/preparedness of people. But this property can also be understood as an opportunity. Nowadays flood risk management is not done considering the long-term effects such as population growth. Instead of steering those societal processes, flood risk management only reacts to it. This is one of the reasons for the risk spiral leading to ever higher dikes (Seo 2006: 43). Thus measures aiming at the boundary conditions could be used much more to achieve beneficial long-term effects.

Many measures setting in on reducing the exposure interact with the flood characteristics and thus have effect on the flood risk in neighboring areas. Thus if those measures are implemented their side-effects can be decrease by minimizing their interaction with the surroundings. Out of this reasoning houses on poles are to be preferred to houses on terps.

Measures setting in on vulnerability show the least interaction with their surroundings and thus the least side-effects. But there is an optimum to reducing the vulnerability because investing in less vulnerability means a higher value of the building and thus a larger potential loss maximum.

Definition Interaction: In this study interaction is assumed to take place if two or more flood management measures influence each other's effect on flood risk.

Figure 4-5: Definition of Interaction

4.3 Interaction

Interaction between measures is the second property that is crucial for the performance of MLS. It is important to MLS because different measures can interfere with each other disadvantageously. This chapter starts with an in-depth discussion of the relevance of interaction between measures to MLS (Chapter 4.3.1). Following that, interaction in general will be analyzed.). Chapter 4.3.2 describes the implications of interaction for the risk reduction and Chapter 4.3.3 for the cost-efficiency. This subchapter on interaction concludes with a discussion of its findings.

4.3.1 Relevance of interaction to MLS

In most regions used by humans the hindrance by flooding is experienced as acceptably low. For centuries people have first settled on higher grounds. There were still few houses and the hazard thus not very severe. The remaining risk was anticipated by adapting the houses using early versions of flood-proofing and the experience of the people with floods. They thus chose strategies lying low in Haddon's sequence (see Chapter 3.5). This was partly due to the limited technical knowledge. But since the population density was low, such low-ranked strategies were sufficient.

Over the centuries the population grew and space became scarce. When people in the Netherlands went to live in the lower lying areas flood-defenses were necessary to make urban life possible there. As the technology improved it was possible to build increasingly stronger flood defenses. It even became possible to climb up the sequence of strategies: River discharges were redistributed of the river arms and the awareness grew that flood peaks can be smoothed by holding water back and giving the water system more space.

This history deviates for each country or region, but it comes down to the fact that wherever people live in the vicinity of water some flood management measures have already been taken. Thus Multilayered Safety will be applied close to never to a tabula rasa. In most cases one or more MLS layers and strategies have already been chosen.

In the Netherlands, it is mainly distinguished between areas inside a dike ring and areas outside a dike ring. Clearly, in an area surrounded by a dike ring the MLS layer Prevention, more specifically even, the family of flood defenses (strategy 6) has been applied heavily. Outside the dike ring Spatial Solutions and Crisis Management – Layers 2 and 3 – and more specifically strategy 8 (Preventing damage from occurring among the exposed) is put into practice by relaying on (temporary) flood-proofing.

The idea of Multilayered Safety only has an added value if more than one layer respectively strategy is used on the same area, otherwise Multilayered Safety is not more than the status quo. Considering the above, usually one is not free to choose a random package of flood management measures that interact and supplement each other optimally. To apply MLS it has to be inventoried which flood managements are already implemented. Only then measures the optimally interact with the existing measures and surroundings can be chosen.

When choosing a package of measures ideally the measures should interact with each other to their advantage. If measures reinforce each other it is called synergy. This could be symbolized as follows: 1+1>2. But it is of course also possible that flood management measures interfere with each other. In that case the following is true: 1+1<2. The following paragraphs will examine if MLS will trigger synergy of suffers from negative interference of its measures and layers.

4.3.2 Effect of interaction on risk reduction

Flood management measures reduce the risk in a number of different ways. Each strategy of the theoretical framework from Chapter 3.5.3 describes another form of risk reduction. While all measures first and foremost are meant to decrease the risk, they might have negative side-effects. A measure might e.g. decrease the flood risk in a certain area but increase it in a neighboring region. Dikes are an example of this mechanism. Thus, flood management measures might be faced conditions they are not designed for, due to unintended effects of other measures.

But also if measures function in exactly the way they are meant to do or even have positive side-effects, this will influence the performance of other flood management measures. The risk reduction achieved by a measure very much depends on the initial safety level. If measures reduce the loss, generally the actual risk reduction depends on the probability with which this loss occurs. Vice versa, the same is true for probability-reducing measures. If the probability is lowered, events with an increasingly lower frequency of occurrence will be prevented. This is shown in a simple manner in Figure 4-6.

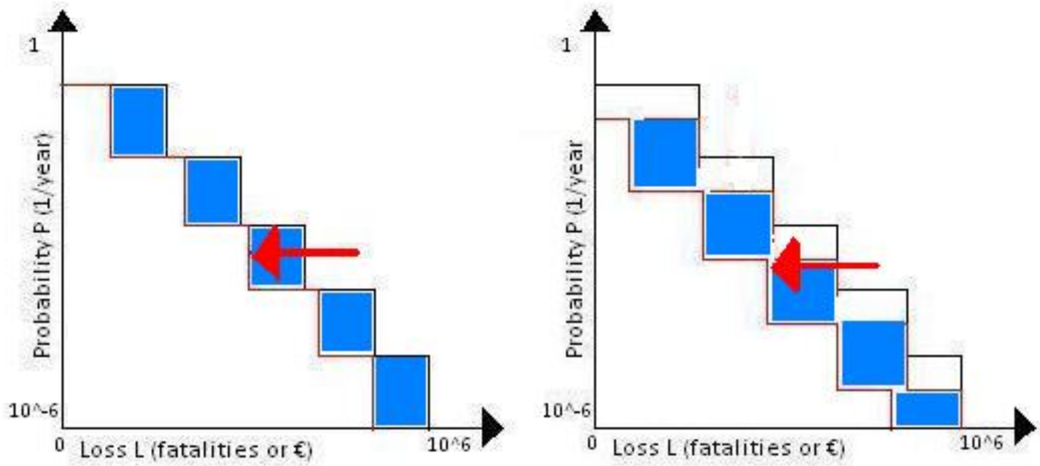


Figure 4-6: Risk reduction by a loss-reducing measure given two different initial flood risk levels. In the right figure the probability of flooding is higher than in the left figure. Thus, the same loss-reducing measure achieves less risk reduction in the situation shown in left than in the one shown in right figure.

In flood risk management another circumstance comes into play: Adding up loss-reducing measures usually means preventing loss under increasingly higher flood levels. Since those higher water levels occur with a lower probability, the more measures are added up, the less effective every additional measure will be. In example if elevating the houses with a terp is combined with flood-proofing, the flood-proofing will be of use much less often than the terp. Note, this says nothing about the question if a terp or flood-proofing is more effective. It only shows that increasing adding up measures does not linearly decrease the risk. The same is true for probability-reducing measures. They lower the probability of certain flood levels.

Given the above it turns out that combining MLS layers 1 and 2 (Prevention and Spatial Solutions) can be described with 1+1 < 2. The reason for this is that the effect of those measures mainly depends on the water level respectively the probability of those.

The effect of Crisis Management (MLS layer 3) is more independent of the water level. It comes into action as soon as a flood threatens to course harm. If such floods happen less frequently Crisis Management will be called on less often. But once it is called on, it functions better the less harmful a flood is. **Thus, combining probability-reducing measures with MLS layer 3 can best be described with 1+1<2 as well. But if Crisis Management is combined with loss-reducing measures, the effect is rather characterized by 1+1>2.**

4.3.3 Effect of interaction on cost-efficiency

It was explained above how adding up flood management measures leads to increasingly less risk reductions. This of course has consequences for the cost-efficiency of those measures. After all, the smaller the risk reduction with costs staying equal, the less cost-efficient a measure is. Arends (2005: 223) states that the investments needed for a further increase of the safety level grow exponentially with that safety level. In economics this mechanism is called the Law of Diminishing Returns. In terms of flood risk management this means that a certain amount of money buys increasingly less risk reduction. Thus, the cost-efficiency of flood management measures decreases with an increasing safety level. It follows that **it is dependent on the initial safety level if one and the same measure is economically desirable**. In the following it is discussed per MLS layer how much they suffer from the Law of Diminishing Returns and what the consequences are.

The above is shown in a short example. As described in Chapter 2.2.4 the cost-efficiency is measured by the ratio between benefits and costs of a measure. This is elaborated in the following formula.

$$\frac{Investment}{Risk\ Reduction} = \frac{I}{\Delta R} = \frac{I}{\alpha * P * Dam}$$

With I = investment [€]
R = initial risk [€/yr]
α = reduction coefficient of probability resp. damage [-]
P = initial probability of flood [yr^{-1}]
Dam = initial damage due to flood [€]

The smaller the ratio given above, the more cost-efficient a measure is. It follows from the formula that a measure becomes more cost-efficient if one or more of the following are true:

- Smaller investment
- Larger Probability
- Larger Damage
- Larger reduction coefficient

An investment is economically responsible if the investment is smaller than the achieved risk reduction. The ratio given above is then smaller than one. A simple example can show the influence of the initial safety level on such an economic decision.

Table 4-1: Simple calculation example to show influence of initial risk on cost-efficiency. NOTE: Net present value of risk reduction has been used: NPV(dR)=dR/r.

	Situation 1	Situation 2	Situation 3
I	50 mln	50 mln	50 mln
P	1/10,000	1/100	1/10,000
α	0.4	0.4	0.4
Dam	2,000 mln	2,000 mln	200,000 mln
I/dR	**12.5**	**0.125**	**0.125**
(interest rate = 0.02)			

The calculation example in Table 4-1 shows that changes in the initial risk alter the cost-benefit-ratio significantly. In Situation 2 the probability and in Situation 3 the damage have been increased. Whereas in Situation 1 the investments exceed the risk reduction, this is not the case in the other two situations.

The fact that the cost-efficiency of flood management measures is dependent on the initial safety level will be demonstrated in the first and second case study. Please see Chapters 5.7.3 and 6.5.3 for results.

There is an exception to the observation above. If Crisis Management is combined with loss-reducing measures, the cost-efficiency of those measures should not suffer. Interestingly though, for Crisis Management measures themselves the Law of Diminishing Returns does apply more severely than for the other two MLS layers. After all, the costs of heightening a dike are less dependent on the dike height than the organization of Crisis Management on the existing organization. If something is organized well, it is extremely expensive to still improve that. Thus, while it creates synergy to combine MLS layer 3 with the other MLS layers, the deployment of Crisis Management is limited by an optimum.

Additional comment

Paradoxically, negative side-effects of one measure might make other measures more cost-efficient. A negative side-effect increases the risk. The cost-efficiency of all measures is dependent on the initial safety level. Summing up, if a negative side-effect increases the risk, the initial safety level decreases and thus the cost-efficiency of measures increases.

4.3.4 Summary interaction

In terms of MLS layers it was found that the layers 1 and 2 (Prevention and Spatial Solutions) interfere with each other leading to 1+1<2. Crisis Management though can easily adapt to all circumstances. Thus its interaction with other loss-reducing measures can be symbolized with 1+1>2. This is not the case for probability-reducing measures though.

4.4 Failure

This subchapter on failure begins with a discussion of failure in flood safety in general. Since the theoretical framework approaches a flood-prone area as a system (see Chapter 3.4.2) first some background information will be given about failure in systems. Then it will be examined which failures lead to loss through flooding. Following that the effect that different flood management measures have on those failures will be shown. The subchapter closes with a discussion about the failure behavior of individual or groups of flood management measures.

4.4.1 Failure in flood risk management

In Chapter 3.4.2 the advantages of using a system approach on flood risk management have been explained. This approach facilitates studying the failure behavior of MLS, too. As safety is an emergent property of a system, a system approach allows looking at safety at a level above the subsystem. Different kinds of failure that cause floods can then be identified. Possible failures can be breaching of the dike ring, people being present in the inundation area or buildings located in high-risk areas. This means that many characteristics of the flood-prone area affect the flood safety, making safety indeed an emergent property. The layers of MLS address different kinds of failures of the protection system and of what is protected by it.

The theoretical framework derived above is based on the system approach as well. It shows which characteristics of the system the individual flood management measures influence. Globally those characteristics have been divided into three groups: boundary conditions, exposure and vulnerability. The fault tree in Figure 4-7 shows the contribution of those characteristics to the failure of the flood safety system and thus loss due to flooding.

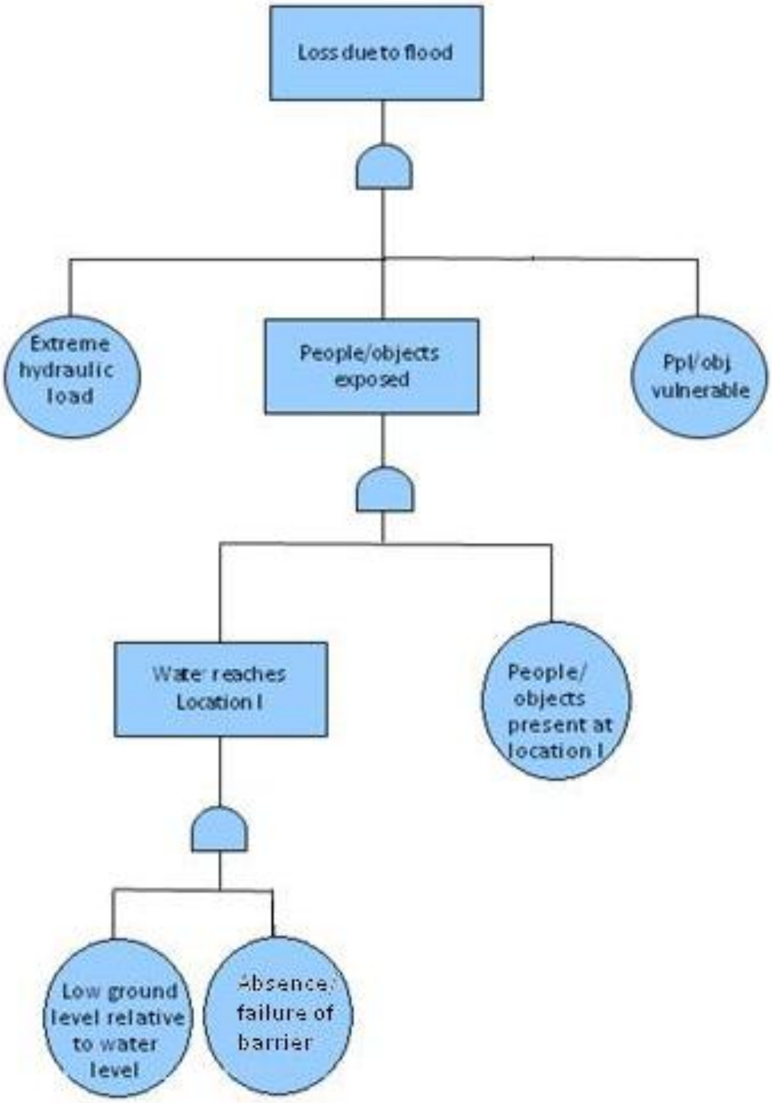


Figure 4-7: Fault tree flood risk management

The choice if lowering of the boundary conditions, the exposure or the vulnerability should be more reliable has many cultural and political aspects. In the Netherlands exposure is chosen and most recently with projects like *Ruimte voor de Rivier* the boundary conditions have been added to the choice as well. Other countries like might decided to lower the probability of vulnerability. Some cultures might even find loss due to flooding itself no problem and go for increased resilience.

4.4.2 Sense and None-sense of safety nets

MLS was developed out of the impulse to have more than one safety net in the protection against flooding. Nowadays the protection system relies on a single line of defense, namely the primary flood defenses. If they fail there is barely any back-up. This is felt to be irresponsible. The following paragraph scrutinizes if introducing safety nets is a good idea. This will be discussed with the help of two notions: redundancy and component/system reliability. Chapter 4.4.3 continues to examine if MLS does function like safety nets at all. Figure 4-8 shows an example of a functioning but undesirable safety net.

Redundancy

Moving away from a single line of defense and adding a number of safety nets is called introducing redundancy. Each layer can be seen as a safety net to prevent a hazard, in case of MLS intruding water, from doing harm. Each safety net prevents the flood disaster from moving on to a later stage. In other words, if one or more layers (partially) fail the other layers might fall in instead. Globally it can be said that Layer 1 Prevention aims to prevent and control the release of the hazard. Layer 2 and 3 are meant to reduce the impact by targeting the exposure and vulnerability of the people and objects at risk (compare Chapter 3.4.3, 3.5.2). In the following it is discussed if introducing redundancy in flood risk management is a good choice.

Studies on complex systems have proven that adding more redundancy is one of least cost-effective to increase the reliability of a complex system. Increasing complexity results in accidents that are not the consequence of component failure but of dysfunctional interaction of perfectly functioning components (Leveson 2004: 234ff.). In agreement with that hypothesis, experience has shown that most accidents happen because of unexpected failure mechanisms (CUR 1997: 3-7). Thus redundancy does not necessarily increase the reliability of a system.

In Chapter 3.5.3 the flood management measures were sorted into the theoretical framework. In the following discussion (Chapter 3.5.4) it is observed that the Layer 2 and 3 of MLS (Spatial Solutions and Crisis Management) are implemented at a smaller geographical scale than Prevention. Often the measures set in at the level of the individual. This indeed makes estimating the probability of failure (thus the probability of loss due to flooding) much more complex. The smaller the geographical scale of implementation, the more properties and circumstances matter. For example, for the failure of a dike the amount of knowledge about floods of the each and every citizen does not matter as much as for evacuation.

Thus redundancy introduces much uncertainty and complexity. Unexpected failure mechanisms as mentioned above become much more likely and the actual safety level is difficult to determine. From the perspective of uncertainty and complexity it is thus smart to choose for flood management measures whose behave relies on as little system characteristics as possible. Those are often measures which are implemented at a relatively large geographical scale.

Introducing redundancy means an increased presence of flood safety in people's daily life. In example, a flood-proof house requires more cooperation than a dike. If it is invested in making it less likely that people and objects are vulnerable, the consequence might be that they are exposed more often to floods. Again these are cultural and political choices. But it is concluded that not every functioning safety net is necessarily a desirable safety net (see Figure 4-8).

Figure 4-8: Example of a functioning but undesirable safety net

System and component reliability

Each failure identified in the fault tree in the paragraph above (Chapter 4.4.1) has a probability of occurring. According to that fault tree flood safety behaves like a parallel system. In this case probability of failure of the whole system can be derived by multiplying the probability of failure of all root causes. The root causes are presented as circles in the fault tree in Figure 4-7.

In practice the safety nets of MLS mean piling up different flood management measures to minimize the probability of failure and thus the probability of loss due to flooding. In the following it is discussed if piling up measures is a good idea. It will then be discussed which flood management measures are suitable to minimize the probability of failure.

In the hypothetical case that enough resources were available the failure probability of each root cause could be lowered substantially by implementing as many measures as possible. The probability of loss to occur would then decrease to unrealistic small values such as 10^{-18}. Vesely *et al.* comment on this as follows:

> "The low numbers simply say that the system is not going to fail by the ways considered but instead is going to fail at a much higher probability in a way not considered." (Leveson 1995: 168).

Leveson uses this quote to illustrate that the problem of reliability models lies in the fact that those models never include all the possible failures of a system. The world is too complex for that. As an example, in flood safety a lower failure probability of the dike ring would result in much more severe flood characteristics increasing the probability and amount of damage. So a higher reliability of the flood defenses does not automatically result in a lower probability of damage to occur. Accordingly, Leveson suggests that the reliability of each system is naturally limited and cannot be pushed beyond certain values. Instead she sees the value of reliability analysis in supporting the optimal allocation of resources. Most importantly Leveson stresses that high reliability by no means guarantees high safety. According to her, unforeseen dysfunctional behavior of different system components has a major potential for jeopardizing safety (Leveson 1995: 167-168). This last observation is in line with the discussion of redundancy above.

The conclusion from this discussion for flood safety might be that there will never be absolute safety. MLS should be implemented with the thought of optimally allocating resource instead of trying to achieve maximum safety at any price. When adding redundancy, care should be taken to make the failure of the components as predictable as possible.

4.4.3 Potential of safety nets in flood safety

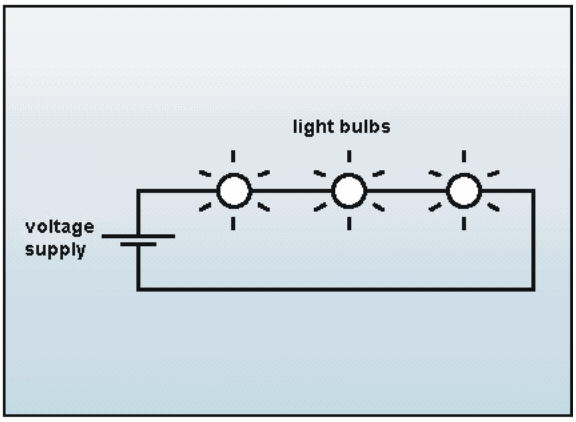
Introducing redundancy or adding safety nets to a system theoretically comes down to adding links to a serial or parallel system. To find out if in the case of MLS adding safety nets does lead to a substantial reduction in failure probability it will be examined if protection is a serial or parallel system. First it will be discussed though if more redundancy is wise for both serial and parallel systems.

Serial and Parallel Systems & Redundancy

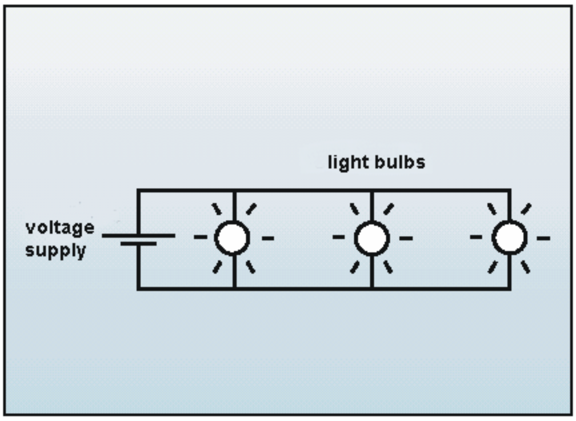
There is a fundamental difference between series and parallel systems (see Table 4-2). In the serial system the system fails if one of the links fails. To make the parallel system fail all links will have to fail. Consequently, in a series system the probability of system failure is calculated by adding up the failure probabilities of the individual links while in a parallel system they are multiplied.

Table 4-2: Principle of serial and parallel systems

Serial System (light bulbs)



Parallel System (light bulbs)



Thus by approximation series systems are as weak as the weakest link and parallel systems are as strong as the strongest link. In a series system the most logical strategy would be strengthening the weakest link. But for a parallel system it seems more logical to make the strongest link even stronger.

As said before improving redundancy means adding more links to a system. In a serial system that does not make sense because the system is only as strong as the weakest link. Adding links will not make the weakest link stronger. Furthermore, each added link has its own probability of failing. Since only one failed link results in system failure with each added link the probability of system failure will increase.

In a parallel system each added link decreases the probability of failure. After all, each and every link has to fail before the system fails. So here redundancy does make sense. At the same time the parallel system is as strong as the strongest link. Thus making the strongest link even stronger is another option.

Redundancy in flood safety

For application of the notions parallel and serial system it has been assumed in this study that the flood protection system has completely failed if the loss due to flooding equals the loss without all flood management measures. That means the system has completely failed if the flood management measures have no effect on the loss.

From a systems point of view it can be noted that the area surrounded by a dike behaves like a parallel system. This is also indicated in the failure tree in Figure 4-7. For the system to fail and damage due to flooding to occur there have to be extreme hydraulic boundary conditions AND people and objects have to be exposed AND people and objects have to be vulnerable. If one of those three characteristics is not given, the system will not fail. This rather contradicts intuitive feelings when thinking about flood safety. When thinking about a flood happening water first enters the dike ring and then causes damages. This is a series of events and in time the failures also occur in a series. But these failures at the end *all* do have to take place before harm is done, so flood safety turns out to be a parallel system. Picking up the observations from above it is thus found that **adding redundancy is an alternative to strengthening the strongest link**. This does not take away the (disadvantageous) observations done when discussing redundancy and component-/system reliability in Chapter 4.4.2.

Looking more into depth it should be noted that failures are not necessarily independent events. As an example, the erosion and subsequently failure of a terp and a fiasco in evacuation are likely to have a strong correlation. After all, their success is highly dependent on flood and weather conditions. Another example would be different Crisis Management measures that rely on the same source of information or organization. Strong correlations increase the probability of system failure compared to systems with independent or less correlated failure events. **When choosing a package of measures for implementing MLS it is thus smart to pick measures whose failure is correlated as little as possible**.

4.4.4 Failure of individual measures

As noticed in Chapter 3.5.4 the concept of MLS does not say much about the actual functioning of the layers and their individual measures. Therefore the analysis of the failure behavior of the individual measures will rely on the theoretical framework derived in Chapter 3.5. Because each MLS layer consists of flood management measures, the findings on those measures will later be extended to the layers and MLS itself.

Failure is a very black-and-white notion. Either something functions perfectly or it fails. To most flood management measures this is not applicable. Only for measures like flood defenses total failures are likely to occur. For other flood management measures, e.g. evacuation or flood-proofing, total failures are very rare. For this reason it is more appropriate to estimate which degree of effect each measure has and with what likelihood. An example of this approach is a recent study that estimates evacuation fractions of dike rings in the Netherlands (Maaskant *et al.* 2009: 5-5). Using such an approach lower and upper boundaries of failure can be derived.

Other flood management measures like terps escape the black-and-white failure notion in a different way: Terps might turn out too low and the houses on top of them will flood. But even then terps will have decreased the flood risk with their full capacity. After all, the inundation depth of the flooded houses will be significantly less than without the terp. Put differently, the local risk on the terp is smaller and complete failure of a terp (e.g. by eroding away) is relatively unlikely.

In Chapter 4.4.1 a fault tree was given. Using the theoretical framework from Chapter 3.5.3 it can be determined at which root causes the measures set in. The root causes are indicated by ellipses in the fault tree. An overview of the root causes is given in Table 4-3. The theoretical framework bundles flood management measures by the way the function. Measures belonging to the same strategy function the same way and thus set in on the same root cause of failure. This is shown in Figure 4-9. The notions *hazard, exposure* and *vulnerability* introduced earlier (Chapter 3.4.3) are to be found in the second row of the fault tree.

As observed in Chapter 3.5.4 Layers 2 and 3 (Spatial Solutions and Crisis Management) depend more on the lower ranked strategies whereas Prevention generally consists of higher ranked strategies. Thus all MLS layers reduce the probability of exposure. Layer 1 decreases the probability of extreme boundary conditions and Layers 2 and 3 the probability of damage as a consequence of vulnerability.

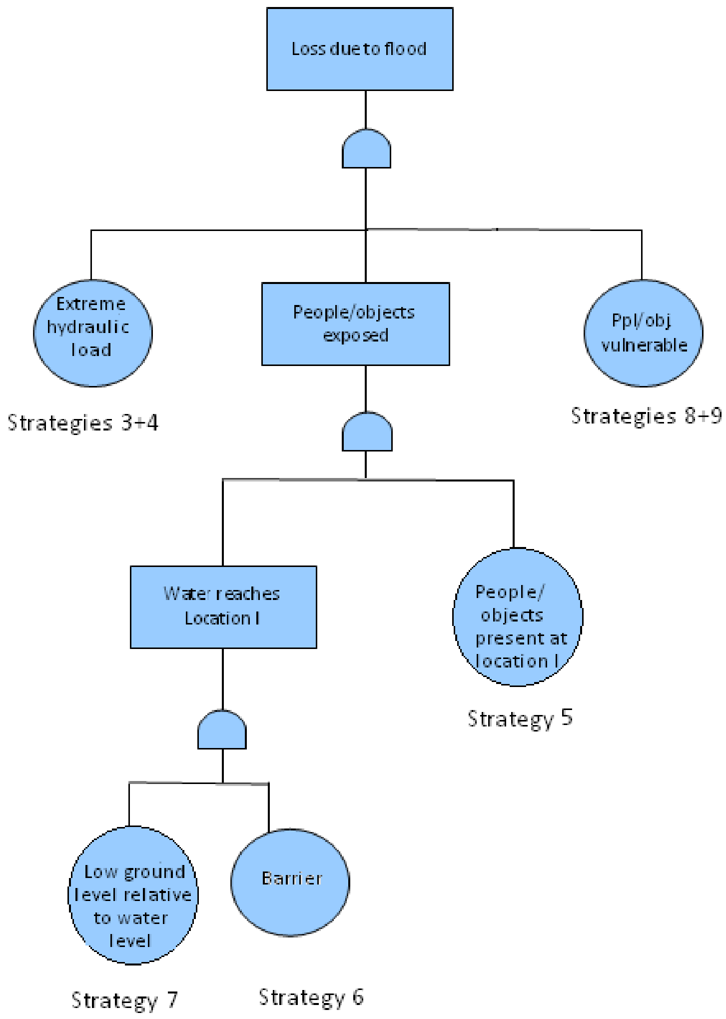


Figure 4-9: Fault tree of flood risk management including strategies

Table 4-3: Root causes of failure of flood risk management

Root causes	Failure condition
1. extreme hydraulic load (S) resulting in water level WL	
2. ground level lower than water level (z<WL) 3. insufficient strength of flood defense (R)	(z < WL) ∩ R < S
4a. People/objects residing at location l (n) 4b. People/objects remaining in location l ($n_{exposed}$)	$n_{exposed}$ = Ef*n; $n_{exposed}$ > 0
5. People/objects being vulnerable (d resp. m)	d resp. m > 0
(Ef = evacuation factor, see Chapter 2.3)	

Now that the way in which the measures respectively strategies reduce the failure probability is clarified, a number of other observations can be made:

Serial or parallel systems

Flood defenses are the only flood management measures that function like a serial system. A dike is only as strong as its weakest section. In the case of all other flood management measures the system does not fail if one link fails. A few examples are given here: If the flood-proofing of one house fails, it will not lead to failure of the other flood-proof houses (strategy 8). If a person stays behind the flood-prone area he or she does not put all other people in jeopardy (strategy 5). If a river is given more space it might happen that due to failed communication some space is taken from it again. This is a kind of failure of strategy 3. But nonetheless, all the other extra space given to the river will keep its function and lower the water levels. Thus all those strategies function like parallel system. Picking up the analogy of light bulbs from Chapter 4.4.3 again, the protection against floods looks like Figure 4-10.

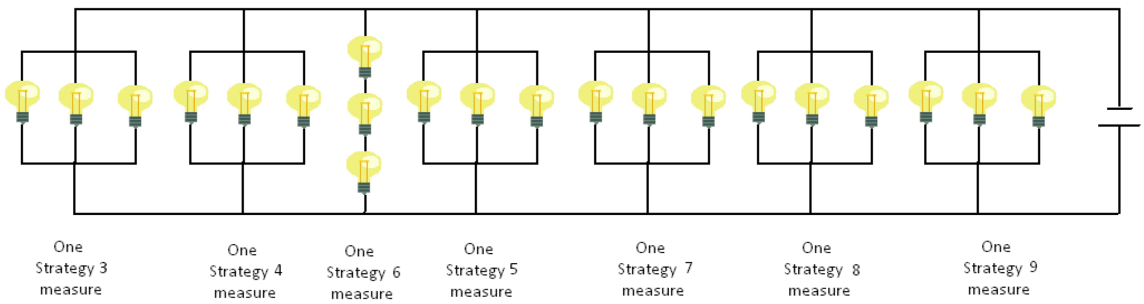


Figure 4-10: Failure properties of MLS translated to light bulbs. Flood defenses are the only strategy that fails like a serial system. It is assumed here that the system has failed if the loss equals the loss without any flood management measures.

Right now, the flood safety in the Netherlands usually relies on one line of flood defenses. That means that the protection system right now is a serial system. It does not make use of the fact that loss due to flooding equals failure of a parallel system (see above). **Thus introducing MLS to an area means moving from a serial to a parallel flood protection system.**

A series system implies that the loss will always be the same if any part of the flood management measures fails. In a small dike ring everything will flood no matter where the dike breaches. The loss is thus always the same and the dike ring can be seen as a series system. In larger dike rings different breach scenarios will cause different extents of flooding. One flooding scenario might cause more damage than another scenario and vice versa. Then the dike ring should rather be seen as a parallel system. The failure of a dike section does not cause total failure of the system equaling the maximum damage. **Thus, the larger the dike ring is the more the flood defenses will move from being a serial system to being a parallel system**.

Reliability of individual measures

When looking at the reliability of individual measures, a difference has to be made between permanent and temporary measures. In this study permanent measures happen to be structural measures. Temporary measures are organizational, non-structural measures as used in Crisis Management.

If the performance of any measure is approached probabilistic, the capacity will have an expected value. But there is a chance that the measure has a higher or lower capacity than expected. The variance around the expected value is expressed by the standard deviation. For temporary measures standard deviation is larger than for permanent measures. Put differently, the performance of temporary measures varies more than of permanent measures. The main reason for that is the fact that the success of organizational measures depends on much more (uncertain) factors than the success of structural measures. Whereas structural measures function to the degree they were designed for with a probability in the range of P= 0.01 - 0,0001 [1/yr.], non-structural measures might only live up to their design value with a probability of P=0.5 [1/year]. The likelihood that those measures reach their full physical capacity lies in the same range of P= 0.01 - 0,0001 [1/yr.]. Also the standard deviation in performance is much larger for non-structural measures. **From this point of view MLS Layers 1 and 2 add more reliability to a parallel flood protection system than Layer 3.**

It was mentioned above (Chapter 4.4.2) that introducing redundancy to a system means adding complexity. The success of many measures, especially in the Case of Spatial Solutions, depends on a large number of system characteristics. From this point of view linear flood defenses (strategy 6) are advantageous. After all putting a barrier between the water masses and the objects and people to be protected means just adding safety to a system without changing the system itself (compare Chapter 3.4.2). Maintaining the quality of a dike is much less complex than for example ensuring the all houses in a neighborhood stay flood-proof. Thus much less (societal) processes jeopardize the reliability of flood defenses than of all other measures (see also Chapter 4.3). **Among all structural measures flood defenses (strategy 6) are thus have a relatively larger reliability.**

4.4.5 Summary Failure

If flood risk management is approach from a system perspective it functions like a parallel system. Thus adding redundancy, as MLS is intended to do, is an alternative to strengthening the strongest link. Nonetheless, redundancy also means making flood safety very complex. As more redundancy would make flood safety depended on a large number of area respectively system characteristics, it increases the uncertainty considerably as well. Additionally, not matter how much redundancy is introduced there will never be absolute safety. Theoretically extreme high levels of safety are even very likely to be unrealistic because the complexity that redundancy will bring along causes unexpected failures. Thus instead aiming at increasing safety to norms of miniscule probabilities of failures (as the trend now) heading for an As-Low-As-Possible (ALAP) approach to failure probability might be useful. Extending this thought flood risk management would not be used anymore to live up to (national) standards for flood safety but to allocate the assigned resources optimally.

Redundancy like proposed in the MLS approach makes flood safety also interfere much more with people's dailies lives. It was mentioned before that this increases the complexity and uncertainty of flood risk management. But even if uncertainty and complexity are kept under control perfectly, it is not a given that more interference with people's daily lives is desirable.

Moving from a Prevention-dominated policy to a MLS policy would mean changing the flood risk management from a serial to a parallel system. This is a consequence of an interesting property of flood defenses. Among all safety measures, flood defenses (strategy 6) are the only measures that function like a line of defense. They are characterized as serial systems whereas all other measures function like parallel systems. Thus, having more than one line of defense and introducing measures that are parallel systems makes the entire flood protection function like a parallel system as well.

As to the reliability of single flood management measures, it is concluded that organizational measures (Crisis Management) show much larger variance than all other measures and are therefore much less likely to life up to their maximum capacity.

5 Case Study 1 – Hypothetical Dike Ring

5.1 The fictive case of dike ring *Mouillé*

Figure 5-2: Fictive dike ring *Mouillé*

A first assessment of the effectiveness and efficiency of the MLS layers and their categories will be elaborated by doing simple calculations on a fictive dike ring. This dike ring has been invented for this study. A fictive dike ring situated at the fictive river *Fleuve* shall be imagined. It will serve as the object for the examination of the effect of a neighborhood to be built new on the overall flood risk of the dike ring and the flood risk of the neighborhood itself. Then each family of flood measurements as introduced above will be modeled and its effectiveness on the flood risk on both the dike ring in general and the new neighborhood in particular will be calculated. In terms of interaction this fictive case examines the interactions of flood defenses with other measures. It does not examine dynamic interactions/feedbacks.

Characteristics of fictive dike ring *Mouillé*

Surface:	100km^2	Probability of flooding:	1:2000 per year
Ground level:	-1.0m NAP (Section1: 0m NAP)	Flood level:	+2.5m NAP
Value of a building: (source: HIS-SSM)	241,000 EUR		
Existing buildings		**New Neighborhood**	(in Section 3)
Number of buildings:	10,000 (8,000 in Section 1; 2,000 in Section 2)	Number of buildings:	2,000
Number of inhabitants per building:	2.5	Number of inhabitants per building:	2,5
Evacuation factor:	0.0		

Figure 5-1: Characteristics of fictive dike ring

5.2 Objectives

The fictive dike ring Mouillé is the basis for the computations that need to be done for the real-life case study of Dordrecht. The computations are meant to be kept simple for this fictive case study. The objectives of it are as follows:

1. explore ways to model flood management measures
2. indication of effects of measures (risk reduction: how much, where)
3. indication of cost-efficiency of measures (Cost-effectiveness-analysis)
4. indication of static interaction of flood defenses with other measures
5. compare efficiency of measures relative to each other
6. explore ways of visualizing the results

5.3 System description

The dike ring called *Mouillé* has a square shape of the size 10x10 km^2 and lies along the river *Fleuve*. *Mouillé* is divided into four sections. With a ground level at NAP section 1 lies one meter higher than the rest of the dike ring. As a historical consequence the major part of the city lies in this section. Apart from those 8000 houses there is another 2000 houses situated in section 2. The new neighborhood consisting of 2000 houses is planned to be build in section 3. All houses are family houses with an individual value of 241,000 EUR (source: HIS-SSM). It is assumed that the same amount of people lives in each house, being 2,5 people per house. The properties of *Mouillé* are listed in Figure 5-1.

5.4 Modeling the risk

In the following the conditions and characteristics in and around the fictive dike ring are described (see also Appendix. 9.1).

5.4.1 Boundary conditions

As mentioned before *Mouillé* lies along the river *Fleuve.* It is assumed that a water level of 2.5m occurs with a probability of 1/2000 per year. Lower water levels occur more often. This is not relevant though because it is assumed that the dike will not breach with those water levels. Figure 5-3 shows the boundary conditions for the river *Fleuve.*

The model includes four scenarios. Each scenario represents a dike breach in another section. It is supposed that all these scenarios

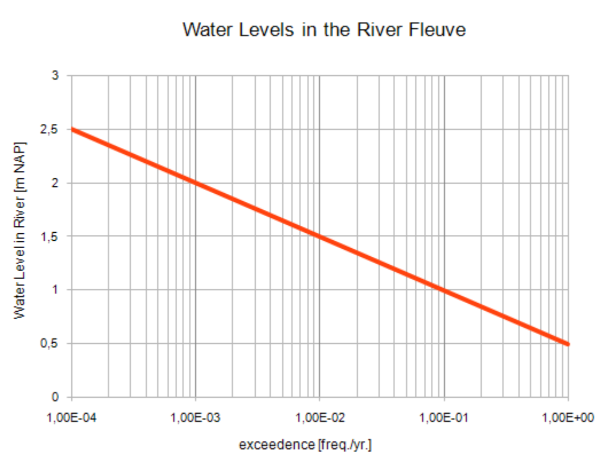


Figure 5-3: Boundary condition for hypothetical case

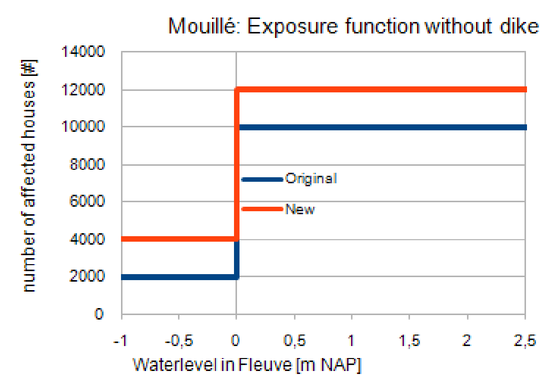
have the same probability of happening adding up to 1/2000 per year for the total dike ring.

As of today it is assumed that a dike breaches once the water level in the river exceeds the dike's crest height. Thus water levels lower than the dike's crest show no effect in the dike ring area. If the water level in the river is equal or larger than the crest height, the water level in the dike ring is assumed to equal the water level in the river. To keep this fictive case simple only a water level with the probability of occurrence of 1/2000 per year is calculated for the dike ring *Mouillé.*

5.4.2 Exposure

The dike ring of *Mouillé* severely influences the exposure functions. It is assumed that nothing is effected by the water (n=0) until the dike ring breaches. As it is assumed that the dike ring breaches at a water level of WL = 2.5 m NAP, all houses inside the dike ring are affected immediately after a dike breach. After a dike breach the water level inside the dike ring is assumed to be 1.75m. The inundation depth differs per section.

(Original = without new neighborhood; New = with new neighborhood)



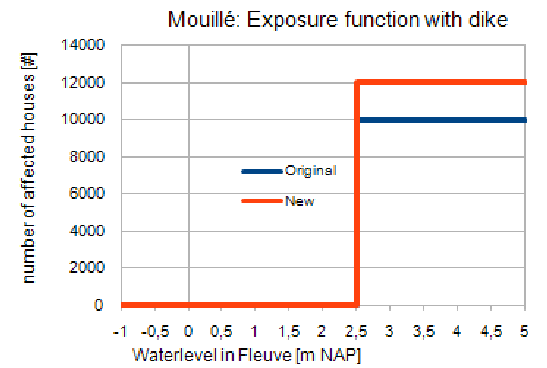
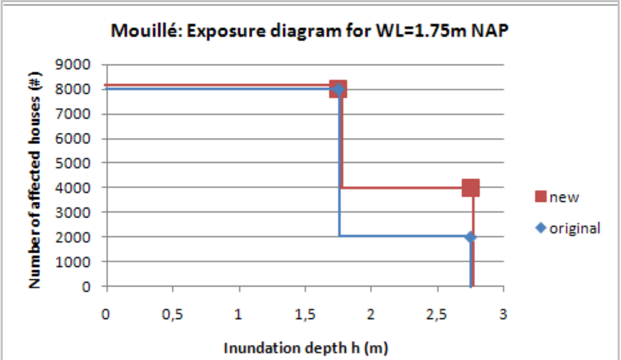


Figure 5-4: Exposure diagrams for *Mouillé*



5.4.3 Vulnerability

For the case of *Mouillé* the vulnerability resp. damage functions for houses and fatalities as introduced in Chapter 2.3.2 have been simplified to the following equations:

- for houses: d = 0.2*h
  with
  h = inundation depth [m]
  d = damage of object in percentage of total value [%]

- for fatalities:
  with μ=7.6, σ=2.75

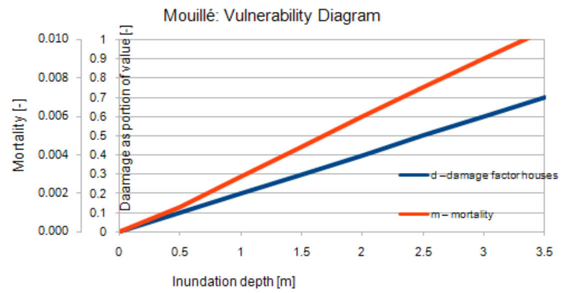


Figure 5-5: Vulnerability diagram for *Mouillé*

5.4.4 Calculation

The risk is calculated for the dike ring area with and without new neighborhood in Section 3. These are the two reference cases. Following this, the computation including the new neighborhood will be repeated once for each flood management measure. In each of those computations a flood management measure will be modeled as described in Chapter 5.5.1. The risk reduction achieved by each flood management measure is the difference in risk between the calculation including the flood management measure and the reference cases. A measure might let the risk below the risk level of the reference without the new neighborhood. Another possibility is that a measure only eases the risk increase due to the new neighborhood.

The risk will be expressed in Societal Risk, Individual Risk and Economic Risk, both locally and aggregated over the entire dike ring area. Van Dantzig's method as described in Chapter 2.2.4 will be used to do a Cost-effectiveness-analysis (CEA) regarding the Economic Risk. To analyze the economics of reducing the number of fatalities, the costs per extra saved life (CSX) will be used as measure for the CEA (see Chapter 2.2.4).

5.4.5 Discussion of representativeness

Here the quality with which the computational model represents the reality is discussed.

Probability of failure

The probability of failure of the flood management measures has not been included. The only exception is made for the overflow and subsequent breach of the dike ring.

Loss

First of all it is stated that of the flood characteristics rise rate, flow velocity and the duration of inundation are omitted and only the inundation depth is considered. This means that the loss suffered at the breach location is probably underestimated. Some preliminary runs with HIS-SSM showed though that the loss suffered close to the breach location is rather minor compared to the overall loss.

Side-effects

To reduce the negative side-effects measures have with each other elevating houses is done on poles instead of terps. Furthermore it is assumed that evacuation is organized inside the neighborhood.

Simplifications

The scenarios of the surrounding (social characteristics and physical environment) have been replaced by four simple flooding scenarios (physical environment) and the given object characteristics (social characteristics). Dynamic interactions/feedback, such as the question what effects other processes in the surroundings (e.g. climate change, migration rate, quality of life) have on e.g. the number of people living in the dike ring, have been ignored for now. Following this trend also the influence the probability of flooding has on the number of inhabitants has been left out of the model. Furthermore only one type of land use and one type of object have been used, namely family houses.

Effect of measures

As said before the vulnerability functions have been simplified and therefore the calculation compares measures only relatively to each other on terms of order of magnitude. The same is true for the flooding scenarios and the measures themselves.

Cost-benefit analysis

The investment costs of the different measures are very rough estimates meant to indicate an order of magnitude. Maintenance costs and other follow-up costs have been neglected. It is not included in the model that some measures are subject to the Law of Diminishing Returns.

5.5 Modeling measures

Based on the overview of families of measures given in Chapter 3.5.3, the figure below shows how each family in modeled in this fictive case of *Mouillé.* The table following that overview shows how these families of measures are modeled practically.

The numbering of the measures is derived as follows: (i-j) with I = number of MLS layer, j= number of Haddon strategy.

Modeling Multilayer Safety in the fictive case *Mouillé*

Way of functioning theoretically	Way of functioning physically	Strategy No.	Prevention	Spatial Solutions	Crisis Management
Reduce hazard source	*Prevent extreme amounts of water in system*	3	*Retain excessive discharge:* 1-3: Decrease probability of occurrence P_{flood}=1/4000		
	Relief extreme hydraulic situation	4	*Relief hydraulic load:* 1-4: Decrease probability of occurrence P_{flood}=1/3000		
Reduce exposure	*Prevent that objects/people are in the dangerous area*	5		*Re-consider location:* 2-5: Build new neighborhood in Section 1 instead of Section 3	*Preventive Evacuation:* 3-5a: Evacuate 15% of new neighborhood 3-5b: Evacuate 80% of new neighborhood
	Reduce number of affected by erecting barrier between water masses and vulnerable people/objects	6	*Flood defenses:* existing: dike Pflood=1/2000 *Flood defenses:* 1-6a: Heighten dike P_{flood}=1/4000 1-6b: Heighten dike P_{flood}=1/10000	*Compartmentalization:* 2-6: Surround Section 3 with compart. dike	*Temporary flood defenses:* 3-6: strengthen primary dike with sand bags: P_{flood}=1/2500
	Decrease degree by which objects are effected	7	*Flood defenses allowing overflow or controlled inlet:* 1-7: Ease flood characteristics -> lower inundation depth by 1m	*Elevate:* 2-7: New buildings on pillars of 1m	
Reduce vulnerability	*Prevent damage from occurring among exposed*	8		*Flood-proofing:* 2-8a: No damage on new buildings up to 1m inundation depth (no effect on fatalities) 2-8b: No damage on new buildings up to 3m inundation depth (no effect on fatalities)	*Self-reliance:* 3-8: Preparation and Warning in new neighborhood reduces damage by 10%
	Reduce occurring damage among exposed	9			*Emergency relief & Rescuing* not modelled

Figure 5-6: Modeling Multilayered Safety in Mouillé

Table 5-1: Practicalities of modeling MLS in *Mouillé*

Practicalities of modeling MLS measures in the fictive case *Mouillé* The numbers of the measures are derived as follows: (i-j) i = number of MLS layer; j = number of strategy				
Measure No.	Family of measure	Description		Scale of implementation
Layer 1: Prevention				
1-3	Retain excessive discharge*	Reduce probability of occurrence hazard source	P_{occ}= 1/2,000 -> 1/4,000	*applied at delta scale
1-4	Relief hydraulic load*	Reduce water level of hazard source	P_{occ}= 1/2,000 -> 1/3,000	*applied at delta scale
1-6a	Flood defenses*	Heighten dike	P_{flood}= 1/2,000 -> 1/10,000	*applied to existing dike ring
1-6b	Flood defenses*	Heighten dike by decimating height	P_{flood}= 1/2,000 -> 1/20,000	*applied to existing dike ring
1-7	Flood defenses allowing overflow*	Ease flood characteristics	Δh = -1m*	*applied to existing dike ring
Layer 2: Spatial Solutions				
2-5	Re-consider location	Build new neighborhood in Section 1 instead of Section 3 *	move 2000 houses from Section 3 to Section 1*	* Section 1 has higher ground level
2-6	Compartmentalization	Surround section 3 by compart. dike	- do not let Section 3 flood when breach in Sections 1,2 or 4 - do not let Sections 1,2 and 4 flood if breach in Section 3	
2-7	Elevate	New buildings of poles of 1m	Δh = -1m*	* Only buildings in **Section 3** are elevated
2-8a	Flood-proofing	No damage on new buildings up to 1m inundation depth	Adapt damage function* Dam = 0 if h < 1m Dam = 0.2* if h ≥ 1m	* Only buildings in **Section 3** are elevated
2-8b	Flood-proofing	No damage on new buildings up to 3m inundation depth	Adapt damage function* Dam = 0 if h < 3m Dam = 0.2*h if h ≥ 3m	* Only buildings in **Section** 3 are elevated
Layer 3: Crisis Management				
3-5a	Preventive Evacuation	Evacuate 15% inside new neighborhood	Ef = 0 -> 0.15*	* Only people in **Section 3** are being evacuated
3-5b	Preventive Evacuation	Evacuate 80% inside new neighborhood	Ef = 0 -> 0.80*	* Only people in **Section 3** are being evacuated
3-6	Temporary flood defenses	Strengthen primary dike with sand bags*	P_{flood}= 1/2,000 -> 1/2,500	* applied to existing dike
3-8	Self-reliance	Prepare and warn people in new neighborhood	Reduce damage by 10%* Dam = 0.2* h -> 0.9* (0.2* h)	* Only people in **Section 3** are being warned/prepared

5.5.1 Calculation

Four scenarios have been calculated having the same probability (P=1/4*1/2,000 [1/year]). The total probability thus adds up to P_{tot}=1/2,000 [1/year]. Each scenario represents a dike breach at another section. It is assumed that in each scenario the entire dike ring floods with the same water level.

In total 16 cases have been calculated: 14 measure plus two reference cases. The two reference cases are meant to compute the flood risk for the dike ring area without the new neighborhood (REF1) and with the new neighborhood having been built (REF2).

The following formulas have been used:

Table 5-2: Formula's for calculating risk in *Mouillé*

$IR = \Sigma_{scenarios} * \ m(h_{aection\ x}) * P_{scenario\ x}$	With
$ER = \Sigma_{scenarios}\ \Sigma_{sections}\ \ d(h_{aection\ x}) * n_{houses} * p_{house} * \ P_{scenario\ x}$	m – mortality function [-]
$GR = \Sigma_{scenarios}\ \Sigma_{sections}\ \ m(h_{aection\ x})\ * P_{scenario\ x}\ *\ Ef * \ n_{people}$	d – damage function [%]
	h – inundation depth [m]; $h_{aection\ x} = Z_{aection\ x}$ -WL
	WL – Water level [m NAP]
	n_{houses}= number of houses [#]
	p_{house} = value of house [€]
	$P_{scenario\ x}$ = probability of scenario [1/yr.]
	n_{people} = number of people; $n_{people} = n_{houses}$*2.5
	Ef = evacuation factor [%]

5.5.2 Investment costs

Table 5-3 shows the investment costs that have been assumed for the measures as described in Table 5-1. These costs are the total amount of money need to implement the respective measures, regardless of its geographical scale of implementation. Thus, nothing is said about who and how many people/households have to come up for the costs.

Table 5-3: Investment costs for MLS measures in *Mouillé*

Measure	**Description**	**Costs**	**Source**
1-3: Retain excessive discharge		60 million €	KBA Ruimte voor de Rivier [Ebregt *et al.* 2005: 43]
1-4: Relief hydraulic load		30 million €	Estimation
1-6a: Flood defenses	Heighten dike by 0.3 m over 40 km	60 million €	Expert judgment HKV
1-6b: Flood defenses	Heighten dike by 0.6 m over 40 km	90 million €	Expert judgment HKV
1-7: Flood defenses allowing overflow*[1]	Widen dike over 40 km	110 million €	Estimation
2-5: Re-location	Re-locate 2000 houses, per house 30,000€ value loss	60 million €	Estimation
2-6: Compartmentalization	Build 10 km of compart. Dike	100 million €	Expert judgment HKV
2-7: Elevate	Houses on poles: lengthen foundation columns by 1m. , 5,000€ per house	10 million €	UfM (Geronisus *et al.* 2008 :74)
2-8 a: Flood-proofing 1m	Per house 3,000€	6 million €	UfM (Geronisus *et al.* 2008 :74)
2-8 b: Flood-proofing 3m	Per house 8,000€	16 million €	UfM (Geronisus *et al.* 2008 :74)
3-5a: Preventive Evacuation 15%	750 people, 1 mln € per 100 persons for refuge shelter	7,5 million €	Expert judgment HKV
3-5b: Preventive Evacuation 80%	4000 people, 1 mln € per 100 persons for refuge shelter	40 million €	Expert judgment HKV
3-6: Temporary flood defenses	10,000€ per year, for 50 yrs, interest rate 2%	3,7 million €	Expert judgment HKV
3-8: Self-reliance	30,000€ per year, for 50 yrs, interest rate 2%	2,77 million €	Expert judgment HKV

5.6 Results

In the following paragraphs the calculation results is described. First the flood risk for both references cases (compare Chapter 5.3) is discussed. Afterwards the risk reduction of the individual flood management measures is quantified and visualized. This is done per Multilayered Safety [MLS] layer. Along the way the assumptions made for the computation is mentioned for each measure. Furthermore, it is shown which measures are probability- respectively loss-reducing.

5.6.1 Reference

The fictive case study has two reference cases. The first reference case (REF 1) is the situation without the new neighborhood in Section 3 (except IR). Thus the risk in Section 3 is originally zero. With the new neighborhood (REF 2) the risk in Section 3 increases. As a consequence the risk also becomes larger for the entire dike ring. This is shown for both material damage (FS-curve) and fatalities (FN-curve) in Table 5-5 below.

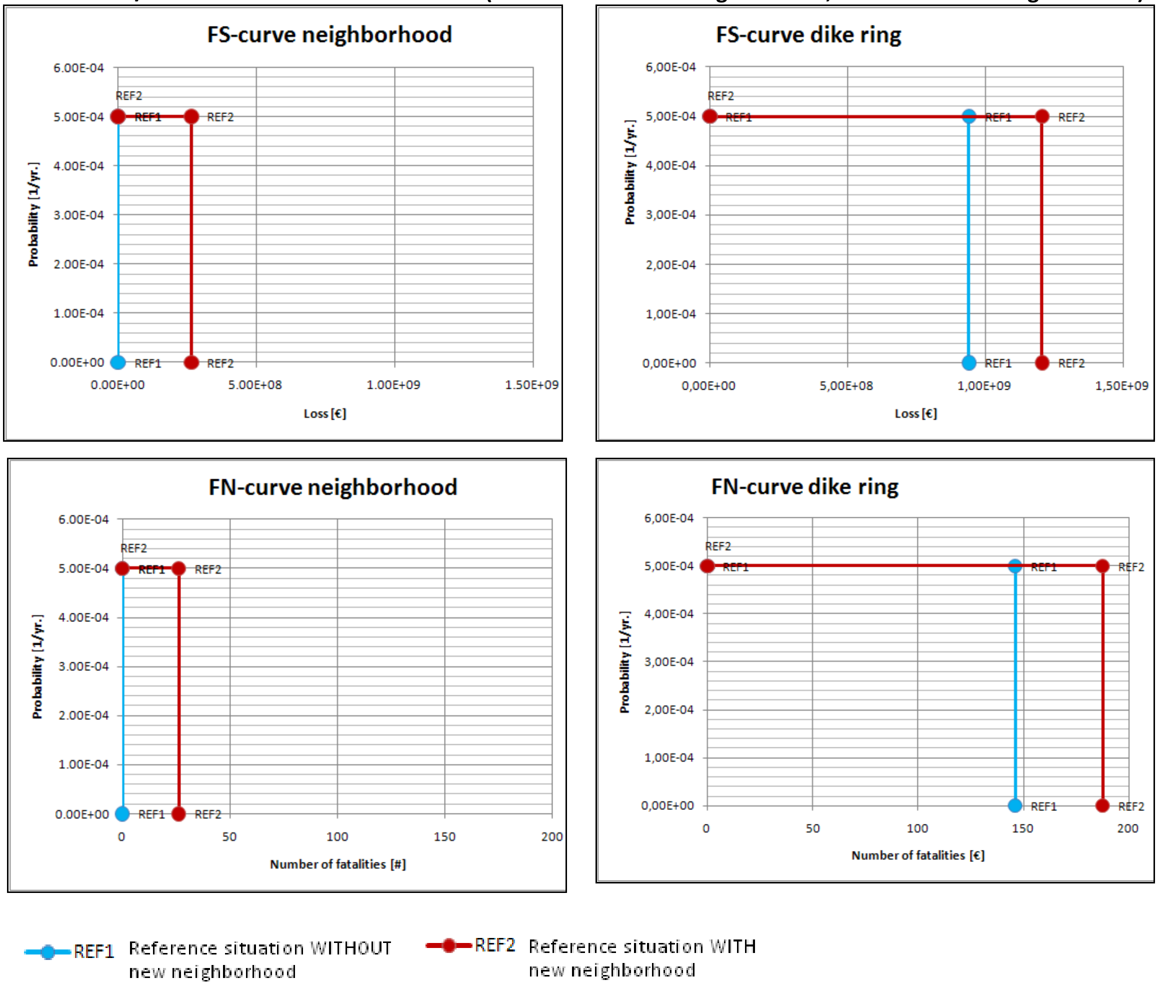
Table 5-4: Flood risk for both reference cases

Whole dike ring	Economic risk [€/yr]	Expect. Fatal.[#/yr]
REF1	470,00	0.073
REF 2	600,00	0.094
Risk increase	+ 130,000 (+ ca.27%)	+ 0,021 (+ ca.29%)

Section 3	Economic risk [€/yr]	Expect. Fatal.[#/yr]
REF1	0	0
REF 2	130,000	0.021
Risk increase	+130,000	0.021

The new neighborhood does not change the Individual Risk. Thus, there are no diagrams included here showing the IR.

Table 5-5: FS-/FN-curve for both reference cases (REF1=without new neighborhood, REF2=with new neighborhood)



In the analysis of case study the risk reduction of each flood management measure relative to the reference situations will be studied. Then difference can be made between measures that decrease the risk only in Section 3 or in the whole dike ring. It will also be interesting to see if measures make the area saver than it originally was (risk < REF1) or if they only ease the risk increase due to the new neighborhood (REF1 < risk < REF2).

5.6.2 Prevention

This section presents the calculation results for all flood management measures of the first MLS layer Prevention. Prevention includes the measures redistribution of water masses of river arms (1-3), relieving extreme hydraulic situations (1-4), heightening the dike (1-6a/b) and making the dike overflow-resistant (1-7) (compare Chapter 5.5). For the FN-curve for the neighborhood and the two FS-curves, please see Appendix 9.4.1. There also data on the effect of the measures on the average local risk can be found.

Table 5-6: Risk with prevention measures

Dike Ring	Economic risk [€/yr]	Expect. Fatal.[#/yr]
REF1	470,000	0,073
REF 2	600,000	0,094
1-3	300,000	0,047
1-4	400,000	0,063
1-6a	120,000	0,019
1-6b	60,000	0,009
1-7	310,000	0,047

New Neighborhood	Economic risk [€/yr]	Expect. Fatal.[#/yr]
REF1	0	0
REF 2	130,000	0,021
1-3	70,000	0,010
1-4	90,000	0,014
1-6a	30,000	0,010
1-6b	10,000	0,004
1-7	80,000	0,013

Prevention measures are considered to be probability-reducing. The only exception in this case study is the measure of making a dike overflow-resistant (1-7) to prevent total failure if the water level is higher than the crest height. The frequency with which the water level exceeds the dike crest stays the same but that has different consequences for an overflow-resistant dike. Thus, measure 1-7 has been considered as loss-reducing in this study (see Table 9-6).

All Prevention measures modeled in this case study are applied at delta (1-3, 1-4) or polder scale (1-6, 1-7).

It was assumed that if the dike breaches, the damage is the same regardless of the probability of a dike breach. In reality there will be some deviations in damage, negative or positive. On the one hand it needs higher water levels in the supplying body of water to cause a dike breach with a lower probability. Those higher and stronger dikes, on the other hand, might keep back more water so that the damage will possibly be higher. Therefore, the damage will not differ much for different breaching probabilities. The damage also does not differ for different locations of a dike breach.

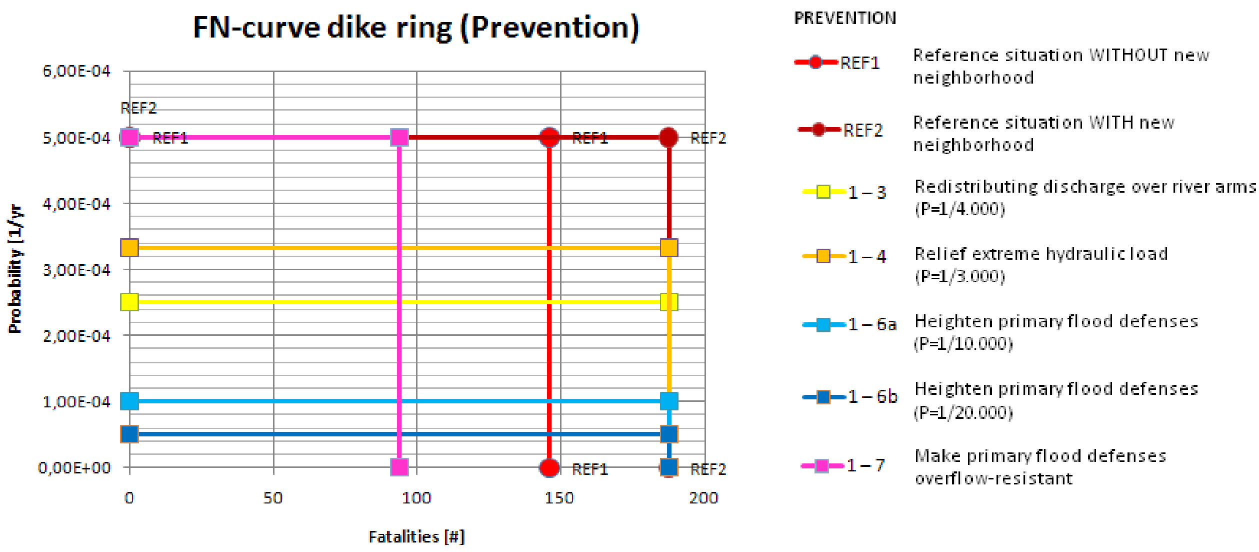


Figure 5-7: FN-curve dike ring - Prevention measures

5.6.3 Spatial Solutions

This section presents the calculation results for all flood management measures of the second MLS layer Spatial Solutions. Spatial Solutions includes the measures re-locating of neighborhood (2-5), compartmentalization (2-6), elevating the neighborhood (2-7) and flood-proofing the new buildings (2-8a/b) (compare Chapter 5.5). For the FN-curve for the neighborhood and the two FS-curves, please see Appendix 9.4.1. There also data on the effect of the measures on the average local risk can be found.

Table 5-7: Risk with Spatial Solution measures

Whole dike ring	Economic risk [€/yr]	Expect. Fatal.[#/yr]
REF1	470,000	0.073
REF 2	600,000	0.094
2-5	550,000	0.086
2-6	530,000	0.083
2-7	550,000	0.086
2-8a	600,000	0.094
2-8b	470,000	0.094

New Neighborhood	Economic risk [€/yr]	Expect. Fatal.[#/yr]
REF1	0	0
REF 2	130,000	0.021
2-5	80,000	0.013
2-6	40,000	0.007
2-7	80,000	0.013
2-8a	130,000	0.021
2-8b	0	0.021

Spatial Solutions are considered to be loss-reducing. Only compartmentalization (2-6) is not purely loss-reducing (see Table 9-7). This is discussed below. All measures of MLS Layer 2 are applied at neighborhood (2-6) resp. building (2-5, 2-7, 2-8) scale.

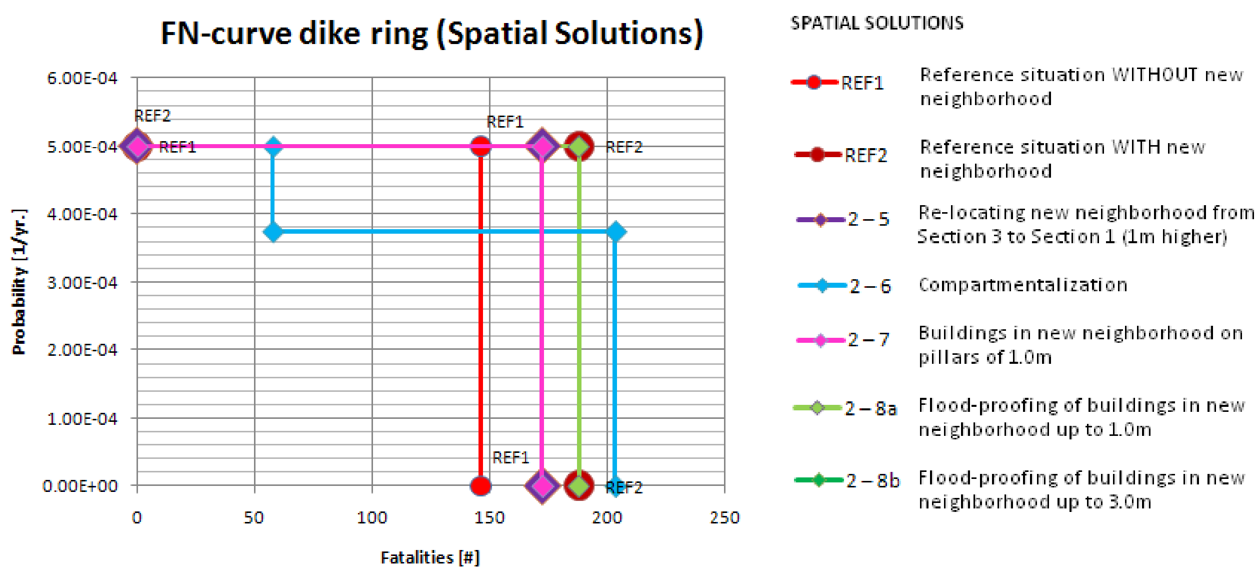


Figure 5-8: FN-curve dike ring - Spatial Solutions measures

Some of the measures are further commented in the following:

- *Re-location (2-5) and Elevation (2-7):* Re-locating inside the unit of analysis has the same effect (though not costs) on the ER and SR as elevating houses. Moving houses to an area with a ΔZ= x m higher ground level essentially equals elevating the houses by x m.

- *Compartmentalization (2-6):* In *Mouillé* four different scenarios have been modeled, each representing a dike breach in one of the four sections. It was assumed that all scenarios have the same probability of happening and the same consequences. The compartmentalization dike changes this. With the dike in one of the four scenarios only Section 3 floods and in three scenarios the other three sections inundate.

  The following observations on compartmentalization in this case study are very much a result of the way with which the compartmentalization dike was implemented in *Mouillé.* Therefore, these will be discussed here in length. In addition to the choice of location of the compartmentalization dike two more assumptions have been made. First of all, the inundation depth in the flooded part increases by 0.75m to h=2.5m. Furthermore, the mortality was increased by 10% in the assumption that the rise rate of the water level will increase when only one instead of three or four sections is flooded. This means that the increase in damage in the neighborhood for scenario 3 is more severe for fatalities than for material damage.

  The compartmentalization dike will only be a benefit if the decrease in probability of flooding that this dike brings about outweighs the increase of loss. The compartmentalization dike decreases the risk for Section 3 (the right-upper corner of the FN-/FS-curve disappeared). But due to the assumption that the loss in the inundated areas increases, the FN-/FS-curve shifts to the right. Overall that leads to a risk decrease in this case (see Table 9-7).

- *Flood-proofing (2-8):* The risk diagrams show that flood-proofing up to 1m (2-8a) shows no effect in the FN- or FS-curve whereas flood-proofing up to 3m (2-8b) does. The reason for this is that flood-proofing as been modeled as a sort of barrier here (compare Chapter 5.5.1). This means that if the water level exceeds the level of flood-proofing, the measure will have no effect. Since the inundation depth in the area with the new neighborhood and its potentially flood-proof houses is h=1.75m, the flood-proofing until 1m shows no effect.

  Flood-proofing, furthermore, was assumed to be irrelevant for the mortality, so that in the FN-curve both flood-proofing variants (2-8a, 2-8b) show no effect.

5.6.4 Crisis Management

This section presents the calculation results for all flood management measures of the third MLS layer Crisis Management. Crisis Management includes the measures evacuation (3-5a/b), sand bags (3-6) and preparation & warning (3-8). For the FN-curve for the neighborhood and the two FS-curves, please see Appendix 9.4.1. There also data on the effect of the measures on the average local risk can be found.

Crisis Management is considered to be loss-reducing. Only sand bags (3-6) are understood as probability-reducing in this study (see

Table 9-8). All measures of MLS Layer 2 are applied at polder (3-6) resp. building (3-5, 3-8) scale.

Table 5-8: Risk with Crisis Management measures

New Neighborhood	Economic risk [€/yr]	Expect. Fatal.[#/yr]
REF1	0	0
REF 2	130,000	0.021
3-5a	130,000	0.018
3-5b	130,000	0.004
3-6	110,000	0.017
3-8	120,000	0.019

Whole dike ring	Economic risk [€/yr]	Expect. fatal.[#/yr]
REF1	470,000	0.073
REF 2	600,000	0.094
3-�a	600,000	0.091
3-5b	600,000	0.077
3-6	480,000	0.075
3-8	590,000	0.092

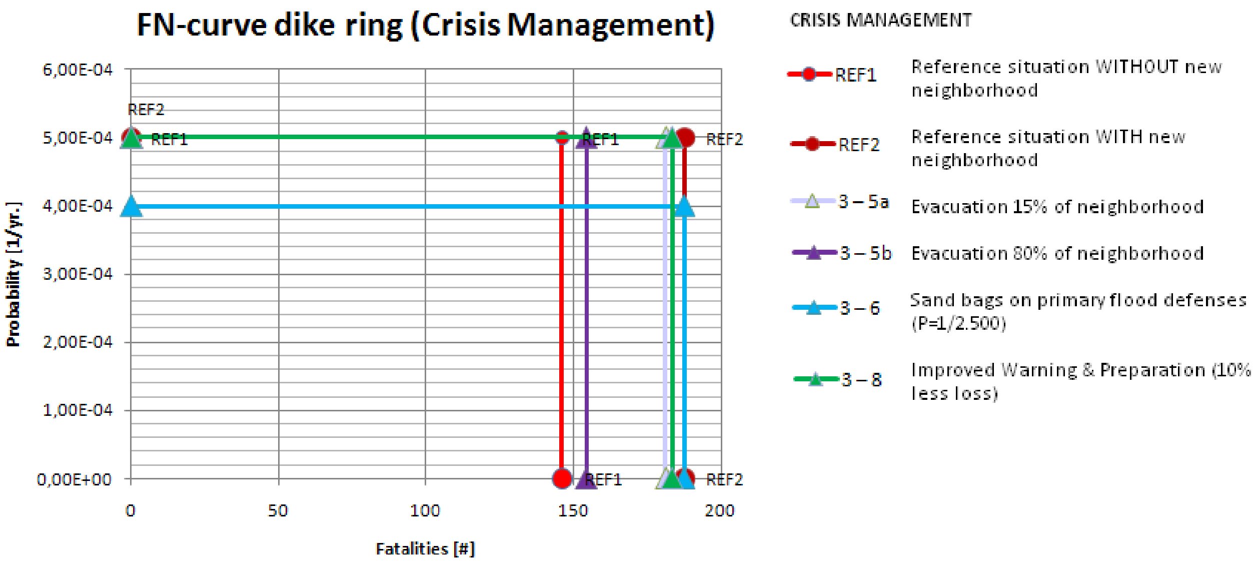


Figure 5-9: FN-curve dike ring - Crisis management measures

Some of the measures are further commented in the following:

- *Evacuation (3-5):* Evacuation (3-5a, 3-5b) has no effect in the FS-curve because it was assumed that only people are being evacuated and no material values. To decrease the interaction between different areas in the dike ring (see Chapter 4.3.2), evacuation is understood in this hypothetical case as taking refuge in shelters inside the neighborhood (vertical evacuation).

5.7 Analysis

In this chapter the measures described above will be analyzed. In Chapter 4 three properties of the MLS and its measures have been discussed: (side-) effects, interaction and failure. The case studies have not tested anything to do with failure, but they did examine aspects of (side-) effects and interaction. Furthermore, a cost-benefit analysis has been done.

Before discussing (side-) effects, interaction and cost-efficiency in the following, a couple comments on the form of the analysis need to be given. The analyses are done for two different geographical units, namely the dike ring and the new neighborhood (compare Chapter 5.6.1). This has been done to show how important the choice of scale is for the outcome of the analysis. Furthermore, the three dimensions of risk as introduced in Chapter 2.2 are used to provide a comprehensive analysis of the risk reduction. It will be examined if there are differences in risk reduction with regard to Societal Risk (SR), Economic Risk (ER) and Individual Risk (IR).

5.7.1 Effects

Effects

Two observations can be made regarding the effect of the flood management measures on the risk.

The **FIRST** observation is that probability-reducing measures decrease the risk homogenously for all affected *locations*. The risk reduction brought along by loss-reducing measures depends on the characteristics of the locations of implementation (see Figure 5-10).

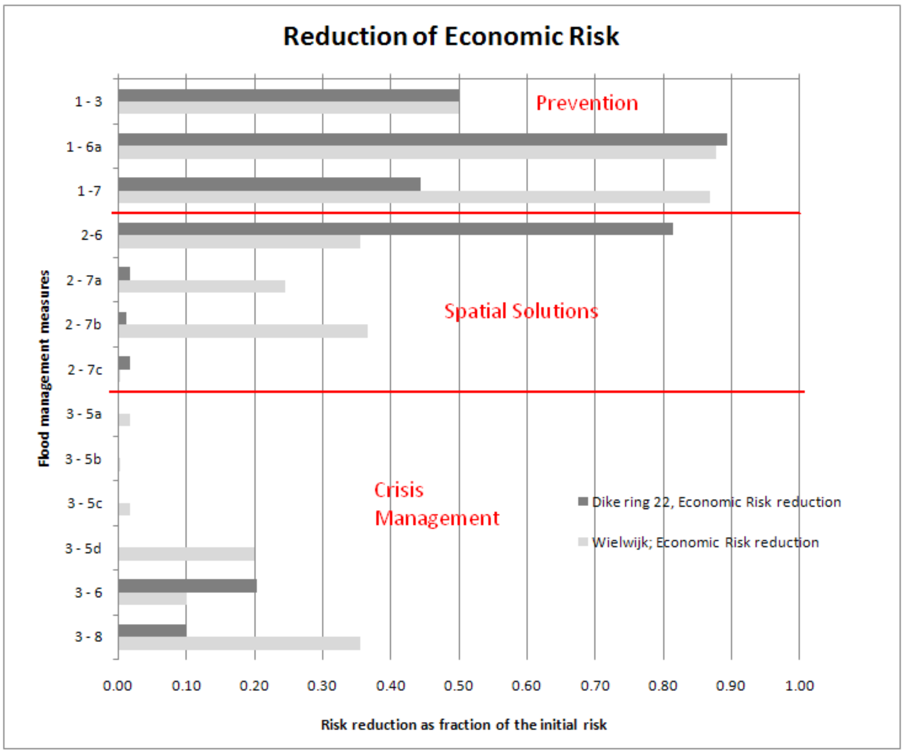
The probability-reducing measures (1-3, 1-4, 1-6, 3-6) have in relative terms the same risk-reducing effect on the dike ring as they have on the neighborhood. This is due to the fact that the risk at whatever location or geographical unit equally depends on the probability. Thus, if the probability is lowered all locations will be affected equally. The absolute risk reduction though will depend on the initial flood risk (compare Interaction).

Note that in reality probability-reducing measures will not decrease the risk so extremely homogenous as in this case studies. E.g. giving the rivers more space (1-3) will benefit some locations more than others.

The **SECOND** observation is that probability-reducing measures decrease the risk homogenously for all *dimensions of risk.* The risk reduction brought along by loss-reducing measures, however, depends differs across the dimensions of risk (see Figure 5-11).

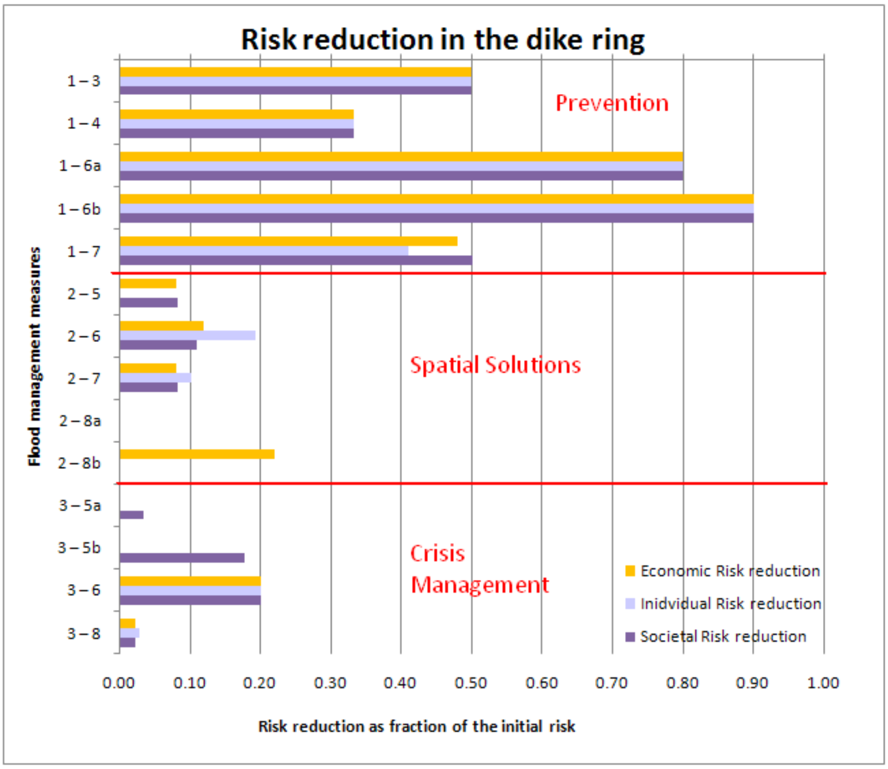
The probability-reducing measures (1-3, 1-4, 1-6, 3-6) have in relative terms the same risk-reducing effect on all three dimensions of risk (ER, SR, IR). The reason is that each dimension of risk equally depends on the probability. It follows that all risk dimensions will be affected equally, if the probability is lowered. The absolute risk reduction though will depend on the initial flood risk (compare Interaction).

Practically the two observations above imply that **probability-reducing measures are suitable for decreasing the overall risk but are less fit for customizing flood risk management to local conditions (*maatwerk*). Extending this observation to MLS, it turns out that MLS opens up the possibility to tailor flood risk management to local conditions and address hotspots.**



REF = reference case
1 – 3 = redistribute river discharge
1 – 4 = relief extreme hydraulic loads
1 – 6a = higher dikes (1/10,000)
1 – 6b = higher dikes (1/20,000)
1 – 7 = overflow-resistant dikes
2 – 5 = re-location buildings
2 – 6 = compartmentalization
2 – 7 = elevating buildings
2 – 8a = flood-proofing buildings (1m)
2 – 8b = flood-proofing buildings (3m)
3 – 5a = evacuation neighborh. 15%
3 – 5b = evacuation neighborh. 80%
3 – 6 = sand bags
3 – 8 = preparation & warning

Figure 5-10: The reduction of the economic risk as a fraction of the initial risk shown for all flood management measures. Different to the loss-reducing measures, the probability-reducing measures reduce the risk by the same fraction for the new neighborhood and the dike ring. The absolute risk reduction depends on the initial flood risk.



REF = reference case
1 – 3 = redistribute river discharge
1 – 4 = relief extreme hydraulic loads
1 – 6a = higher dikes (1/10,000)
1 – 6b = higher dikes (1/20,000)
1 – 7 = overflow-resistant dikes
2 – 5 = re-location buildings
2 – 6 = compartmentalization
2 – 7 = elevating buildings
2 – 8a = flood-proofing buildings (1m)
2 – 8b = flood-proofing buildings (3m)
3 – 5a = evacuation neighborh. 15%
3 – 5b = evacuation neighborh. 80%
3 – 6 = sand bags
3 – 8 = preparation & warning

Figure 5-11: Risk reduction in the dike ring as a fraction of the initial risk, shown for all flood management measures and dimensions of risk. Different to loss-reducing measures, the probability-reducing measures reduce the risk by the same fraction for all three dimensions of risk. The absolute risk reduction depends on the initial flood risk.

Side-effects

In this case-study, only the side-effects of compartmentalization (2-6) have been studied.

The side-effects of compartmentalization on the flood characteristics have been built into the computational model: If there is a flood, the inundation depth will be higher due to the fact that a smaller area floods (compare Results). In Section 3 the mortality is additionally increased by 10%. Thus, in the case of flooding the loss will be higher. But compartmentalization decreases the probability of flooding. In only one of the four scenarios Section 3 will flood. The other three sections will flood in three out of four scenarios. Compartmentalization will only lead to risk reduction if the risk decrease due to a lower probability is larger than the risk increase due to a higher loss. In this case study that is the case. Thus, even if compartmentalization increased the flood risk for a part of the area, it could lead to a reduction of the total flood risk. In that case the compartmentalization would have redistributed the flood risk across the area to some extent.

It is concluded that **in the case of compartmentalization its side-effects lower the risk reduction brought along by it, but not necessarily make it a risk-increasing measure**.

The conclusion just made about compartmentalization is equally true for all other linear flood defenses. Compartmentalization is the probability-reducing measure that was applied *inside* the dike ring and thus became the only one whose side-effects on the flood characteristics were accounted for in the computational model. The other probability-reducing measures have the same side-effect at a larger scale than the dike ring. E.g. if the river dikes in Germany are heightened the flood risk in the Netherlands will increase.

See Case Study 2 (Chapter 6.5) for more observations on Compartmentalization (2-6).

5.7.2 Cost-effectiveness-analysis

The Cost-effectiveness-analysis (CEA) will be done using two criteria, one for material loss and one for fatalities. Those are shortly reviewed below. Following that the cost-efficiency of first the individual flood management measures will be analyzed. Secondly, the cost-efficiency of the MLS layers will be evaluated.

Short review

In Chapter 2.2.4 two criteria were introduced to evaluate the cost-efficiency of flood management measures. To make an investment into flood safety economic the net present value of the risk reduction has to be larger than the investment. That ratio will be called T here. The smaller the T factor is, the more cost-efficient a measure is. The T-factors for the flood management measures are shown in Figure 5-12.

$$T = \frac{I}{\Delta ER/_{r}} \leq 1$$

With I = Investment [€]
ΔER = reduction in economic risk [€/yr]
r = rate of interest [-]

The criterion reviewed above is mainly applicable for material loss that can be expressed in value. To evaluate the cost-efficiency with regard to saved human lives, the CSX has been introduced in Chapter 2.2.4. The smaller the CSX factor, the more cost efficient a measure is. The CSX-factors for the flood management measures are shown in Figure 5-13.

$$CSX = I/\Delta E(N)$$

With CSX = costs of saving an extra life per year [€/#/yr]
I = investment [€]
E(N) = expected number of fatalities [#/yr]

CEA Individual measures

When analyzing the cost-efficiency of the individual flood management measures, three observations can be done.

1. The most eye-catching result of the computation is that fact that **most of the measures do not fulfill the criterion with regard to the reduction of the economic risk** given in Chapter 2.2.4. The investment costs are higher than the net present value of the risk reduction (red line in Figure 5-12). Only the sand bags (3-6) are an exception (see Figure 5-12,Figure 5-13).

Regardless of the observation just made it might still be decided to improve the flood safety nonetheless. Reasons might be the desire for equality or other emotional values that have not been included in the Cost-effectiveness-analysis of this study. A societal Cost-effectiveness-analysis is needed to appreciate those values. See also the subchapters on interaction (Chapters 4.3, 5.7.3) for the influence of the initial safety level on cost-efficiency.

2. With regard to both criteria reviewed above, **the sand bags (3-6) are the most cost-efficient and the re-locating (2-5) and compartmentalization (2-6) the least cost-efficient measures**. For re-locating (2-5) the reason are the high costs resulting from the fact that flood risk is only one of a lot of arguments for a certain location choice. Re-locating only to reduce the flood risk is perceived as a great sacrifice. The disadvantageous interaction with the flood characteristics causes compartmentalization (2-6) to be so inefficient. The cost-efficiency of the sand bags is deceptive because they were modeled as re-enforcing the existing primary flood defenses. Thus, investing more money to put more sand bags will not linearly increase the safety.

REF = reference case
1 – 3 = redistribute river discharge
1 – 4 = relief extreme hydraulic loads
1 – 6a = higher dikes (1/10,000)
1 – 6b = higher dikes (1/20,000)
1 – 7 = overflow-resistant dikes
2 – 5 = re-location buildings
2 – 6 = compartmentalization
2 – 7 = elevating buildings
2 – 8a = flood-proofing buildings (1m)
2 – 8b = flood-proofing buildings (3m)
3 – 5a = evacuation neighborh. 15%
3 – 5b = evacuation neighborh. 80%
3 – 6 = sand bags
3 – 8 = preparation & warning

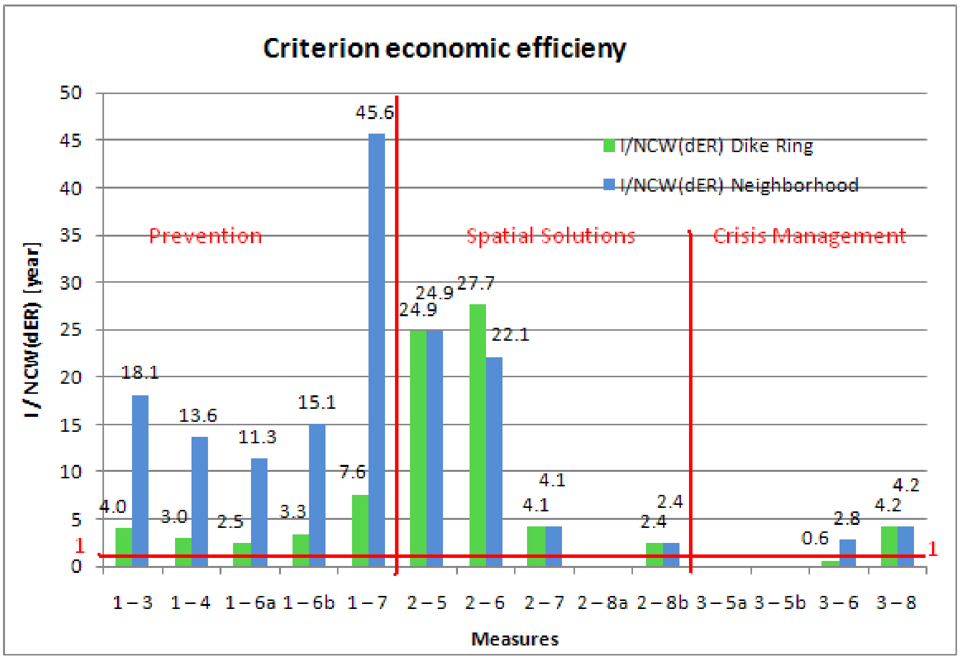


Figure 5-12: Cost-efficiency with regard to economic risk. The lower the ratio between investment and net present value of the risk reduction, the more cost-efficient a measure is. A measure becomes economically desirable if the risk reduction (NPV) is larger than the investment. This is the case if the columns in the diagram stay below the horizontal red line.

REF = reference case
1 – 3 = redistribute river discharge
1 – 4 = relief extreme hydraulic loads
1 – 6a = higher dikes (1/10,000)
1 – 6b = higher dikes (1/20,000)
1 – 7 = overflow-resistant dikes
2 – 5 = re-location buildings
2 – 6 = compartmentalization
2 – 7 = elevating buildings
2 – 8a = flood-proofing buildings (1m)
2 – 8b = flood-proofing buildings (3m)
3 – 5a = evacuation neighborh. 15%
3 – 5b = evacuation neighborh. 80%
3 – 6 = sand bags
3 – 8 = preparation & warning

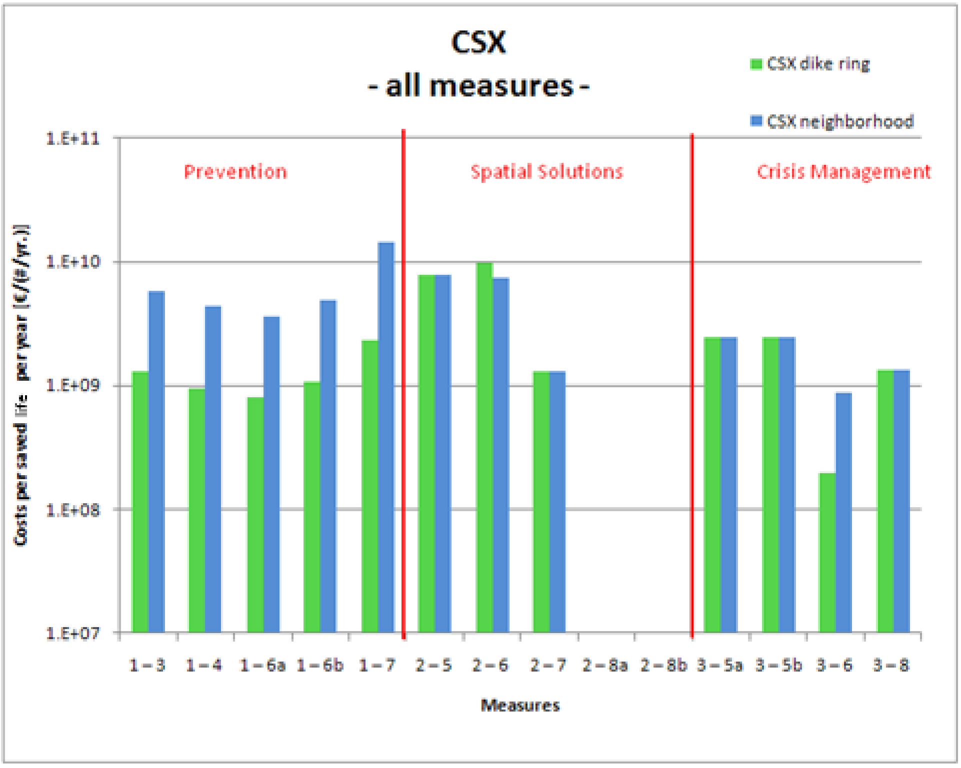


Figure 5-13: Cost-efficiency with regard to the expected number of fatalities per year. The lower the ratio between investment and saved statistical lives, the more cost-efficient a measures is. This diagram says nothing about the (monetary) value of a human live.

3. Furthermore, it is interesting to note that flood management measures are most cost-efficient for the unit they have been implemented in. Thus, measures that have been implemented in the entire dike ring are more cost-efficient for the dike ring than for the new neighborhood. All the measures that have only been implemented in the new neighborhood are, vice versa, more cost-efficient for the new neighborhood than for the dike ring.

This is due to the fact that each flood management measure is tailored to the area it is implemented in. E.g. a dike ring protects much more people than is necessary to increase the safety in only one neighborhood. Another example is that if houses are made flood-proof up to the same height, that height can be more precisely tailored to the local flood risk for a neighborhood than for a whole dike ring area.

It was found in the analysis of the effect of flood management measures (Chapter 5.7.1) that MLS opens up the possibility to customize flood risk management more precisely to local differences (*maatwerk*). This CEA shows that it is also cost-efficient to do so.

CEA MLS-layers

The MLS-layers have been compared with two methods. One time they have been ranked according to the average of the measures in a layer (Av.). Additionally, they have been ranked by the most cost-efficient measure in a layer (Best). The result can be seen in Table 5-9.

Best	Economic Risk		CSX	
Rank-ing	Neighbor-hood	Dike Ring	Neighbor-hood	Dike Ring
1.	SS	CM	CM	CM
2.	CM	SS/P	SS CM	P
3.	P	CM	P	SS CM
Av.	**Economic Risk**		**CSX**	
Rank-ing	Neighbor-hood	Dike Ring	Neighbor-hood	Dike Ring
1.	CM	CM	CM	P
2.	SS	P CM	SS	SS
3.	P	SS	P	CM
(P=Prevention, SS=Spatial Solutions, CM=Crisis Management)				

Table 5-9: Ranking of MLS layers according to the most cost-efficient measure per layer (Best) and the average cost-efficiency per layer (Av.). The red notes and arrows indicate the results if the measure 'sand bags' (3-6) is excluded. That measure is rather unrealistically cost-efficient.

It is observed that Crisis Management scores exceptionally well in all cases. This is rather deceptive though, since the sand bag measure (3-6) in that layer scores unrealistically well. This has also been discussed in more depth in the CEA for individual measures above. The sand bags thus shed an overly positive light on Crisis Management. This is especially the case for the ranking by average for the economic risk. Only two measures reduce the economic risk, thus the sand bags weigh into the average very heavily. Excluding the sand bags lets Crisis Management drop in the rankings, see the red arrows in Table 5-9.

Generally, it is concluded that Prevention scores much better for the dike ring than for the neighborhood. This is in line with the observation above (CEA Individual measures and Chapter 5.7.1), that **loss-reducing measures (Crisis Management and Spatial Solutions) enable cost-efficient flood risk management customized to local conditions**.

The results allow no reliable judgment if any MLS-layer is more suitable for reducing the risk of a certain dimension (SR, IR, ER). Only the observation from Chapter 5.6 can be repeated: Spatial Solutions measures sometimes have no effect on the expected number of fatalities. The same is true for Crisis Management and the economic risk.

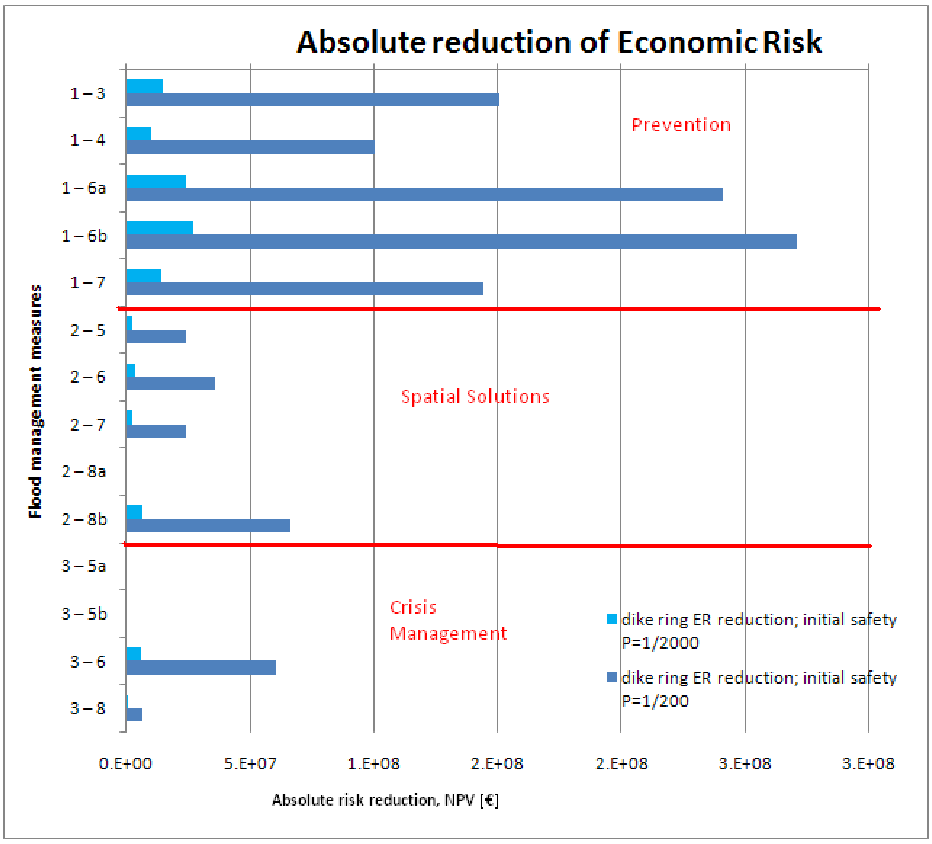
5.7.3 Interaction

In Chapter 4.3 it has been explained that the effect of many flood management measures and thus their cost-efficiency depends on the initial safety level. To illustrate this, the case study has also been done with another initial safety level. Instead of a probability of flooding P=1/2,000 (1/yr.) a probability of P=1/200 (1/yr.) has been chosen.

Reducing the initial safety level has no effect on the relative risk reduction. The fraction with which the initial risk is decreased stays the same, independent of the initial probability of flooding. But the total risk is higher if the initial safety level is lower. Therefore, the absolute amount of risk reduction sharply increases if the initial probability of flooding is higher. This is shown in Figure 5-14.

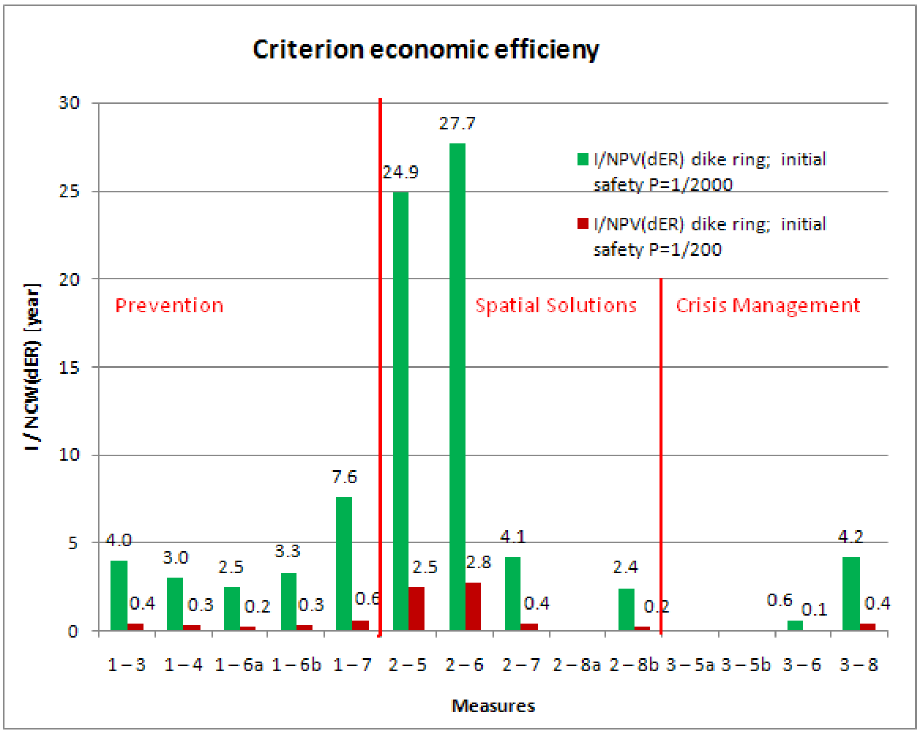
If the measures cause a much larger absolute risk reduction, their cost-efficiency becomes much more favorable as well. This can be seen in Figure 5-15. With the probability of flooding in the original case study (P=1/2,000) all except one measure were not cost-efficient (see Figure 5-12). With the higher probability of flooding the investment costs are larger than the net present value of the risk reduction for only the two least efficient measures: relocating (2-5) and compartmentalization (2-6). Thus, **the cost-efficiency of all measures increases sharply if the initial flood risk is increased in the model**.

In this study, the initial safety level has only been varied by changing the initial probability of flooding. It is expected that if the initial safety is decreased by other means, e.g. lowering the ground level, the effect on the absolute risk reduction, and subsequently the cost-efficiency, will be the same.



REF = reference case
1 – 3 = redistribute river discharge
1 – 4 = relief extreme hydraulic loads
1 – 6a = higher dikes (1/10,000)
1 – 6b = higher dikes (1/20,000)
1 – 7 = overflow-resistant dikes
2 – 5 = re-location buildings
2 – 6 = compartmentalization
2 – 7 = elevating buildings
2 – 8a = flood-proofing buildings (1m)
2 – 8b = flood-proofing buildings (3m)
3 – 5a = evacuation neighborh. 15%
3 – 5b = evacuation neighborh. 80%
3 – 6 = sand bags
3 – 8 = preparation & warning

Figure 5-14: Absolute reduction of the economic risk in the dike ring. The diagram shows a sharp increase in absolute risk reduction if the initial probability of flooding is increased from P=1/2,000 to P=1/200.



REF = reference case
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2 – 8b = flood-proofing buildings (3m)
3 – 5a = evacuation neighborh. 15%
3 – 5b = evacuation neighborh. 80%
3 – 6 = sand bags
3 – 8 = preparation & warning

Figure 5-15: Cost-efficiency of flood management measures with regard to the economic risk. The diagram shows that the cost-efficiency increases sharply if the initial probability of flooding is increased from P=1/2,000 to P=1/200.

5.8 Conclusion Case Study 1

This study of the fictive dike ring *Mouillé* has given a few insides concerning the (side-) effects, the cost-efficiency and the interaction of flood management measures in general and Multilayered Safety in particular. Those findings are listed below.

Effects

- Probability-reducing measures are suitable for decreasing the overall risk but are less fit for customizing flood risk management to local conditions (*maatwerk*). Extending this observation to MLS, it turns out that MLS opens up the possibility to tailor flood risk management to local conditions and address hotspots.

Side-effects

- In the case of compartmentalization its side-effects lower the risk reduction brought along by it, but not necessarily make it a risk-increasing measure.

Cost-efficiency

- In this case study, the investment costs for most flood management measures are larger than the net present value of the reduction of the economic risk.
- With regard to both criteria reviewed above, the sand bags (3-6) are the most cost-efficient and the re-locating (2-5) and compartmentalization (2-6) the least cost-efficient measures. In case of the sand bags this outcome is rather deceptive.
- The CEA confirms that the cost-efficiency of flood risk management is improved by customizing flood risk management to local conditions. Since MLS provides this opportunity, it has potential to increase the cost-efficiency of flood risk management.

Interaction

- The cost-efficiency of all measures is heavily dependent on the initial safety level. Flood management measures are tremendously more cost-efficient if the initial safety level is lower.

6 Case Study 2 – Dike Ring 22: Island of Dordrecht

The computational models introduced above will be applied to a case study, being the dike ring 22 called Eiland van Dordrecht. In the following this dike ring will be described and analyzed, focusing on a restructuring project on the scale of a neighborhood where MLS measures could actually be applied in reality. Then the model that simulates the effect of MLS will be explained and its results be represented. The chapter closes with an analysis of those results and a conclusion that will provide feedback to the framework developed beforehand (Chapter 3.5and the earlier hypothetical case study (Chapter 5).

Figure 6-1: Artist impression of the of Isle Dordt (Source: UfM)

6.1 Objectives Case Study 2

This case study is done with a few objectives in mind:

- Verify the outcomes of the hypothetical first case study
- Examine interaction with flood characteristics where relevant
- Deeper understanding of the effect of flood management measures on flood risk
- Study combining measures with an existing dike ring/compartment. dike
- Explore the possibilities of Multilayered Safety in dike ring 22

6.2 Case dike ring 22 – Isle of Dordt

In the following paragraphs an introduction to the Isle of Dordt will be given. This introduction will concentrate on the geographical and hydraulic positioning, the flood protection and the relevant living circumstances. It will also include a description of the city of Dordrecht and how Multilayered Safety relates to it.

6.2.1 Topographics

The Isle of Dordt (Eiland van Dordt) is formed by the *Beneden Meerwede* and the *Oude Maas* in the North, the *Nieuwe Meerwede* in the South and the *Dordtsche Kil* in the West. Another significant water is the *Wantij* which divides the island into a Western and an Eastern part. The island covers about 10,000 ha and most of the Western part consists of dike ring 22. Basically only part of the Nature Park Biesbosch in the South of the island and the historical center of the city of Dordrecht in the North are situated outside the dikes. It is geographically relatively highly positioned with the lowest water front situated at +1.75 m NAP. The rest of the dike ring lies at a ground level of 0m NAP with a margin of ±1m. The city itself covers about 2.800 ha and is bounded by the old Wieldrechtse Zeedijk and the Zuidendijk (both old dikes) (Waterplan Dordrecht 2009: 14ff.).

Figure 6-2: Isle of Dordt from birdview (Source: Google Maps)

6.2.2 The city of Dordrecht

Nowadays the city of Dordrecht, founded in the 12th century, has 120,000 inhabitants. It is part of the agglomeration Drechtsteden counting 280,000 inhabitants. Until the harbor of Rotterdam became dominant, Dordrecht was an influential trading city because it is surrounded by waterways suitable for shipping. In cooperation with the Drechtsteden mentioned above Dordrecht now concentrates more on the service industry.

The form of the city has very much been determined by the (compartmentalization-) dikes. The dike ring area is divided into half by the Zeedijk, a secondary dike that runs from East to West through the dike ring. Among the community's politicians and the public the opinion is usually shared that the urbanization should not spread further than the Zeedijk and the Zuidendijk which lies a little more north in the Eastern part of the dike ring. The municipal election in 2010 have reinforced this agreement. In that election the building project Zuidpolder was a major issue. The public expressed its preference to not urbanize more agriculture ground but to first use the already urbanized areas to the maximum. Since the new to be build city quarter Zuidpolder is not going to be build in the near future due to the outcome of the election, restoration and restructuring projects like the Wielwijk now draw more attention.

According to different studies, e.g. by the Netherlands Environmental Assessment Agency (*Planbureau voor de Leefomgeving),* the flood risk in Dordrecht is relatively high (see Figure 6-8). For this reason, the municipality is enthusiast to give flood safety more attention in new building projects. A recent example is the neighborhood *Stadswerven* outside the dike ring. More specifically the city has embraced the concept of Multilayered Safety as an opportunity to trigger innovation and become a forerunner in modern flood risk management.

6.2.3 Restructuring project – Wielwijk

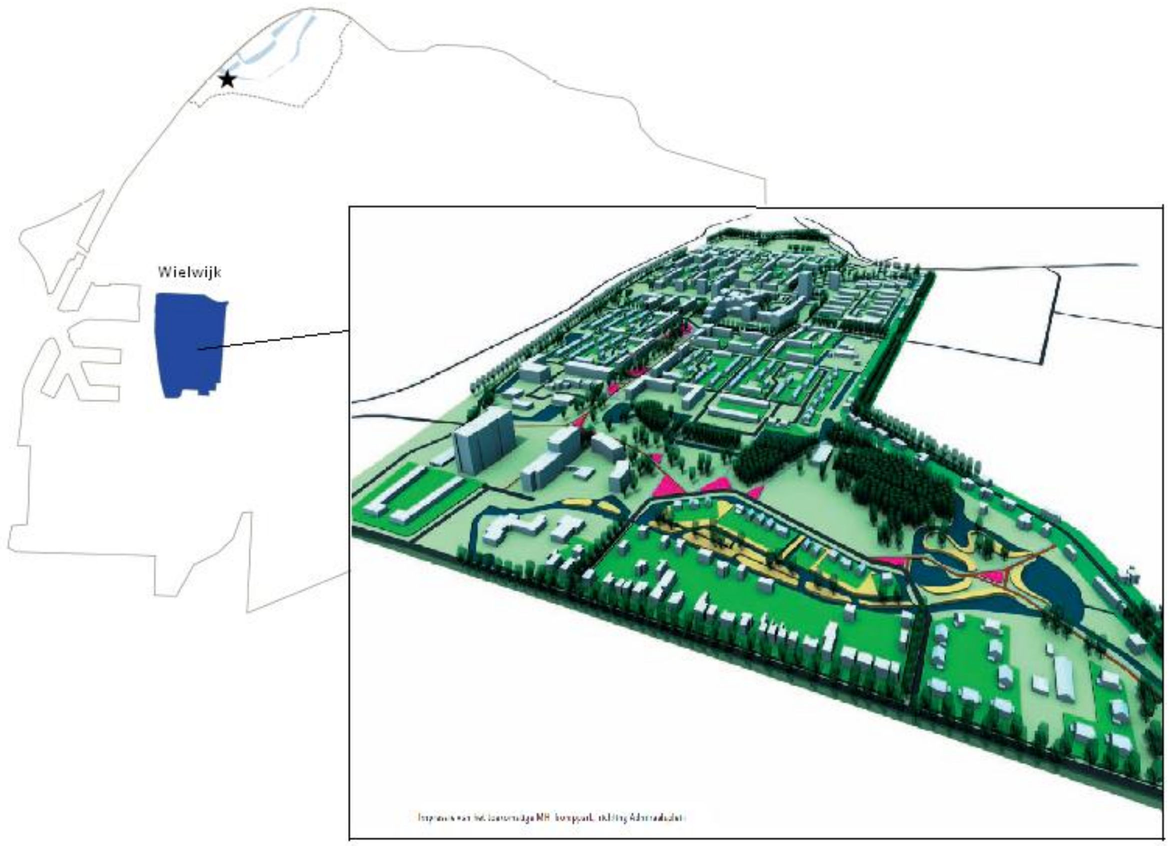


Figure 6-3: Location and artist impression of Wielwijk; Note, the artist impression includes the adjacent park. (Sources: Woonbron & Gemeente Dordrecht 2007: 2; Urban Fabric, Steenhuis Stedenbouw/landschap 2005: 1)

Since the City of Dordrecht would like to apply MLS mainly in the frame of building projects considering new and existing neighborhoods, it is chosen to study MLS on the basis of one of these neighborhoods. The selected neighborhood, the Wielwijk, is undergoing a restructuring process since 2006. Furthermore, the flood risk in the Wielwijk is relatively average for Dordrecht, so that the results of this study can easily be transferred to other neighborhoods. If MLS is beneficial in an area with a relatively low risk, it will most probably be so for areas with a higher flood risk. In the hypothetical case study it has already been examined how MLS behaves in more risky neighborhoods (Chapter 5). Combining the two case studies will then give a complete picture of flood risk management.

The Wielwijk has been built in the late 50's and early 60's of the last century. Its 2155 housing units cover 59 ha. Three quarters of those homes are situated in flat buildings with 3-7 floors. The rest are family homes. The flats are grouped into four quarters that are arranged around the central square *Admiraalsplein.* The quarters of the Wielwijk are separated by green zones. Furthermore there is the Wielwijkpark to be found in the South of the area (Urban Fabric, Steenhuis Stedenbouw/landschap 2005: 1).

	2000	%	Stand van zaken voor de visie	%	Projecten visie	2025	%
Eengezinswoningen	1099	35%	1234	38%	+ 265	1499	49%
Meergezinswoningen	2056	65%	2052	62%	- 469	1583	51%
Totaal	3155		3286		- 204	3082	

Figure 6-4: Fractions of housing today and in the project plan (Source: Woonbron & Gemeente Dordrecht 2007: 9)

The restructuring plans mainly focus on better traffic management, better accessibility of the park and most importantly improving the dull neighborhoods. About half of the housing is going to be replaced with new buildings and 3000 m^2 of office space will be added. It is the aim to attract a diversity of buyers, so that the new houses will cover a large price range (Woonbron & Gemeente Dordrecht 2007: 9-10).

A study of 2005 concludes that the post-war architecture does not justify awarding the Wielwijk a monument status. It was rather necessary to add value to the neighborhood to improve the quality of life and prevent further crowding by new building projects not fitting into the concept of the neighborhood. A disadvantage of the nearby highway A16 the air quality in the Wielwijk is rather poor so that the neighborhood has to be given extra qualities to make it attractive for higher incomes. (Urban Fabric, Steenhuis Stedenbouw/landschap 2005: 3).

Figure 6-5 Wielwijk scale 1:5000 (Source: Urban Fabric, Steenhuis stedenbouw/landschap 2005: 27)

6.2.4 Water system

Evolvement & Characteristics of dike ring 22

Looking back into history the Isle of Dordt was formed during the Saint Elizabeth-flood in 1421. Before, the present island was part of an agricultural area called Hollandsche Waard which was protected by dikes. The flood was caused by a strong North-Westerly storm in combination with high river discharges. This caused many badly maintained dikes of the Hollandsche Waard to break. Much of the agricultural ground was flooded resulting in the death of at least 2,000 people. The city of Dordrecht ended up being surrounded by waterways changing its trade position significantly to the better. Out of need for agricultural ground land reclamation and inpoldering enlarged the island during the 16th to the 18th century. During the industrialization

Table 6-1: Characteristics of dike ring 22

- Province: Zuid-Holland
- Water board: Waterschap Hollandse Delta (WHSD)
- Municipality: Gemeente Dordrecht
- 120,000 inhabitants
- 4916 ha
- Expected/max. Damage 9 billion Euro (2008)
- Expected number of victims: 74 (2008) (min.: 10, max.: 393)
- 37,1 km primary flood defenses
- 17 civil engineering works in the flood defenses
- 24 km regional flood defenses (mostly compartmentalization dikes)

the island was principally given the form it has today by e.g. harbor construction (Waterplan Dordrecht 2009: 14ff.).

During the major flood in 1953 the water level rose to +3.60 NAP flooding 130 ha of the city. All polders outside the primary flood defenses of that time were inundated as well. As part of the Deltawerken the Haringvliet was closed in 1970. Closing off the estuary shut out the tides so that water level oscillates with an amplitude of ca. 0.3 m nowadays instead of the former 2.00m. Additionally 14 dike sections were reinforced. Furthermore, the dike ring was given its present shape by constructing the Wantijdijk dividing the original island into halves (Water board Hollandse Delta 2005: p. 7).

A pecularity of dike ring 22 is the Voorstraat. This is a centuries-old sea dike with part of the historical city on top of it. As a consequence of the buildings on the dike it still has its original height. To provide enough safety shutters have been introduced to close off the house entrances. Furthermore the construction of the Maeslantkering in the Nieuwe Waterweg has decreased the design water level. Taking those two developments into account, the Voorstraat is sufficiently safe nowadays. This is expected to change in the near future due to policy changes (see Chapter 2.5.2) and processes as climate change. Since the Haringvliet has been closed extreme water levels have not occurred (Water board Hollandse Delta 2005: pp. 8).

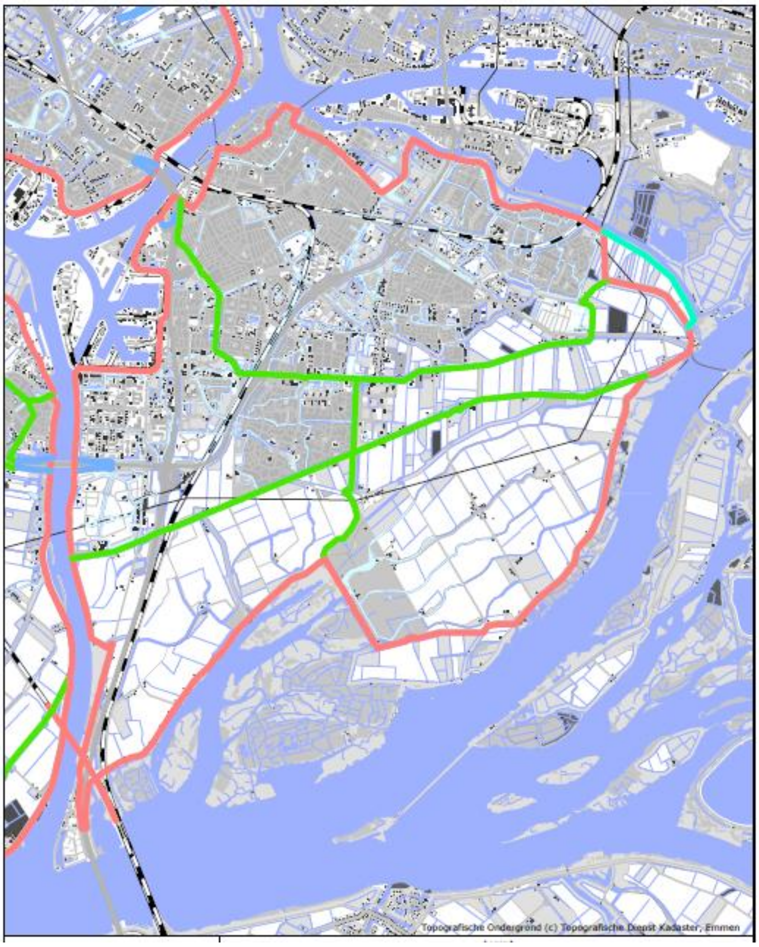


Figure 6-6: Dike ring 22. Primary flood defenses are indicated in red, secondary flood defenses in green. Parts of the neighboring dike rings are visible. (Source: Waterschap Hollandse Delta)

The most recent development influencing the dike ring has been the construction of the high-speed rail line HSL. As part of that project a tunnel has been built under the Dordtsche Kil passing under the South-Western part of the dike ring.

This tunnel is not a direct concern for flood protection though since it exits right outside the dikes (Water board Hollandse Delta 2005: p. 9).

Hydraulic characteristics

As the flooding scenario in 1421 already indicated the Isle of Dordt lies in a transition area influenced by the North Sea as well as the country's big rivers Meuse, Rhine and Waal. This is the area where river and sea water meet and influences of the sea tides still play a role. Relevant to dike ring 22, in 2005 the design water level was +3,00m NAP for the Oude Maas, +2,70m NAP for the Hollandsch Diep and +3,30m NAP (Kop van 't Land) respectively +2,80m NAP (Deeneplat) for the Nieuwe Merwede. The norm for the dike ring is 1/2000 years. Furthermore there are a number of old compartmentalization dikes in the dike ring which are not officially part of the flood defense system anymore. Nonetheless they are kept in the present state. Their crest height varies between 2-4 m NAP.

Developments

These characteristics might be influenced significantly by major projects like the 'Kierbesluit' and the 'Afsluitbaar Open Rijnmond' in the near future. The first project aims at opening the Haringvliet, a dammed-off estuary which the Beneden Meerwede flows into. This would highly increase the influence of the tides on the waterways around the island. The second project researches the possibility of generally managing the delta in which Dordrecht lies differently. The object of this project is to decrease the flood risk and the costs of protection against floods significantly (see Figure 6-7).

Figure 6-7: Project Afsluitbaar Open Rijnmond (Closable Open Rhine Mouth)

Nowadays the norm for the dike ring in Dordrecht is 1/2,000 per year. The government is in the process of issuing new norms in the near future though. It is being discussed if the norm for Dike Ring 22 should significantly go up to at least 1/10.00. per year. So even if the dikes are right now considered sufficiently high, though in some cases not strong enough, this is likely to change once the new norms are established.

RESULTAATSTABEL DIJKRING 22 Eiland van Dordrecht					
Kenmerken waterkering dijring 22: categorie A, direct buitenwaterkerend	aantal of lengte [km]	Beoordeling			
		VOLDOET AAN DE NORM		VOLDOET NIET AAN DE NORM	GEEN OORDEEL
Toetsingsspoor per type		goed	voldoende	onvoldoende	
Totaal					
Dijken en dammen					
HT Hoogte	37,1	34,9	0,0	0,0	2,2
ST Stabiliteit					
STPH *Piping en heave*	37,1	33,6	0,0	3,5	0,0
STBU *Macrostabiliteit buitenwaarts*	37,1	35,9	0,1	0,5	0,6
STBI *Macrostabiliteit binnenwaarts*	37,1	27,0	3,5	6,2	0,4
STMI *Microstabiliteit*	37,1	20,2	16,9	0,0	0,0
STBK *Bekledingen:*					
Steenzettingen:	1,9	1,6	0,0	0,3	0,0
Grasmat:	26,4	3,8	0,0	22,6	0,0
STVL *Voorland:*					
AF Afschuiving	37,1	29,7	0,0	0,0	7,4
ZV Zettingsvloeiing	37,1	31,5	0,0	0,0	5,6
NWO *Niet Waterkerende Objecten:*					
Bebouwing					
leidingen	18,0	7,0	1,0	0,0	10,0
Bomen en overige begroeiing	31,2	0,0	16,6	8,9	5,8
overige niet-waterkerende objecten					
Kunstwerken*					
HT Hoogte	17,0	17,0	0,0	0,0	0,0
ST Stabiliteit en sterkte					
STCG *Constructie en grondlichaam*	17,0	6,0	7,0	2,0	2,0
STCO *Constructieonderdelen*	17,0	6,0	11,0	0,0	0,0
STPH *Piping en heave*	17,0	5,0	8,0	3,0	1,0
STVL *Voorland*	17,0	15,0	1,0	0,0	1,0
BS Betrouwbaarheid sluiting	17,0	14,0	0,0	1,0	2,0

***niet alle toetssporen zijn van toepassing op ieder kunstwerk; kunstwerken met score 'niet van toepassing' zijn opgeteld bij 'goed'**

Table 6-2: Test results the safety assessment 2005 of primary flood defenses in Dike Ring 22

Condition of the flood defense

The five-yearly test of the primary flood defenses has last been carried out for dike ring 22 in 2005. Summed up, 60% of the 37.93 km of flood defenses are safe, 14% has to be investigated further and 26% is not safe. No flood defense section was categorized at too low in height but in some cases sections had other shortcomings. The most frequent deficits were related to grass and trees on or along the flood defenses. A number of sections had problems with the macro-stability on the inner side of the dike as well as piping, both important failure mechanisms for a dike. Another major problem are the buildings along the flood defenses. The number of sections affected is relatively small but a majority of the buildings in water defenses were not categorized as sufficient. Of the 17 civil engineering works included in the defense system 8 were sufficiently safe, 5 have not been categorized yet and the remaining 4 are not safe (Water board Hollandse Delta 2005: pp. 15). Appendix 9.5 gives an overview of measures proposed by the water board Hollandse Delta.

Present policy on flood defenses

At the time of writing (March 2010) the results of the third safety assessment of the primary water defenses are being evaluated. The reaction to the results of the previous round in 2005 is being included in the concept plans for dike improvement, see Appendix 9.5. The sections where dike reinforcement will probably be carried out have been indicated. As it has been opted for improving the existing dikes, ways are being sought to strengthen them as much as possible given the financial criteria imposed by regulation (Waterschap Hollandse Delta).

The Voorstraat remains in a delicate state. In 2005 this flood defense has been approved narrowly by taking into account the flood panels with which the doors are closed in case of flooding. For 2010 no final judgment has been made yet. Due to the historical city being situated on the sea dike, it would be major investment to fundamentally solve the problem of the Voorstraat. The most likely option would be to erect a new flood defense along the river shores. But, as described above, on national level a number of plans are being discussed which would ultimately lower the design water level at Dordrecht substantially. Therefore the informal strategy as of March 2010 is to wait for at least another testing round hoping to get more certainty about these regional developments. Until then the Voorstraat will be kept in its present state adjusting the flood protection minimally to fulfill the safety standards (Waterschap Hollandse Delta).

Regarding the historical compartmentalization dikes Dordrecht has been indicated as a dike ring where further study would be useful. On one hand Dordrecht is a very small urbanized dike ring so that the effect of compartmentalization is highly questionable. On the other hand the form of the dike ring and most importantly the existence of compartmentalization dikes provide good conditions to realize a modern compartmentalization strategy. The fact that city and rural area are divided by these old secondary dikes is beneficial as well and corresponds well to the call of damage reduction based on the high level of expected damage in Dordrecht (Asselman *et al.* 2008: 30). Weighing these arguments the water board Hollandse Delta has decided to maintain the old compartmentalization dikes in their present state until a decision has been made on the policy or until the province of Zuid Holland has issued norms for regional flood defenses (Waterschap Hollandse Delta).

6.2.5 Flood risk

The maps below from the Netherlands Environmental Assessment Agency [Planbureau voor de Leefomgeving (PBL)] indicate that flood risk is a salient issue in Dordrecht (Figure 6-8). The flood characteristics based on the level and velocity of inundation are rather severe in most parts of the dike ring. This results into a relatively high flood risk. Considering the inundation depth the same can be stated for economic damage. As a first observation it is interesting to note that there are clearly some spots where the local risk exceeds the norm that is applied in industry and thought to be applicable to flood safety as well (10^{-6} yr^{-1}). A rather big hotspot with high local risk is the industrial quarter Dordtse Kil in the West of the dike ring. But the vast majority of the city does have a risk lower than 10^{-6}. In Chapter 2.5 it was explained that the Netherlands do not have national standards regarding the local risk. But according to the standards of industry, new housing projects should only be developed in areas with a flood risk lower than than 10^{-5} $yr^{-1.}$ In Dordrecht half of the city has a risk higher than 10^{-5} yr^{-1}. This should be a major concern when undertaking restructuring projects such as the Wielwijk.

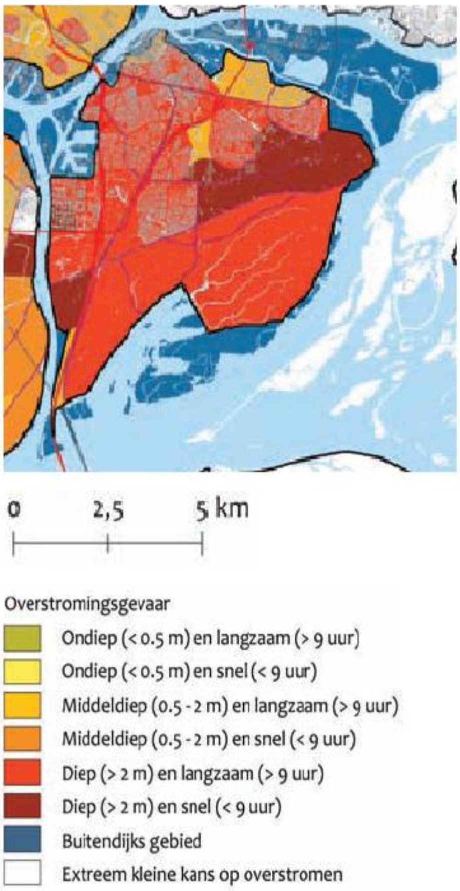


Figure 6-8: Indication of flood characteristics on the Isle of Dordt, probability of flooding 1/2,000 per year. (Source: Planbureau voor de Leefomgeving)

The flood risk conditions are a consequence of certain characteristics of dike ring 22. First of all, with only 4916 ha it is a very small dike ring with the characteristics of a bath tub (as compared to a plane sloping in downstream direction). As a result 100% of the dike ring area would probably flood in the case of a major dike failure as for example at *Kop van 't land* at the very Eastern tip of the dike ring (Asselman *et al.* 2008: 21, 117ff.). According to criteria proposed by Klijn and de Grave, Dordrecht is worth attention on national level as well. Dordrecht's dike ring is among the 15 dike rings where the expected damage caused by flooding would exceed 1% of the Dutch GDP (> 7 billion Euros in 2020). As a comparison, the total economic damage of the flood in 1953 added up to 6% of the GDP at that time. Another relevant fact is that it is expected that 100,000 people in dike ring 22 would be affected by a flood with the maximum number of victims exceeding 100 fatalities (Klijn, de Grave 2008: 7ff.).

6.3 The Model

In the following it will be described how Multilayered Safety has been modeled in the case study of Dordrecht. Furthermore, an introduction to the computational model used for this case study will be given and the input explained.

This case study will concentrate on the area inside dike ring 22. Areas outside the dike ring are not considered.

6.3.1 Multilayered Safety measures

In Chapter 3.5 MLS was given a theoretical basis and families of measures were derived. As already done in the hypothetical case study, MLS was modeled using these families. An overview is given in Figure 6-9.

Having introduced which MLS measures will be modeled in the Dordrecht case, Table 6-3 shows the way in which they were schematized. This is followed by an overview of the assumed investment costs of each measure.

Modeling Multilayer Safety in Dike Ring 22 – Eiland van Dordrecht

Way of functioning theoretically	Way of functioning physically	Strategy No.	Prevention	Spatial Solutions	Crisis Management
Reduce hazard source	*Prevent extreme amounts of water in system*	3	*Retain excessive discharge:* 1-3: Decrease probability of occurrence P_{exc}=1/20.000		
	Relief extreme hydraulic situation	4	*Relief hydraulic load:* Not modeled		
Reduce exposure	*Prevent that objects/people are in the dangerous area*	5		*Re-consider location:* Not modeled	*Preventive Evacuation:* 3-5a: Evacuate 15% of Wielwijk 3-5b: Evacuate 80% of Wielwijk 3-5c: Evacuate 15% of DR 22 3-5d: Evacuate 15% of DR22 and 80% of Wielwijk
	Reduce number of affected by erecting barrier between water masses and vulnerable people/objects	6	*Flood defenses:* existing: dike P_{flood}=1/2000 *Flood defenses:* 1-6a: Heighten dike P_{flood}=1/20.000 *1-6b: Lower dike P_{flood}=1/200*	*Comportm. dikes:* **Existing but not officially part of flood defense, crest height 2-4m NAP** *Compartmentalization:* 2-6: Heighten and strengthen compartmentalization dike (see Figure 6-11)	*Temporary flood defenses:* 3-6: strengthen primary dike with sand bags: P_{flood}=1/2.500
	Decrease degree by which objects are effected	7	*Flood defenses allowing overflow or controlled inlet:* 1-7: Ease flood characteristics -> lower inundation depth by 1m in Wielwijk (same like 2-7a)	*Elevate:* 2-7a: Buildings Wielwijk on 1m pillars 2-7b: Wielwijk on terp of 0.5m 2-7c: Wielwijk on terp of 1.0m	
Reduce vulnerability	*Prevent damage from occurring among exposed*	8		*Flood-proofing:* Not modeled, similar to 2-7a	*Self-reliance:* 3-8: Preparation and Warning in Wielwijk reduces damage by 10%
	Reduce occurring damage among exposed	9			*Emergency relief & Rescuing* not modelled

Figure 6-9 Modelling MLS in the Dike Ring of Dordrecht

Table 6-3: Practicalities of modeling MLS in Dike Ring 22

Practicalities of modeling MLS measures in Dike Ring 22 The numbers of the measures are derived as follows: (i-j) i = number of MLS layer j = number of strategy				
Measure No.	Family of measure	Description		Scale of application
Layer 1: Prevention				
1-3	Retain excessive discharge*	Reduce probability of occurrence hazard source	P_{occ}= 1/2,000 -> 1/20,000	*applied at delta scale
1-6a	Flood defenses*	Heighten dike by decimating height	P_{flood}= 1/2,000 -> 1/20,000	* applied to existing dike ring
1-6c	Flood defenses*	Setting a lower norm for dikes	P_{flood}= 1/2,000 -> 1/200	* applied to existing dike ring
1-7	Flood defenses allowing overflow*	Ease flood characteristics	Δh = -1m	* applied to existing dike ring
Layer 2: Spatial Solutions				
2-6	Compartmentalization	Heighten compartim. dike: Zeedijk and Zuiderdijk (see Figure 6-12)	The existing dike is assumed to not break. The layout is chosen to minimize the effect of the most severe scenario at Kop van t Land.	
2-7a	Elevate using poles	New buildings of poles of 1m	Δh = -1m*	*Only buildings in **Wielwijk** are elevated.
2-7b	Elevate by 0.5m with terp	Build new houses on terp of 0.5m	Ground level grid heightened by 0.5m*	*Only buildings in **Wielwijk** are elevated.
2-7c	Elevate by 1.0m with terp	Build new houses on terp of 1.0m	Ground level grid heightened by 1.0m*	*Only buildings in **Wielwijk** are elevated.
Layer 3: Crisis Management				
3-5a	Preventive Evacuation	Evacuate 15% inside Wielwijk	Ef = 0 -> 0.15*	*Only people inside the **Wielwijk** are evacuated.
3-5b	Preventive Evacuation	Evacuate 80% inside Wielwijk		*Only people inside the **Wielwijk** are evacuated.
3-5c	Preventive Evacuation	Evacuate 15% inside Dike Ring 22	Ef = 0 -> 0.15	*People in the entire **dike ring** are evacuated.
3-5d	Preventive Evacuation	Evacuate 15% inside Dike Ring 22 and 80% in Wielwijk	Ef = 0 -> 0.15° & Ef = 0 -> 0.80*	*People in the **Wielwijk** °People in the entire **dike ring.**
3-6	Temporary flood defenses	Strengthen primary dike with sand bags*	P_{flood}= 1/2000 -> 1/2500	* applied to existing dike
3-8	Self-reliance	Prepare and warn people in new neighborhood	Reduce damage by 10% $Risk_{self-reliance}$=0.9*$Risk_{Total}$	*People in the entire **dike ring** are warned/prepared.

Compartmentalization needs some extra explanation. As said before there do exist compartmentalization dikes in Dike Ring 22 but they are not officially considered part of the flood protection system. In the computational model it is assumed that the compartmentalization dikes break as soon as the water level exceeds their crest height, just as it is the case with primary dikes. Thus the compartmentalization dikes have been considered in a deterministic manner.

Figure 6-11: Ground level in Dike Ring 22 nowadays

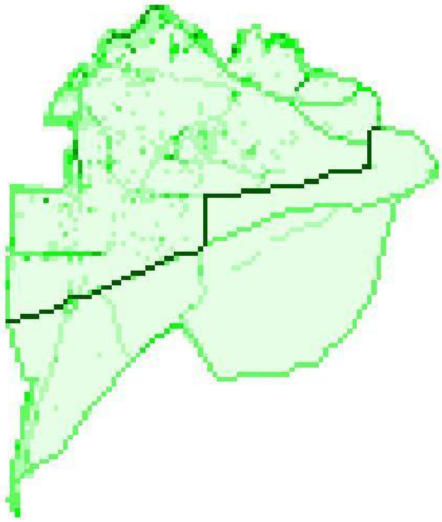


Figure 6-12: Ground level nowadays with heightened compartmentalization dike pasted into it

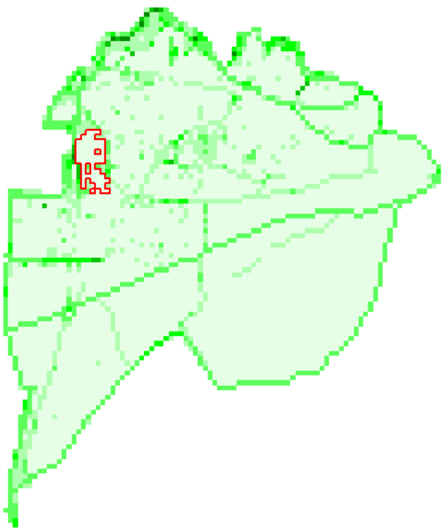
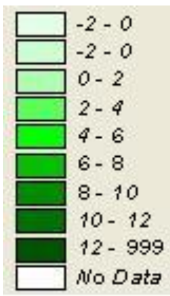


Figure 6-10: Indication of Wielwijk in computational model



When modeling the flood management measure of the compartmentalization dike the dikes are raised to a crest height that will certainly not be reached by the water level, e.g. 50m. This number is of course not realistic. When actually being implemented in reality the crest height of those dikes will have to be derived from the water levels being reached and should be in the same range as the primary flood defenses. After all it is assumed that primary flood defenses will only and completely fail if the external water level reaches their crest height. Thus compartmentalization dikes having a lower standard are theoretically not useful. In practice a breached dike still keeps a lot of water back and reduces the extent of the flood.

Of course different compartmentalization dikes can be heightened. The breach scenario at Kop van t Land at the very Eastern tip of the dike ring is by far the most damaging. Thus the compartmentalization dike has been heightened in a way that diverges the water in such a scenario to the more rural area away from the city (see Figure 6-12).

6.3.2 Modeling Wielwijk

The Wielwijk that serves as the neighborhood where the MLS measures are going to be tried out is represented in the model by 56 grid cells. These are the lower 56 ha of the 59 ha the Wielwijk consists of. Those grid cells are indicated in Figure 6-10. The Wielwijk is an existing neighborhood that is being restructures. Many of the measures from MLS layer 2, Spatial Solutions, are impossible to use for existing buildings. Nonetheless, it has been assumed for this case study that all Spatial Solutions can be implemented for existing buildings.

6.3.3 Investment costs

Table 6-4 shows the investment costs that have been assumed for the measures as described in Table 6-3. These costs are the total amount of money need to implement the respective measures, regardless of its geographical scale of implementation. Thus, nothing is said about who and how many people/households have to come up for the costs. Additionally it has been assumed that the Wielwijk is going to be build new instead of being restructured. Most Spatial Solutions are not applicable for existing buildings.

Table 6-4: Investment costs of MLS measures in Dike Ring 22

Measure	Description	Costs	Source
1-3: Retain excessive discharge		200 million €	KBA Ruimte voor de Rivier [Ebregt 2005: 43]
1-6a: Higher Flood defenses	Heighten dike by 0.6 m over 37 km	90 million €	Expert judgment HKV
1-6c: Lower Flood defenses	Lowering dike	NA	
1-7: Flood defenses allowing overflow	Widen dike over 37km	110 million €	estimation
2-6: Compartmentalization*	Heighten 10 km of compart. Dike	90 million €	Expert judgment HKV *see Figure 6-12
2-7a: Elevate by 1m using poles	Houses on poles: lengthen foundation columns by 1m. , 5,000€ per house, 13700 inhabitants -> ca. 4000 houses	20 million €	UfM (Geronisus *et al*. 2008 :74)
2-7b: Elevate by 0.5m using terp	0.56 km^2 -> 280,000m^2 sand, 15€ per m^2	4.2 million €	Expert judgment HKV
2-7c: Elevate by 1m using terp	0.56 km^2 -> 560,000m^2 sand, 15€ per m^2	8.4 million €	Expert judgment HKV
3-5a: Preventive Evacuation 15% in Wielwijk	2000 people, 1 mln € per 100 persons for refuge shelter	20 million €	Expert judgment HKV
3-5b: Preventive Evacuation 80% in Wielwijk	10000 people, 1 mln € per 100 persons for refuge shelter	100 million €	Expert judgment HKV
3-5c: Preventive Evacuation 15% in Dike ring 22	16500 people, 1 mln € per 100 persons for refuge shelter	165 million €	Expert judgment HKV
3-5d: Preventive Evacuation 15% in Dike Ring 22 + 80% in Wielwijk	25400 people, 1 mln € per 100 persons for refuge shelter	245 million €	Expert judgment HKV
3-6: Temporary flood defenses	20,000€ per year, for 50 yrs, interest rate 2%	3.7 million €	Expert judgment HKV
3-8: Self-reliance	0,5 million € per year, for 50 yrs, interest rate 2%	12.5 million €	Expert judgment HKV

6.3.4 Computational model

The computational model used for this case study is the same as used by the government projects for e.g. the FLORIS project [VNK]. It includes a 1D model of the lower parts of the rivers Maas, Waal en Rijn and a 2D model of dike ring 22. Both models are realized in a Sobek 1D2D model. This model calculates the Water Level WL, the inundation depth, the velocity and rise rate. The output is in a grid format. Each grid cell measures 100x100m. This means that in terms of accuracy and detail the model by far does not tell anything about individual buildings locations etc.

Originally the model included 13 scenarios. From these scenarios three representative ones were selected for this study to limit the computation time.

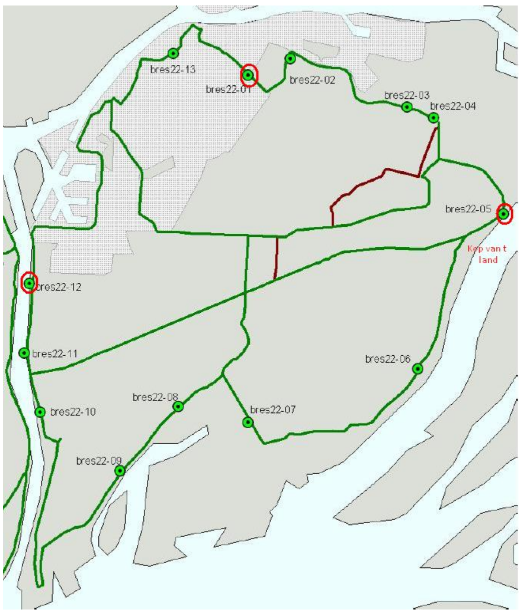


Figure 6-13: Scenarios in the Sobek Model (Source: Piek 2007: 33)

For the boundary conditions used, please see Appendix 9.6. It was assumed that the three chosen scenarios have the same probability of occurrence, adding up to 1/2,000 per year.

The output of the Sobek model is then used as input for the damage model in HIS-SSM. This model calculates the number of affected people and objects, the number of fatalities and the economic damage. The outputs are grids as well.

The application *Risicotool* was used to combine probabilities and damage to derive FN- en FS-curve and maps showing the different dimensions of risks.

6.3.5 Representativeness of the model

A model is a schematization of the reality. Therefore, some restrains have to be dealt with. First of all, not the entire FN- and FS curves can be derived from the results because only a limited number of boundary conditions were calculated. The effect of the different MLS measures was only computed for one boundary condition (with the probability of 1/2000 per year). Since the risk reduction shows a linear correlation with the water level, the results nonetheless give a good indication about the effect of those flood management measures.

To save computation time only 3 of the 12 flooding scenarios have been used. As the objective of this study is to understand the effect of flood management measures in urban areas, dike breaches that mainly flood the rural Southern half of the dike ring have not been included. Furthermore, it was assumed that the three scenarios included have the same probability of occurrence, adding up to 1/2,000 per year. If 13 scenarios would have been included the probability of each scenario would be much lower since they would have to add up to 1/2,000 per year as well. Furthermore, in reality those dike breaches do not have the same probability of occurrence. Additionally, multiple dike breaches have not been considered. Thus, the calculated risks have to be understood as an indication. Nonetheless those outcomes are suited to understand the effect of flood management measures and examine the risk at different location in relative terms.

The Wielwijk is an existing neighborhood so that many Spatial Solutions from MLS layer 2 cannot be implemented there in reality. E.g. it is extremely expensive if not impossible to elevate existing buildings (measure 2-7). However, in this case study this has been ignored. In terms of implementing measures, it was assumed that the Wielwijk is not restructuring project but new housing development.

The investment costs depend very much on the individual case. The estimates made in this study are thought to represent an average and are only meant for areas with family houses. Industrial or commercial areas have been neglected. Nonetheless the computational model by default also calculates the damage to industrial buildings etc. Thus, in this study those types of buildings are treated like family houses.

6.4 Results

In the following paragraphs the calculation results are described. First the flood risk of the reference case without any flood management measures taken is presented. Afterwards the risk reduction of the individual flood management measures is quantified and visualized. This is done per Multilayered Safety [MLS] layer. Along the way the assumptions made for the computation is mentioned for each measure. Furthermore, it is shown which measures are probability- respectively loss-reducing.

6.4.1 Reference

The fictive case study has two reference cases. The analysis of the reference case is done for the entire dike ring and for the Wielwijk separately.

First the flood characteristics of each of the three scenarios are shown and discussed. This is followed by visualization of the Economic Risk (FS-curve), Societal Risk (FN-curve) and Individual Risk (map). The overall-risk is given in Table 6-7.

Later the effect of the flood management measures on the risk will be compared to this reference case.

Probability scenarios

It was assumed that the three chosen scenarios have the same probability of occurrence, adding up to 1/2,000 per year. Thus, the probability of each scenario is 1/6,000 per year.

Flood characteristics

The three scenarios are assumed to appear with the same probability adding up to P=1/2,000 per year in total. Analysis of the three scenarios shows that a breach at *Kop van 't land* (Scenario 5) is most severe. It floods the entire dike ring with a large inundation depth. A breach as in Scenario 1 does not affect the Wielwijk. Thus this scenario does not add to the flood risk in the Wielwijk. Scenario 12 shows well that compartmentalization dikes do not always influence a flood beneficially. In that scenario the rural countryside south of the compartmentalization dike is kept dry and the intruding water is forced to stay inside the city. Note that this compartmentalization dike is officially not in use.

Table 6-5: Maps showing inundation depth for each of the three flooding scenarios. NOTE: The legends of the maps are different!

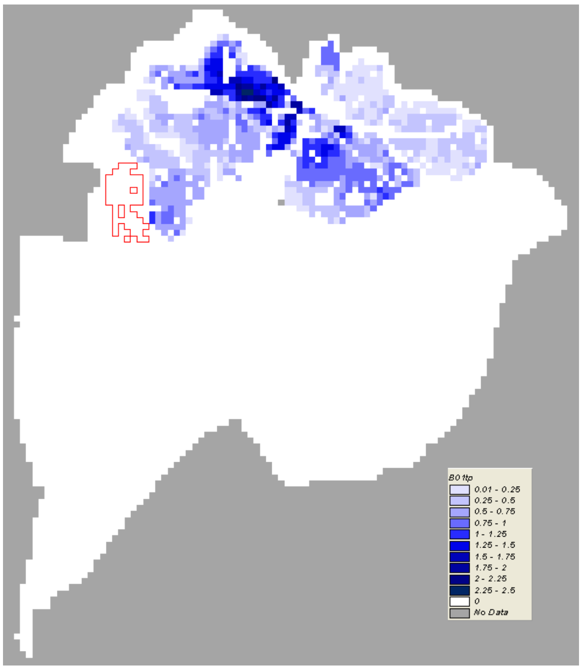


Figure 6-14: Inundation depth Scenario 1

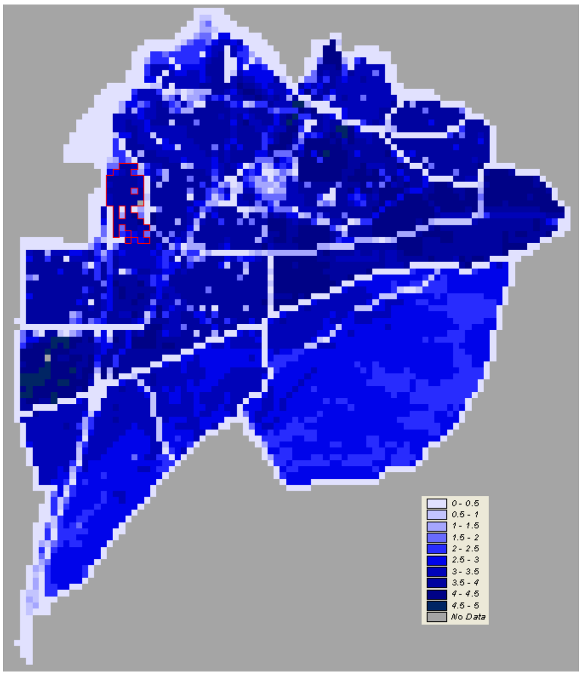


Figure 6-15: Inundation depth Scenario 5, NOTE: different legend scale.

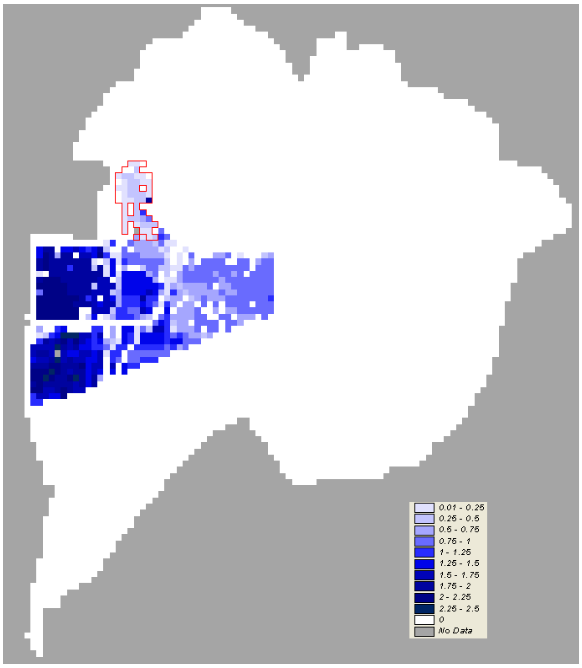


Figure 6-16: Inundation depth Scenario 12

Table 6-6: Loss in each flooding scenario

	Scenario 1	Scenario 5	Scenario 12
Probability	1/3 *1/2,000	1/3 *1/2,000	1/3 *1/2,000
Economic damage in **DIKE RING** [€]	1,150 mln	8,835 mln	680 mln
Fatalities in **DIKE RING**[#]	92	5,041	38
Economic damage in **WIELWIJK**[€]	0	368 mln	51 mln
Fatalities in **WIELWIJK**[#]	0	97	4

Risk

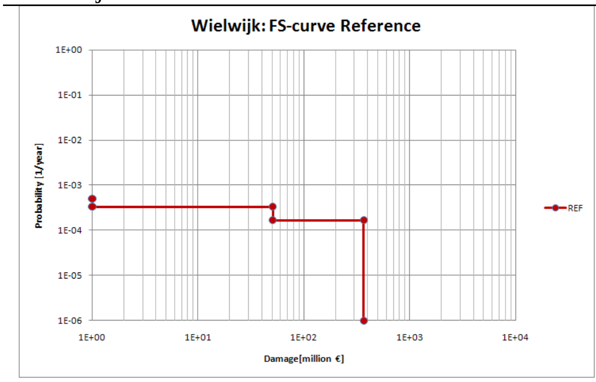
The FN- and FS-curves reflect the observations on the flood characteristics above. All scenarios are assumed to have the same probability of occurrence. The curves of the Wielwijk show one 'step' less. This is due to the fact that Scenario 1 is not relevant for the flood risk in the Wielwijk. But of course that scenario does add to the flood risk in the dike ring. Table 6-7 gives the total risk of the dike ring and neighborhood.

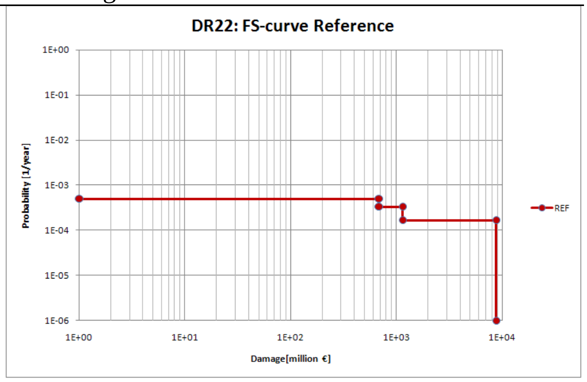
Table 6-7: Flood risk for reference case

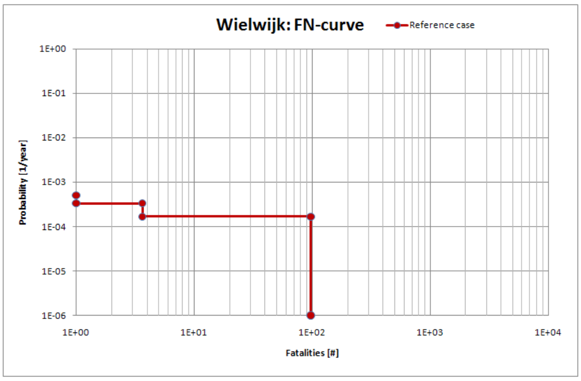
	Economic risk [€/yr]	Expect. Fatal.[#/yr]
Dike Ring 22	89,000,000	0.862
Wielwijk	70,000	0.017

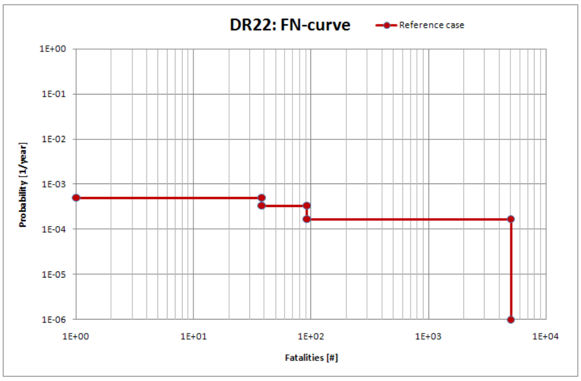
Table 6-8: FN-/FS-curve for reference case

Wielwijk	Dike Ring 22









The existing dike ring is without doubt necessary to make human settlement in large parts of the dike ring possible. The ground level lies in the range of (-0.5m) – (+0.5m) NAP with the majority of the city being below sea level, see Figure 6-17. The location of the city has been influenced very much by the location of the compartmentalization dikes (compare Chapter 6.2.2).Interestingly the rural area mainly covers higher grounds than the city.

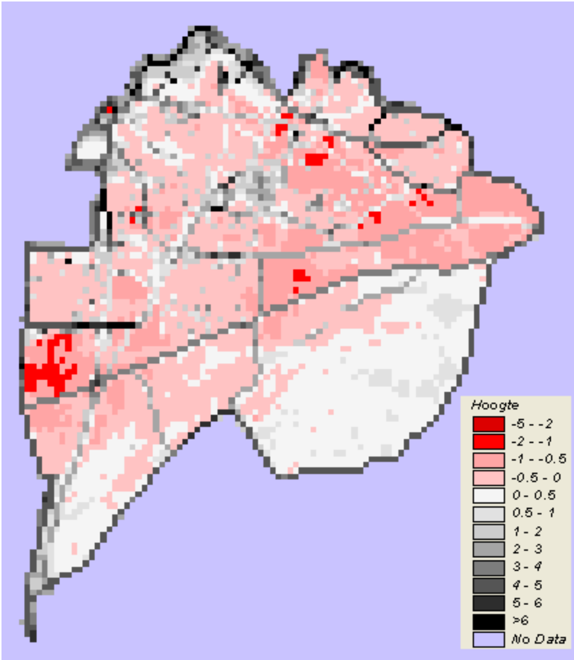


Figure 6-17: Ground level Dike Ring 22

Figure 6-18 shows a map with the Individual (Local) Risk (excluding evacuation). This map makes clear that the safety inside a dike ring differs. Remarkably, the IR is larger in the inhabited parts of the dike ring than in the rural parts. Furthermore, a small number of locations seem to have a larger individual risk than the majority of the dike ring. Those spots are mostly rather small in the range of 5ha. With a surface of a few dozen ha the industry park Dordtse Kil in the very West of the dike ring is by far the largest spot with an increased Individual Risk.

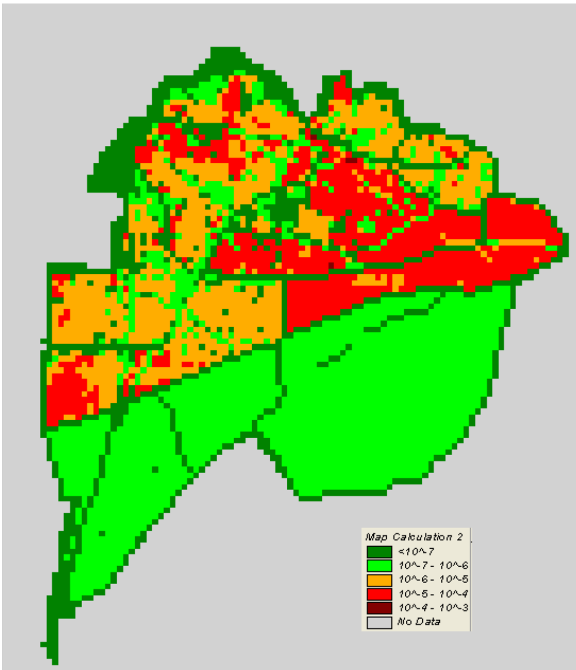


Figure 6-18: Individual Risk in Dike Ring 22

6.4.2 Prevention

This section presents the calculation results for all flood management measures of the first MLS layer Prevention. Prevention includes the measures re-distributing the water masses over the water system (e.g. Ruimte voor de Rivier, 1-3), heightening the dike (1-6a) and overflow-resistant flood defenses (1-7) (compare Chapter 6.3.2). Furthermore it has been modeled to lower the dike ring (1-6c).

Table 6-9: Risk with Prevention measures

	Economic risk [€/yr]	Expect. Fatal.[#/yr]
Dike Ring 22	89,000,000	0.862
1-3	9,500,000	0.0914
1-6a	9,500,000	0.0914
1-6c	693,000,000	2.700
1-7	49,500,000	0.245

	Economic risk [€/yr]	Expect. Fatal.[#/yr]
Wielwijk	70,000	0.017
1-3	9,000	0.002
1-6a	9,000	0.002
1-6c	505,000	0.072
1-7	45,000	0.008

Prevention is considered to be probability-reducing. Only the overflow-resistant flood defenses (1-7) are an exception and modeled as loss-reducing. All measures of MLS Layer 1 are applied at delta (1-3) or polder scale (1-6a, 1-7).

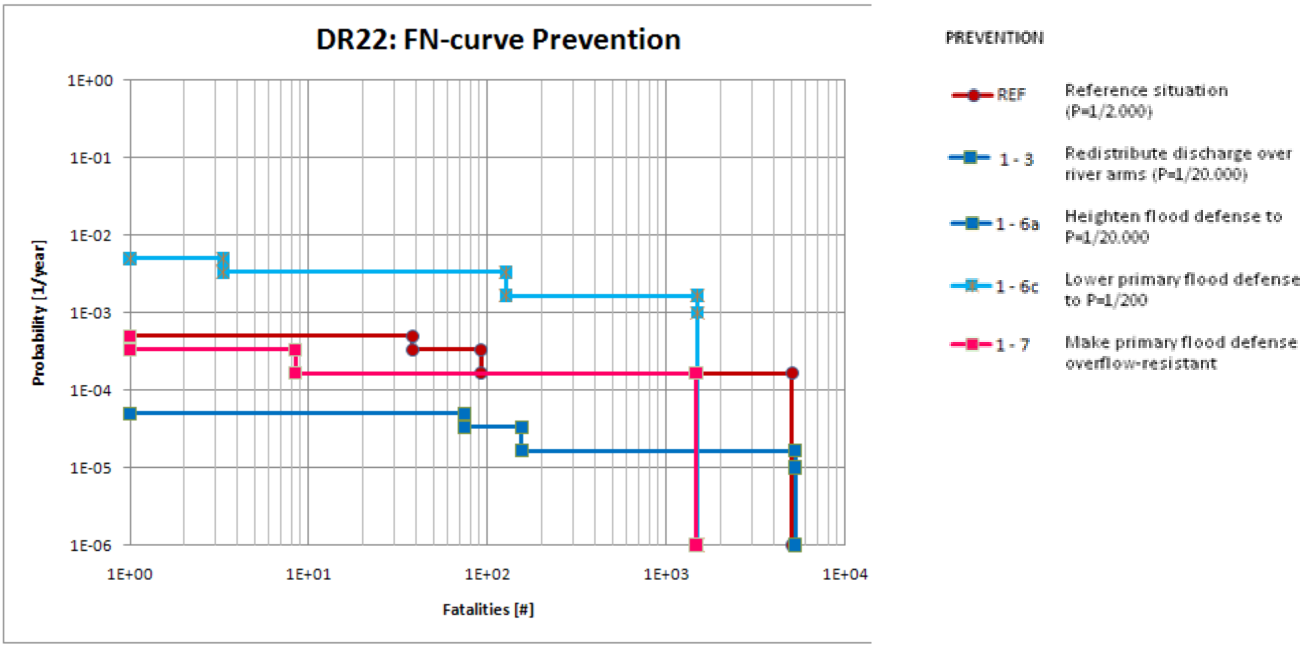
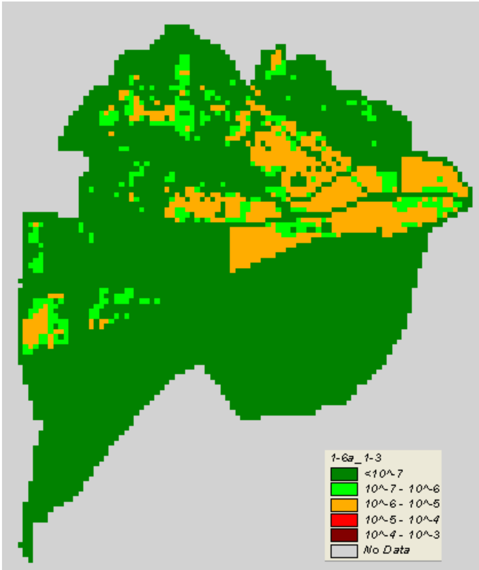
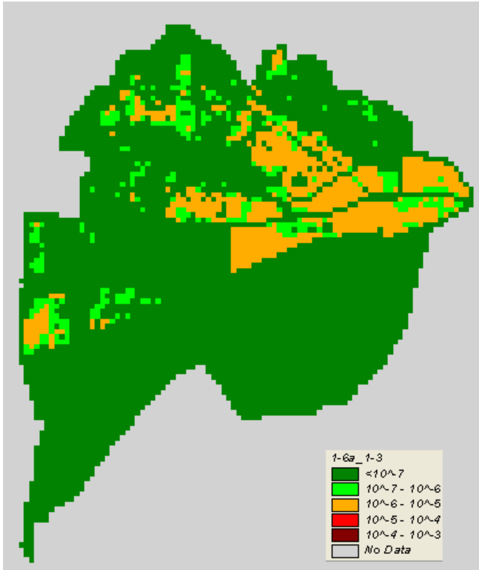


Figure 6-19: FN-curve for Dike Ring 22 - Prevention measures

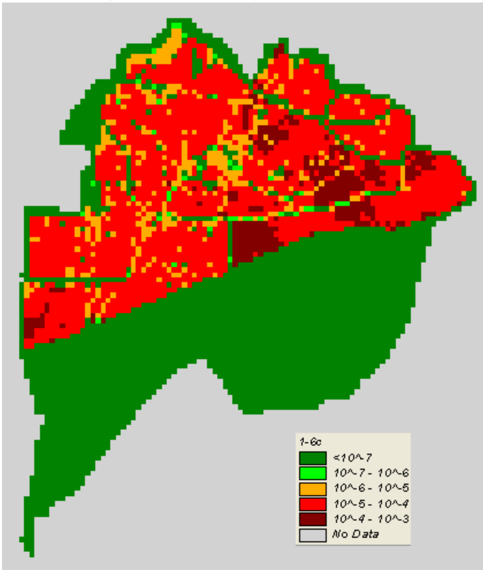
1-3 = 1-6a



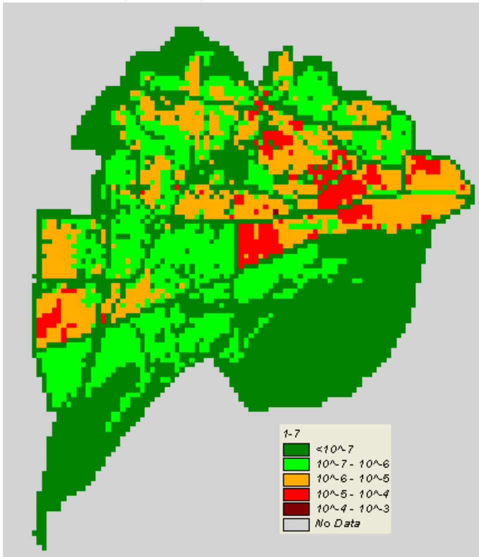
Giving water more space; measure 1-3



Heightening dike; measure 1-6a



Lowering dike; measure 1-6c



Overflow-resistant prim. flood def.; measure 1-7

Figure 6-20: Individual Risk (excl. evacuation) - Prevention measures

The FN-curve and the maps showing the Individual Risk both indicate that the measures giving the river more space (1-3) and heightening the primary dike (1-6a) have the same effect in terms of risk reduction. This is logical because they both lowered the probability of flooding to P=1/20,000 (1/yr.). Those two measures do differ in terms of investment costs and thus cost-efficiency.

Measure 1-6c, lowering the dike, obviously increases the flood risk. FN-/FS-curves and Individual Risk-map reflect that.

6.4.3 Spatial Solutions

This section presents the calculation results for all flood management measures of the second MLS layer Spatial Solutions. Spatial Solutions includes the measures compartmentalization (2-6), elevating the buildings in the Wielwijk with poles (2-7a) respectively terps (2-7b/c) (compare Chapter 6.3.2).

Spatial Solutions are considered to be loss-reducing. Only compartmentalization (2-6) is not purely loss-reducing. This is discussed below. All measures of MLS Layer 2 are applied at neighborhood scale.

Table 6-10: Flood risk with Spatial Solution measures

	Economic risk [€/yr]	Expect. Fatal.[#/yr]
Dike Ring 22	89,000,000	0.862
2-6	16,500,000	0.025
2-7a	87,500,000	0.853
2-7b	88,000,000	0.852
2-7c	87,500,000	0.850

	Economic risk [€/yr]	Expect. Fatal.[#/yr]
Wielwijk	70,000	0.0170
2-6	9,000	0.001
2-7a	45,000	0.008
2-7b	53,000	0.008
2-7c	44,000	0.006

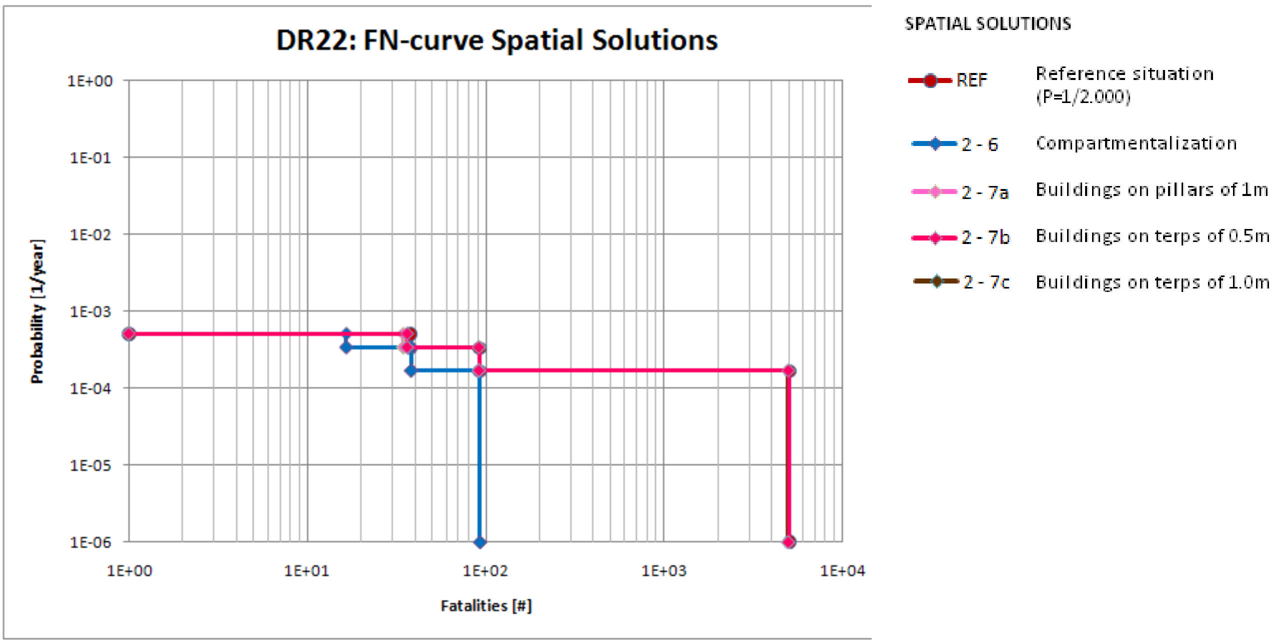
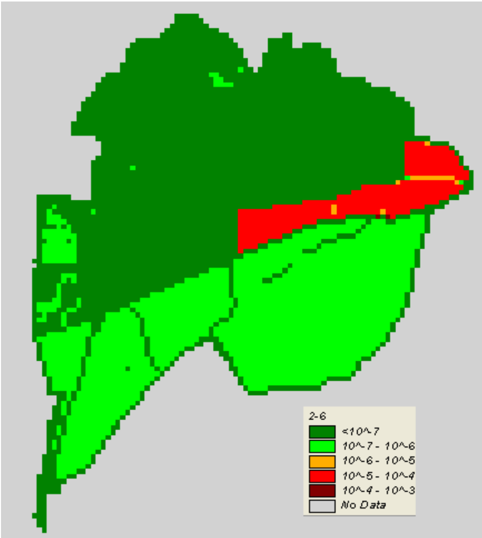
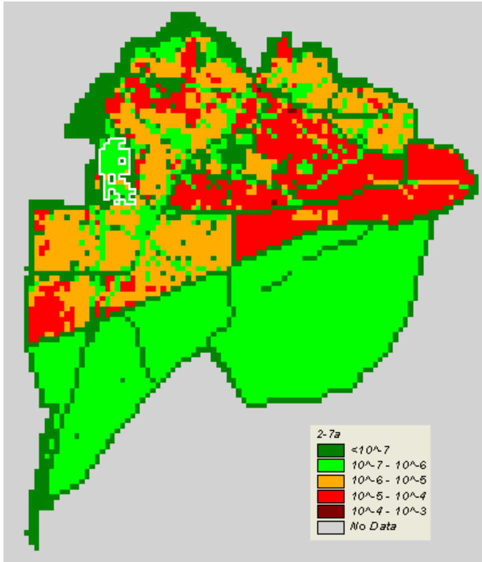


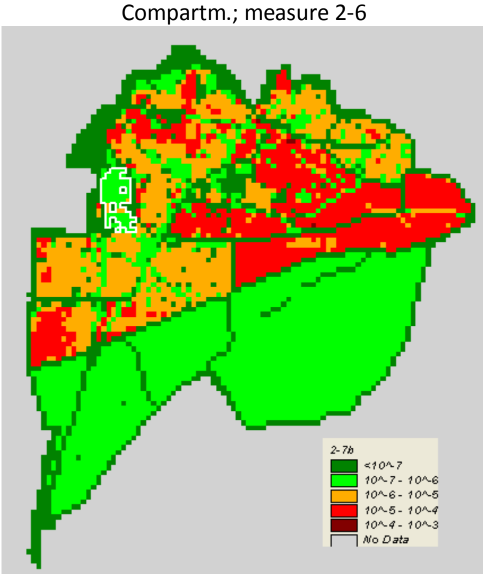
Figure 6-21: FN-curve for Dike Ring 22 - Spatial Solution measures. NOTE: The differences between the 2-7 measures are so small that they are barely visible in this diagram.



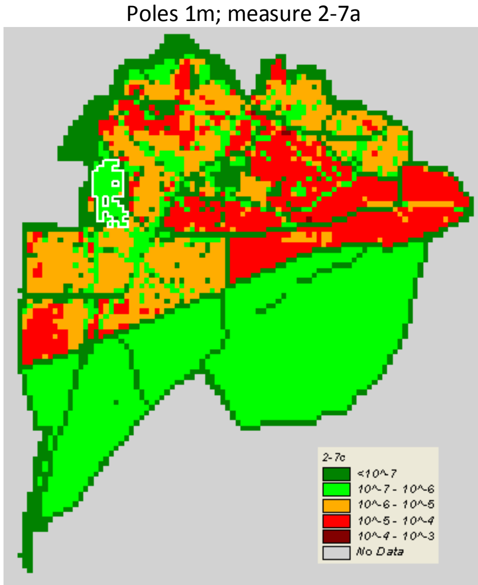
Compartm.; measure 2-6



Poles 1m; measure 2-7a



Terp 0.5m; measure 2-7b



Terp 1.0m¸ measure 2-7c

Figure 6-22: Individual Risk (excl. evacuation) - Spatial Solution measures

The maps showing the Individual risk reflect that the elevation measures (2-7a-c) are only applied in the Wielwijk (marked with a white border). The flood risk decreases there. In the rest of the dike ring it stays unchanged.

A couple of comments on the modeling of the measures are given in the following.

- The *compartmentalization dike (2-6)* is assumed to not breach until it overflows. Such a compartmentalization dike would have to be massive because the inundation depth in front of it exceeds 4m. Its strength would probably have to almost equal the primary flood defenses.

6.4.4 Crisis Management

This section presents the calculation results for all flood management measures of the third MLS layer Crisis Management. Crisis Management includes the measures evacuation (3-5a/b/c/d), sand bags on the primary dikes (3-6) and preparation and warning (3-8) (compare Chapter 6.3.2).

Table 6-11: Flood risk with Crisis Management measures

	Economic risk [€/yr]	Expect. Fatal.[#/yr]
Dike Ring 22	89,000,000	0.862
3-5a	89,000,000	0.859
3-5b	89,000,000	0.848
3-5c	89,000,000	0.733
3-5d	89,000,000	0.722
3-6	71,000,000	0.690
3-8	80,100,000	0.776

	Economic risk [€/yr]	Expect. Fatal.[#/yr]
Wielwijk	70,000	0.017
3-5a	70,000	0.014
3-5b	70,000	0.003
3-5c	70,000	0.014
3-5d	70,000	0.003
3-6	56,000	0.014
3-8	63,000	0.015

Crisis Management is considered to be loss-reducing. Only sandbags (3-6) are not modeled as loss-reducing in this study. After all, they reinforce the primary flood defenses and therefore are seen as probability-reducing. All measures of MLS Layer 3 are applied at polder scale. For some of the evacuation scenarios the evacuation factor is higher for the neighborhood (see Chapter 6.3.2).

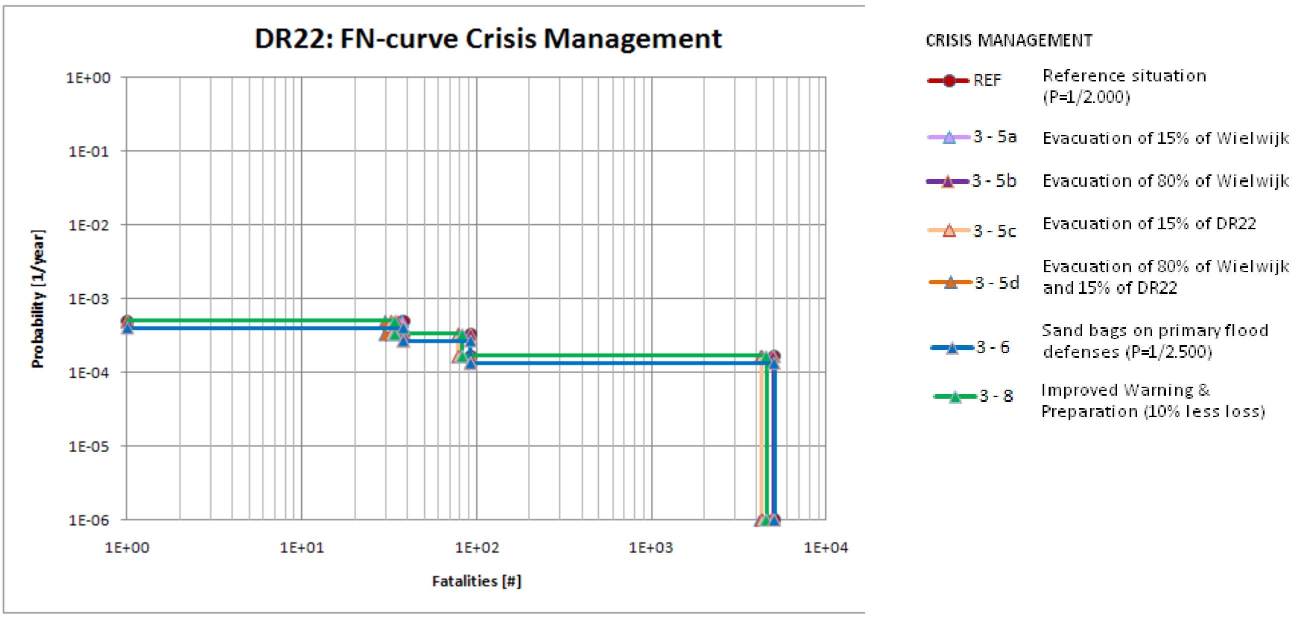
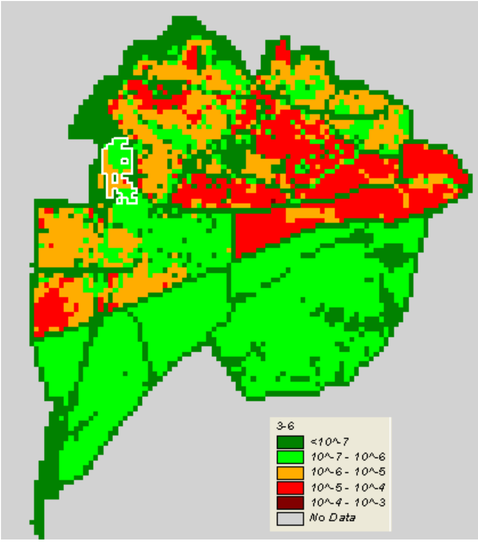
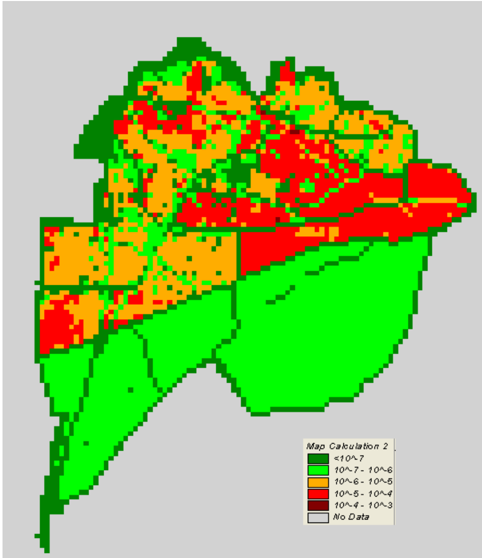


Figure 6-23: FN-curve for Dike Ring 22 - Crisis Management measures

The evacuation measures do not bring about a change in the Individual Risk. For those measures the original map of the IR (Figure 6-18) stays valid.



Sand bags; measure 3-6



Prep./Warn.; measure 3-8

Figure 6-24: Individual Risk (excl. evacuation) - Crisis Management measures

The maps showing the Individual Risk after implementing the evacuation measures have been omitted here. Those measures have no effect on the IR because the number of affected does not matter for that dimension of risk. The maps for the measures 'sand bags' (3-6) and preparation and warning (3-8) reflect the modest risk reduction by those measures.

All measures have only a small effect on the risk in the entire dike ring. This is due to the fact that most measures are applied at neighborhood scale. Only the sand bags are implemented on dike ring scale but only decrease the probability of flooding slightly. All measures have effect with all three breaching scenarios. The sand bags (3-6) lower the probability of each scenario whereas the other measures shift the FN/FS-curve to the left. Those latter measures decrease the damage of each scenario by the same percentage. There are a couple of comments more to be made:

- *Evacuation (3-5):* **Evacuation (3-5a, 3-5b) has no effect in the FS-curve** because it was assumed that only people are being evacuated and no material values. It also has no effect on the Individual Risk, as the number of people is not relevant for that dimension of risk.
- *Preparation & Warning (3-8)* were modeled to have the same effect on the risk for both inhabitants and material values.

6.5 Analysis

In Chapter 4 three crucial properties of MLS and the measures it consists of have been analyzed and discussed: (side-) effects, interaction and failure. The analysis of the first Case study (Chapter 5.7) extended the findings on (side-) effects and interaction. Furthermore, the cost-efficiency of MLS was examined. In the following, the results of the second Case study as introduced above will be used to deepen the analysis of those same three properties.

Before discussing (side-) effects, interaction and cost-efficiency in the following, a couple comments on the form of the analysis need to be given. The analyses are done for two different geographical units, namely the dike ring 22 and the neighborhood *Wielwijk* (compare Chapter 6.3.2). This has been done to show how important the choice of scale is for the outcome of the analysis. Furthermore, the three dimensions of risk as introduced in Chapter 2.2 are used to provide a comprehensive analysis of the risk reduction. It will be examined if there are differences in risk reduction with regard to Societal Risk (SR), Economic Risk (ER) and Individual Risk (IR).

6.5.1 Effects

Effects

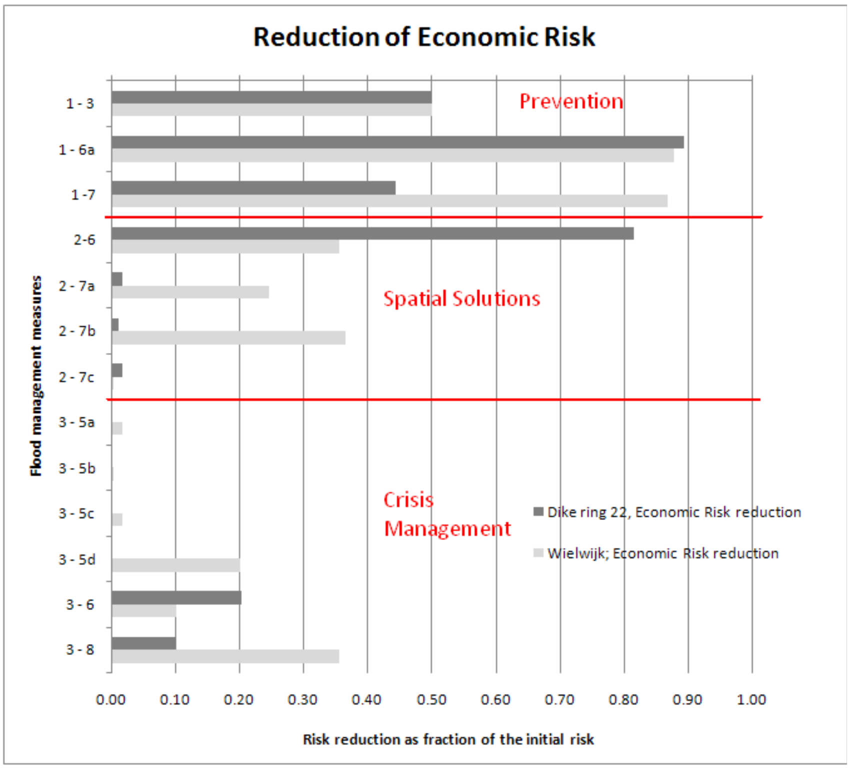
In Case study 1 it was observed that probability-reducing measures are suitable to reduce the overall risk. Loss-reducing measures turned out to have a higher potential to customize flood risk reduction to local conditions. This is caused by the fact that probability-reducing measures achieve the same percentage of risk reduction with respect to the initial risk for both dike ring and neighborhood respectively across the three dimensions of risk. This is not the case for loss-reducing measures (compare Chapter 5.7).

The second case study supports the findings from the first case study. Furthermore, the potential of customizing flood risk management to local circumstances is illustrated by the significant risk reduction due to compartmentalization in the second case study. Both issues are discussed in the following. First, the agreements between the two cases will be discussed. Second, the additional findings of the second case study will be described.

- *Agreements between case studies:*

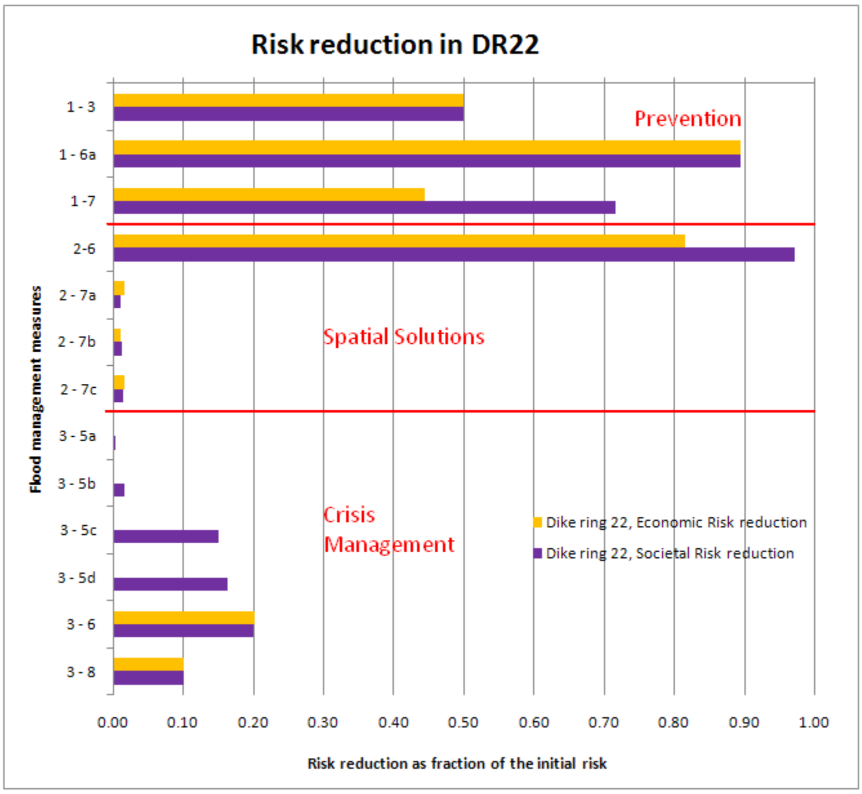
  Figure 6-25 shows that probability-reducing measures (1-3, 1-6a, 3-6) reduce the flood risk by the same percentage for both the dike ring and the neighborhood Wielwijk. This is due to the fact that the flood risk in both units of analysis depends equally much on the probability of flooding. Figure 6-25 indicates that this is not exactly true for heightening the dike, but this is due to rounding off-errors in the computational model.

  A similar observation can be done in terms of dimensions of risk. Since all dimensions of risk equally rely on the probability of flooding, the flood-reducing measures reduce all dimensions of risk by the same percentage of the individual risk. This is shown in Figure 6-26.



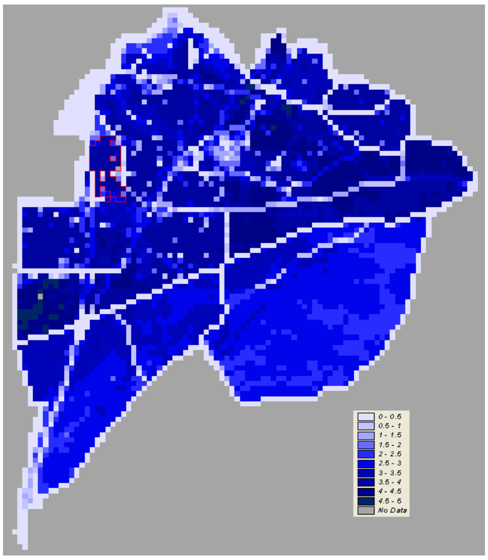
REF = reference case
1 - 3 = redistribute river discharge
1 - 6a = higher dikes (1/20,000)
1 - 7 = overflow-resistant dikes
2-6 = compartmentalization
2 - 7a = buildings on poles 1m
2 - 7b = terp 0.5m
2 - 7c = terp 1.0m
3 - 5a = evacuation Wielwijk 15%
3 - 5b = evacuation Wielwijk 80%
3 - 5c = evacuation DR 22 15%
3 - 5d = evacuation DR 22 15% & Wielwijk 80%
3 - 6 = sand bags
3 - 8 = preparation & warning
1 -6c = lower dike (1/200)

Figure 6-25: The reduction of the economic risk as a fraction of the initial risk shown for all flood management measures. Different to loss-reducing measures, the probability-reducing measures reduce the risk by the approximately same fraction for the Wielwijk and dike ring 22. The absolute risk reduction depends on the initial risk.

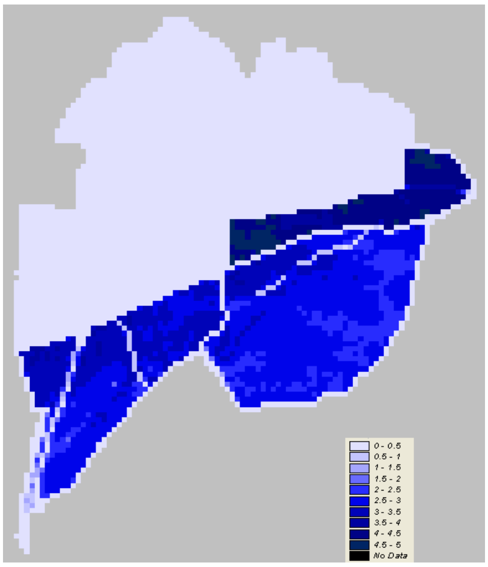


REF = reference case
1 - 3 = redistribute river discharge
1 - 6a = higher dikes (1/20,000)
1 - 7 = overflow-resistant dikes
2-6 = compartmentalization
2 - 7a = buildings on poles 1m
2 - 7b = terp 0.5m
2 - 7c = terp 1.0m
3 - 5a = evacuation Wielwijk 15%
3 - 5b = evacuation Wielwijk 80%
3 - 5c = evacuation DR 22 15%
3 - 5d = evacuation DR 22 15% & Wielwijk 80%
3 - 6 = sand bags
3 - 8 = preparation & warning
1 -6c = lower dike (1/200)

Figure 6-26: Risk reduction in dike ring 22 as a fraction of the initial risk, shown for all flood management measures and dimensions of risk. Different to loss-reducing measures, the probability-reducing measures reduce the risk by the same fraction for all three dimensions of risk. The absolute risk reduction depends on the initial flood risk.



Inundation depth **without** compartmentalization dike



Inundation depth **with** compartmentalization dike

Figure 6-27: Effect of compartmentalization dike (2-6) on flood characteristics

- *Additional findings*

Table 6-12: Loss-reduction by compartmentalization dike in flooding scenario 5

	Initial Scenario 5	Scenario 5 w/ compart.
Probability	1/3 *1/2,000	1/3 *1/2,000
Economic damage in **DIKE RING** [€]	8,835 mln	1,150 mln
Fatalities in **DIKE RING**[#]	5,041	92
Economic damage in **WIELWIJK**[€]	368 mln	0
Fatalities in **WIELWIJK**[#]	97	0

In Chapter 6.4 it was shown that compartmentalization (2-6) achieves a significant risk reduction in dike ring 22 and especially in the Wielwijk (see Table 6-12). **This very large drop in flood risk is due to the fact that the compartmentalization dike was customized to the worst of the three flooding scenarios, namely scenario 5**. In the breaching scenarios 1 and 12 this secondary dike has no effect. But in scenario 5 its effect is significant (see Figure 6-27). This is also reflected by the FN-curve (Figure 6-21). Since scenario 5 affected both Wielwijk and the dike ring most severe, the loss reduction achieved by the compartmentalization is very large (see Table 6-10). If Scenario 5 appeared with a lower probability (relative to the other scenarios), the risk reduction would be smaller in proportion.

In the case the compartmentalization dike only has effect on one scenario; the effect is shown as in Figure 6-27 and Table 6-12). It is concluded that **it can be of great effect to prioritize the reduction of the risk contribution of one scenario and to customize flood risk management accordingly.** However, this will not always be possible as it is in Dordrecht.

It is concluded that the second case study confirms the fact that loss-reducing measures provide more opportunities to tailor flood risk management to local conditions. Additionally, it

showed that setting priorities when customizing flood risk management can lead to significant drops of flood risk.

Side-effects

In the first case study, the side-effects of individual flood management measures with respect to the flood characteristics have been studied as well. There, it was shown that even large changes in flood characteristics due to the compartmentalization due not necessarily jeopardize the risk-reducing effect of that measure.

In the second case study it will be examined if this is also the case in Dordrecht. Furthermore, another flood management measure, elevation on terps (2-7), will be analyzed for its side-effects.

Compartmentalization (2-6) does have effect on the flood characteristics. In Scenario 5 it increases the inundation depth in the rural area by approximately 4cm. Only a small part of the more Northern half of the island is affected more severely. There the increase of inundation depth is close to 40cm (see Figure 6-28). The flood risk is not significantly increased by those higher inundation depths. This is due to the fact that in those areas the population density is very low.

This shows that negative interactions with the flood characteristics do not necessarily lead to an increase in flood risk. The overall risk reduction is thus not jeopardized.

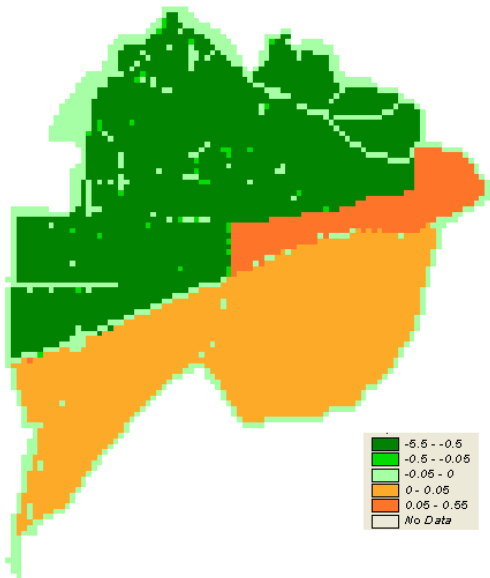


Figure 6-28: Change of flood characteristics in Scenario 5 due to compartmentalization. Δ>0: increase in inundation depth

*Elevating (2-*7) has been modeled in three different versions: on poles (2-7a) and on a higher and a lower terp (2-7b/c). This has been done to understand the magnitude with which the terp affects the flood characteristics. As mentioned in Chapter 4.2 changes in the flood characteristics influence the performance of other measures.

Analyzing the computed flood characteristics shows that a terp until 1m height increases the inundation depth by ca. 1cm in some parts of the surrounding (orange parts in Figure 6-29). The light green parts in Figure 6-29 indicate areas where the inundation depth decreases by ca. 1cm. This is also reflected in the calculated risks. The Economic Risk does not differ between using poles or a terp. Thus, **the side-effect of terps in terms of altering the flood characteristics is very small.**

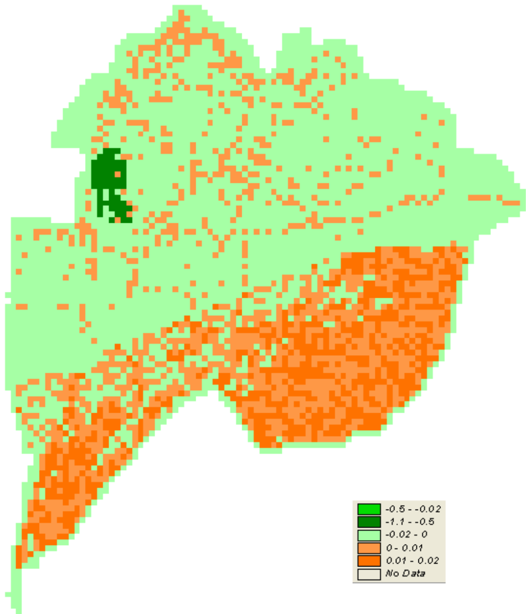


Figure 6-29: Change of flood characteristics in Scenario 5 when using a terp of 1m. Δ>0: increase in inundation depth

6.5.2 Cost-effectiveness-analysis

The Cost-effectiveness-analysis (CEA) will be done using two criteria, one for material loss and one for fatalities. Those are shortly reviewed below. Following that the cost-efficiency of first the individual flood management measures will be analyzed. Secondly, the cost-efficiency of the MLS layers will be evaluated.

Short review

In Chapter 2.2.4 two criteria were introduced to evaluate the cost-efficiency of flood management measures. To make an investment into flood safety economic the net present value of the risk reduction has to be larger than the investment. That ratio will be called T here. The smaller the T factor is, the more cost-efficient a measure is. The T-factors for the flood management measures are shown in Figure 6-30.

$$T = \frac{I}{\Delta ER/_r} \leq 1$$

With I = Investment [€]
ΔER = reduction in economic risk [€/yr]
r = rate of interest [-]

The criterion reviewed above is mainly applicable for material loss that can be expressed in value. To evaluate the cost-efficiency with regard to saved human lives, the CSX has been introduced in Chapter 2.2.4. The smaller the CSX factor, the more cost efficient a measure is. The CSX-factors for the flood management measures are shown in Figure 6-30.

$$CSX = I/\Delta E(N)$$

With CSX = costs of saving an extra life per year [€/#/yr]
I = investment [€]
E(N) = expected number of fatalities [#/yr]

CEA Individual measures

In the first case study three observations in regard to cost-efficiency have been done.

1. For most flood management measures the investment costs were larger than the net present value of their risk reduction.
2. The measure 'sand bags' (3-6) was most cost-efficient, the measures re-locating (2-5) and compartmentalization (2-6) least.
3. The flood management measures are most cost-efficient for the unit they have been applied to. So a measure that has been implemented in only the neighborhood is more cost-efficient in that neighborhood than in the dike ring.

It was concluded that it is cost-efficient to tailor the flood risk management to the local circumstances.

The second case study confirms the first and last observation from the first case study. In the following, those three observations will be reviewed with the new results.

1. Most flood management measures indeed cost more money than they will generate. Except for the measures compartmentalization (2-6) and sand bags (3-6) (at dike ring scale) the columns in Figure 6-30 stay below the red line that indicates the criterion reviewed above.

2. Compartmentalization (2-6) was one of the least cost-efficient measures in the first case study. In the second case study it is together with the sand bags (3-6) one of the three most efficient ones. This is due to the fact that its negative side effects on the flood characteristics do not affect any densely populated areas. Furthermore, it was possible to let the whole city benefit from its effect.

While compartmentalization is the second most cost-efficient measure on dike ring scale, elevation (2-7) is the second most efficient measure for the Wielwijk. This is due to the fact that elevating significantly reduces the loss in the Wielwijk for all three flooding scenarios. Compartmentalization does that for only one scenario, the worst one.

In the first case study it was already mentioned that possibly an overly positive light has been shed on the sand bags (3-6). Most probably they are less cost-efficient since their effect very much depends on the strength on the flood defense which they reinforce.

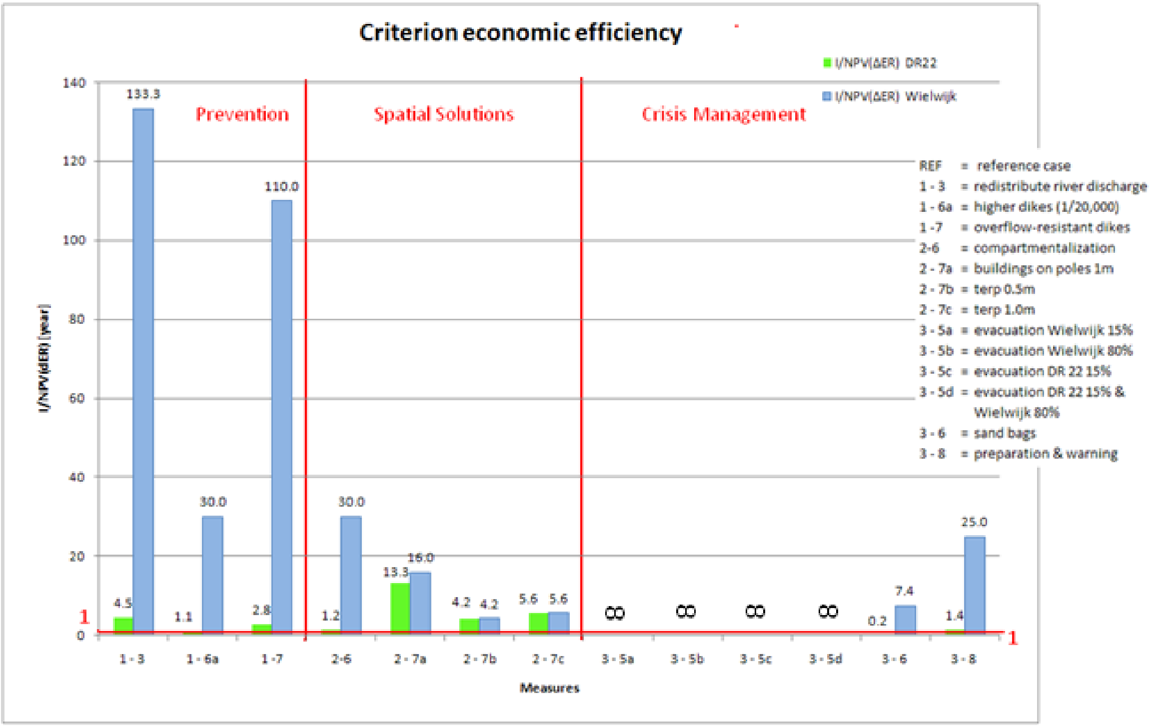


Figure 6-30: Cost-efficiency with regard to the economic risk. The lower the ratio between investment and net present value of the risk reduction, the more cost-efficient a measure is. A measure becomes economically desirable if the risk reduction (NPV) is larger than the investment. This is the case if the columns in the diagram stay below the horizontal red line.

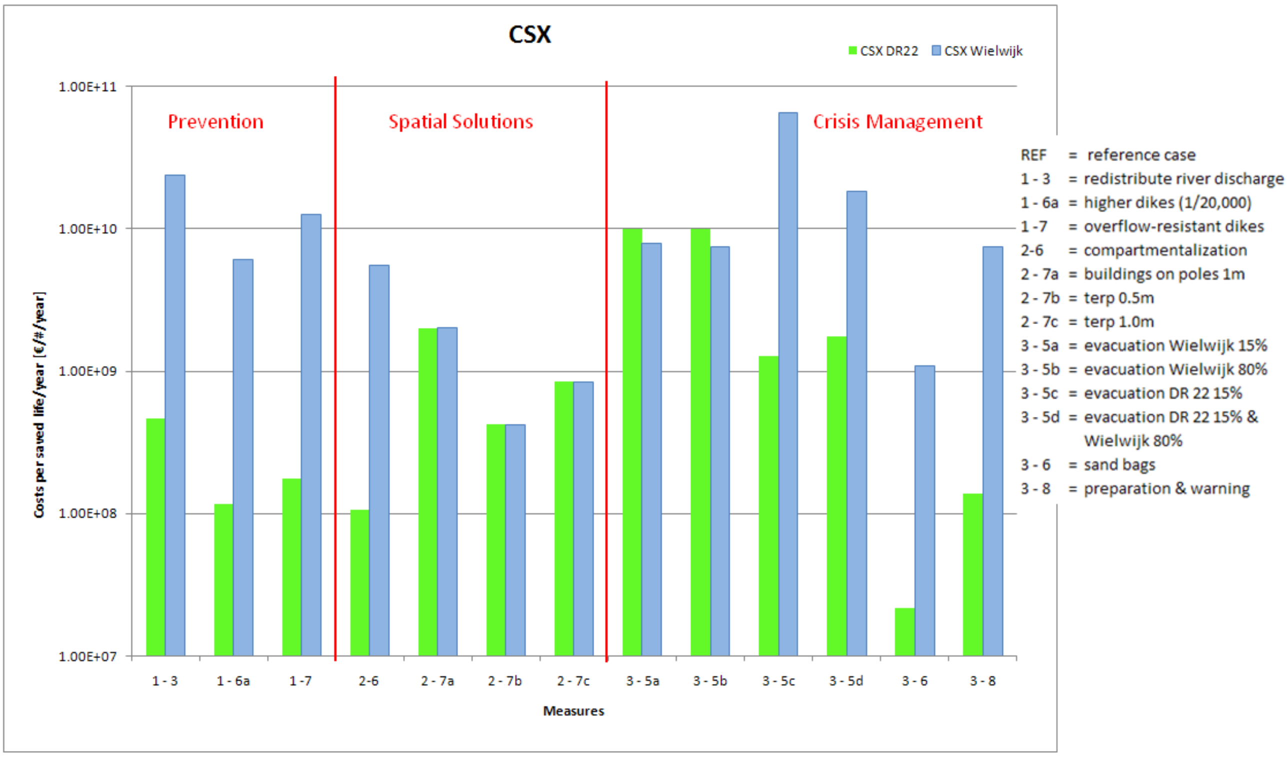


Figure 6-31: Cost-efficiency with regard to the expected number of fatalities per year. The lower the ratio between investment and saved statistical lives, the more cost-efficient a measure is. This diagram says nothing about the (monetary) value of a human live.

On dike ring scale, giving the river more space (1-3) and the overflow-resistant dike (1-7) are among the least cost-efficient measures. In the Wielwijk elevation (2-7) is rather costly. In terms of fatalities also evacuation (3-5) is relatively cost-inefficient. A few comments can be done regarding these cost-inefficient measures:

Redistributing the discharge (1-3) turns out to be a rather cost-inefficient measure among the Prevention measures. This is not entirely true though since such a measure not only decreases the flood risk for one dike ring but for a large part of a delta. Thus the investment costs might be high if the inhabitants of one dike ring have to pay them. But if the costs are spread among everybody who benefits from it – the inhabitants of a large part of the delta – this measures will become much more cost-efficient. This is the same mechanism that can be seen between the dike ring and the neighborhood. Primary flood defenses e.g. are much more cost-efficient for an entire dike ring than they are for a single neighborhood. In the case studies it is found again and again that flood management measures are most cost-efficient at the scale of their application.

The costs of *evacuation (3-5)* were based on the investment needed for refuge shelters. If the strategy is set in more on organizational traffic plans, the costs will probably decrease. But then the disadvantage occurs that the performance of evacuation becomes much less uncertain because of significant system interaction. All the people that want to leave their neighborhood or dike ring will hinder each other. This interaction decreases the performance and makes it very uncertain. So certainty has its price here. As it is budgeted in this study, evacuation leads to a low risk reduction per Euro. The more Euros are spent the greater the deviation from the average will become.

Some of the evacuation measures (3-5a, 3-5b) have been implemented exclusively at neighborhood scale. Measure 3-5c (neighborhood ef=0.8, dike ring area ef=0.15) and measures 3-5d (dike ring area ef=0.15) have been partially or totally applied at dike ring scale. This distorts the Cost-effectiveness-analysis at neighborhood scale. At that scale the risk reduction due to evacuation in the rest of the neighborhood is not accounted for. Thus evacuation seems to be more expensive for those cases than if only the neighborhood is evacuated.

For the implementation of *Elevation (2-7)* it is noted that elevation using terps turns out to be more cost-effective on dike ring level than poles. Due to their scale of implementation the elevation measures are more cost-efficient at dike ring than at neighborhood scale.
Elevation on terps seems to be less cost-effective the higher the terps are (2-7b is more cost-effective than 2-7c). This is due to the fact that with a terp of 0.5m (2-7b) some houses already stay dry in the modeled scenarios. For them an increase in terp height to 1.0m (2-7c) as no additional risk-reducing effect.

3. The second case study confirms the observation from the first case study that flood management measures are most cost-efficient at the scale that they are implemented at. E.g. a measure such as elevation (2-7) has been implemented only in the Wielwijk and thus is more cost-efficient in the Wielwijk than for the whole dike ring. This is because those measures have been tailored to the risk reduction aimed at.

Generally, the second case study confirms the conclusion of the first case study, but it also extends it. The Cost-effectiveness-analysis shows that it is indeed cost-efficient to tailor flood management measures to the local conditions. Additionally, it is found that it depends very much on the local conditions which flood management measures are more or less cost-efficient. Compartmentalization is the best example for this.

CEA of MLS layers

In the first case study it was found to be difficult to do a judgment about the cost-efficiency of the MLS layers. It could only be observed that Prevention is more cost-efficient for the dike ring, whereas Spatial Solutions and Crisis Management work better for a neighborhood. This is again due to the possibility of those last two layers to customize flood risk management to local conditions. No judgment could be done if any layer is better for any dimension of risk (SR, IR, ER).

Table 6-13: ranking of MLS layers

AV.	Economic Risk		Societal Risk	
Rank-ing	Neighbor-hood	Dike Ring	Neighbor-hood	Dike Ring
1.	SS	CM	SS	P
2.	CM	P	P	SS
3.	P	SS	CM	CM
(P=Prevention, SS=Spatial Solutions, CM=Crisis Management)				
BEST	Economic Risk		Societal Risk	
Rank-ing	Neighbor-hood	Dike Ring	Neighbor-hood	Dike Ring
1.	CM	CM	CM	CM
2.	P	P	P	SS
3.	SS CM	SS CM	SS CM	P CM
(P=Prevention, SS=Spatial Solutions, CM=Crisis Management)				

Table 6-13 shows the MLS layers ranked once bye the average cost-efficiency per layer (AV.) and once ranked by the most cost-efficient measure per layer (BEST). The red arrows in the table indicate what happens if the overly cost-efficient measure 'sand bags' (3-6) is omitted.

As in the first case study it is found that the possibly unrealistic cost-efficient sand bags distort the cost-efficiency of Crisis Management very much. When looking at the average cost-efficiency of the layers, this circumstance matters less than when looking at the most cost-efficient measure per layer. While the most cost-efficient measure for reducing the risk is in most cases a Prevention measure (heightening the dikes, 1-6a), on average Spatial Solutions are more cost-efficient than Prevention in the Wielwijk. This confirms what was found in the first case study.

Crisis Management scores rather weak in terms of cost-efficiency. It looks like it is suitable to reduce the economic risk when looking at the average cost-efficiency per layer. But this is very deceptive, since only two out of six Crisis Management measures are relevant to the ER.

As in the first case study, the second case study does not provide the grounds to say anything about the cost-efficiency of any MLS layer with regard to a dimension of risk. It can only be repeated that some Crisis Management measures are not relevant for the ER (e.g. evacuation).

It is concluded that this Cost-effectiveness-analysis with regard to the MLS layers only confirms that loss-reducing measures as provided by the MLS layers Crisis Management and Spatial Solutions are cost-efficient due to the possibility of customizing flood risk management inside the dike ring. Additionally it was found that Crisis Management seems less cost-efficient than Spatial Solutions.

6.5.3 Interaction

In the first case study it was found that the initial safety level determines the cost-efficiency of any flood management measure. In practice this means that if a flood management has been implemented already, any further measure will be less cost-efficient.

In the second case study lowering the dike, measure 1-6c, has been included to examine the influence of the initial safety level on cost-efficiency more closely. The objective is to find out if flood risk management can be adapted to respond better to this interaction between measures. This aspect could have been studied with any combination of measures. Here it is chosen for successive heightening of the primary flood defenses because those measures are easy to compare. In the computational model, heightening the dike comes down to letting the dike ring area flood with water levels occurring with a lower probability. A lower probability means higher water levels and consequently more loss.

By modeling different dike heights in this case study (REF, 1-6a, 1-6c) it becomes possible to find out what the FN/FS-curves would look like without a dike ring or in this case with a lower one. Table 6-14 shows the number of fatalities for each scenario given the three different dike heights, Figure 6-32 visualizes that data. As a clarification, it is incorrect to say that higher dikes decrease the probability and increase the loss. They merely exclude scenarios with a lower loss. After all, if the dikes breach with water levels occurring with a probability P=1/200, water levels with a lower probability causing more damage can still appear. That implies that the light blue line, indicating the situation with P=1/200 is not the correct FN-curve for that situation. It should rather be the envelope of all three FN-curves shown in the diagram in Figure 6-32. That envelope, thus the alternative FN-curve for situation 1-6c, is shown in Figure 6-33. To achieve even higher accuracy of that FN-curve modeling more situations with different probabilities would be necessary. As a logical consequence of the above, the FN-curve of the reference situation REF should be the envelope of the diagrams for REF and 1-6a.

Table 6-14: Number of fatalities per scenario, given different dike heights. Each scenario contributes a third to the total probability. The total risk if the envelope of the three FN-curves is used (Figure 6-33) is given in brackets. The boundary conditions for each probability of occurrence have been derived by R. Piek, compare Appendix 9.6.2.

<table>
<tr><th></th><th colspan="2">Ptotal=1/200
(1-6c)</th><th colspan="2">Ptotal=1/2,000
(REF)</th><th colspan="2">Ptotal=1/20,000
(1-6a)</th></tr>
<tr><td>Fatalities Scenario 1</td><td colspan="2">126</td><td colspan="2">92 (-34)</td><td colspan="2">155 (+63)</td></tr>
<tr><td>Fatalities Scenario 5</td><td colspan="2">1,490</td><td colspan="2">5,041 (+3,551)</td><td colspan="2">5,255 (+214)</td></tr>
<tr><td>Fatalities Scenario 12</td><td colspan="2">3</td><td colspan="2">38 (+35)</td><td colspan="2">75 (+37)</td></tr>
<tr><td>Total Risk (exp. fatal./yr.)</td><td colspan="2">2.70 (3.29)</td><td colspan="2">0.856 (0.860)</td><td colspan="2">0.086</td></tr>
<tr><td>Risk Reduction (exp. Fatal./yr.)</td><td></td><td colspan="2">-1.84 (-2.43)</td><td colspan="2">-0.77</td><td></td></tr>
</table>

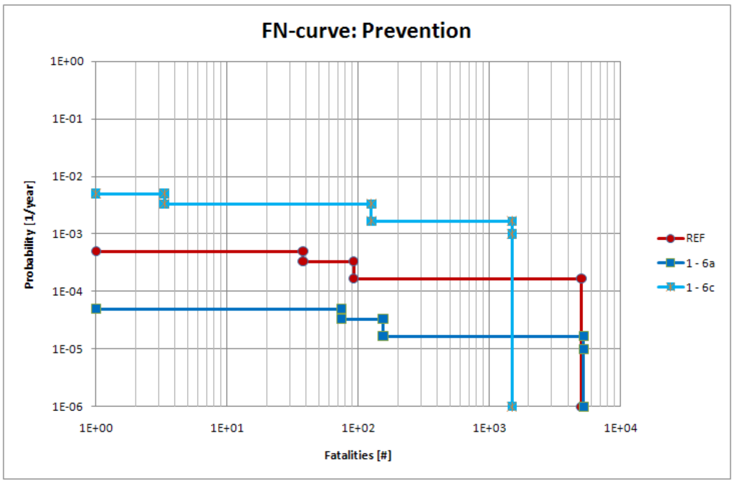


Figure 6-32: FN-curve for different dike heights

REF = reference case (1/2,000)
1 - 6a = higher dikes (1/20,000)
1 -6c = lower dike (1/200)

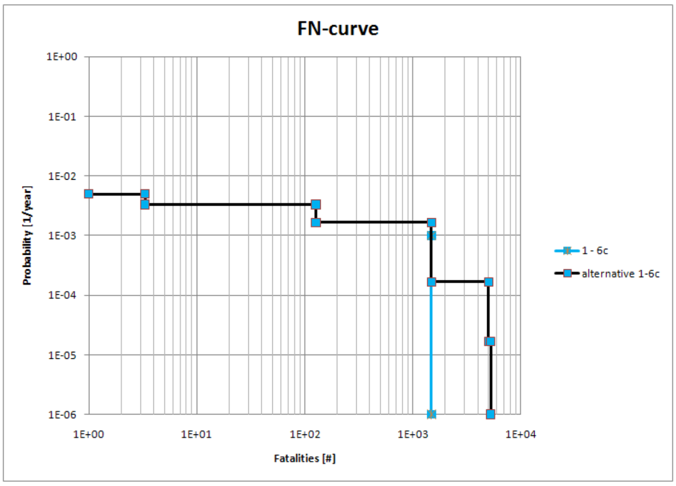


Figure 6-33: Alternative FN-curve for P=1/200 (1-6c)

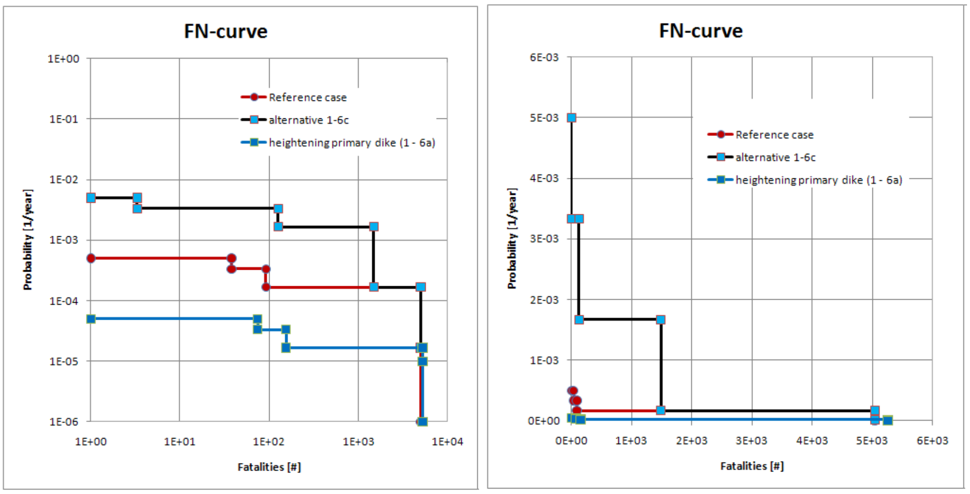


Figure 6-34: Risk reduction in two steps by heightening the dike with one decimating height each time. The figure on the left shows the FN-curve with logarithmic axes and the figure on the right with linear axes. It shows that the probability-reduction of the first step (P=1/200 -> 1/2,000) achieves a significant risk reduction. However, for the remaining risk it might be more efficient to tackle the severe consequences of flooding scenario 5 instead of choosing for another increase in dike height (P=1/2,000 -> 1/20,000).

Table 6-14 and Figure 6-34 show that the risk reduction by moving from P=1/200 to P=1/2,000 is more than the one going from P=1/2,000 to P=1/20,000 [yr^{-1}]. In both cases the risk decreases by 90%. But in absolute terms this is more if the probability goes from P=1/200 to P=1/2,000 than if it decreases from P=1/2,000 to P=1/20,000. This is the mechanism that makes any additional flood management measure less cost-efficient. Its absolute risk reduction is less than that of the forgoing measure even though their relative risk reduction is the same.

Figure 6-34 shows that the severe consequences of flooding scenario 5 by far contribute the largest part to the remaining risk after having gone from P=1/200 to P=1/2,000 [yr^{-1}]. It is therefore much more effective to reduce the severe consequences of scenario 5 instead of heightening the dike once again (P=1/2,000 to P=1/20,000 [yr^{-1}]). This is what makes compartmentalization (2-6) so effective in the case study of Dordrecht (see page 146). The interaction between the individual measures thus might make it more effective to turn to other (loss-reducing) measures instead of continuously intensifying the implementation of one measure, in this case heightening the dikes.

Similar observations as just done for the FN-curve can be done when examining the FS-curve.

It is concluded that the interaction between the individual measures might make it more effective to turn to other measures instead of continuously intensifying the implementation of one measure. In this case this can be achieved by implementing loss-reducing measures to customize the flood risk management to local conditions, such as excessively damaging flooding scenarios.

6.6 Conclusion of second case study

6.6.1 Comparison with earlier case study

The earlier case study had more different strategies per layer so that it provided a wider picture. This second case study was based on facts from the real world so that it goes more into depth.

Effects

- In agreement with the first case study, it was found that probability-reducing measures are suitable for decreasing the overall risk but less fit for customizing flood risk management to local conditions (*maatwerk*). This implies that MLS brings forth the possibility to tailor flood risk management to local conditions and address hotspots.
- In addition to the first case study, it was shown that it can pay off to prioritize reducing the risk contribution of one flooding scenario.

Side-effects

- This second case study confirmed that negative side-effects on the flood characteristics not necessarily jeopardize the risk-reducing effect of measures like compartmentalization. This is the case in Dordrecht but it has been proven to be different in other flood-prone areas.
- Additionally, it was shown that terps have very small negative side-effects on the flood characteristics in Dordrecht.

Cost-efficiency

- It is confirmed that loss-reducing measures as provided by the MLS layers Crisis Management and Spatial Solutions are cost-efficient if used to customize flood risk management inside the dike ring. Fitting flood management measures to the local conditions prevents creating overly save areas.
- Additionally, it was found that Crisis Management is less cost-efficient than Spatial Solutions, at least in Dordrecht.

Interaction

- It is concluded that the interaction between the individual measures might make it more effective to turn to other measures instead of continuously intensifying the implementation of one measure. In this case this can be achieved by implementing loss-reducing measures to customize the flood risk management to local conditions, such as excessively damaging flooding scenarios.

6.6.2 Recommendations for deepening case study

The scope of the study and the limited time made it necessary to do some simplifications and shortcuts. To deepen this case study, the following aspects should be given more attention.

- Interaction has mainly been analyzed theoretically in this study. It would be advisable to verify those findings by modeling and calculating combinations of measures for the case of Dordrecht.
- Furthermore, it has been shown how the initial safety level influences the cost-efficiency of the measures. In this case study, the initial safety level was owed to the dike ring around it. It would be interesting to see what the effect of different initial safety levels brought about by different existing measures (e.g. flood-proofing) would be.
- This case study is indicative. The investment costs are rough estimates and the risk is calculated with a low level of detail. Before reliable decisions can be made, surely for individual neighborhoods or even buildings, this case study would have to be repeated much more detailed.

7 Conclusion

In this last Chapter first the conclusions on Multi-layered Safety (MLS) will be summarized and discussed.

Furthermore, a short comment on the developed theoretical framework will be given. Following that a conclusion about the sense and non-sense of MLS in Dordrecht will be given. That discussion will also be extended to other flood-prone areas.

7.1 Conclusion of Multi-layered Safety

First, the main conclusions will be listed. Following that, these conclusions will be motivated by answering the objectives of this study. This subchapter closes with a review of the expectations for MLS.

7.1.1 Summary: Main conclusions

Below, the main conclusions for MLS are listed. In the following subchapter they will be motivated.

- A flood defense system heavily based on dike rings does not lend itself to implement MLS. There MLS is only cost-efficient to eliminated local differences in risk.
- Introducing redundancy to flood safety by means of MLS is an alternative to only building flood defenses (strengthening the strongest link).
- The cost-efficiency of any flood management measure depends on the initial safety level. This interaction between the individual measures might make it more effective to turn to other measures instead of continuously intensifying the implementation of one measure.
- To implement MLS effectively it is necessary to know that different measures address different key parameters of risk and show different side-effects.
- Policy-making needs to be risk-based to make MLS relevant. Right now most flood management policies are based on Prevention and thus probability-oriented. To supplement those policies with loss-reducing measures, as MLS proposes, policy-makers need to be authorized to base their policies on the risk approach to flood management.

- Given the assumptions of this case study, it is most cost-efficient in Dordrecht to (selectively) reinforce the existing system of primary and secondary dikes. it was found that probability-reducing measures are suitable for decreasing the overall risk but less fit for customizing flood risk management to local conditions (*maatwerk*). This implies that MLS brings forth the possibility to tailor flood risk management to local conditions and address hotspots.

7.1.2 Discussion study: Answering the objectives of the study

In the following the objectives of this study will be answered. By doing so, a concluding assessment of MLS will be given.

Definition and functioning of MLS (Chapter 3)

- *What is the definition of each MLS layer and which actual measure correspond to each? (Chapter 3.2)*

MLS means implementing flood management measures from at least two of the following three layers:

1. Prevention layer: All permanent measures that change the boundary conditions of the considered location (which water levels occur with which frequency).
2. Spatial Solutions layer: All permanent measures that change the exposure and vulnerability of material values and people after water has entered.
3. Crisis Management: All temporary respectively organizational measures that change the exposure and vulnerability of material values and people after water has entered.

- *How can MLS be schematized*? (Chapter 3.5)

To schematize MLS a theoretical framework has been developed. It is based on seven different strategies of countering flood risk. Each strategy describes a different way of how the basic risk parameters can be tuned. The schematization is shown in Figure 3-8.
The basic risk parameters are the boundary conditions (P(WL), the number of objects/people in the flood-prone area n, their vulnerability and their degree of exposure determined by the ground level. A strategy changes one of these parameters or the relationship between two of them. The strategies have been sub-divided into addressing one of the following three: boundary conditions, exposure and vulnerability (compare with definition of MLS above).

Important properties of MLS (Chapter 4)

- *Which properties do individual flood management measures (and thus the MLS layers) have; how do they function? What (unintended) side-effects do individual flood management measures have? (Chapter 4.2)*

Summarized, strategies that address the boundary conditions have long-term effects on the social scenarios such as population density. Strategies aimed at exposure might cause undesirable changes of the flood characteristics. Lastly, strategies meant to lower the vulnerability have little (unintended) side-effects but increase the value of the protected and thus the maximal damage.

- *What is the interaction between MLS layers?* (Chapter 4.3)

The cost-efficiency of all flood management measures is dependent on the initial safety level. Thus any added measure is less cost-efficient due to the other measures that have already been

taken. The cost-efficiency of a measure also depends on the form of the FN-/FS-curve, which might have been altered by other measures.
As Crisis Management adapts best to the initial safety level it combines better with other flood management measures than the layers Prevention and Spatial Solutions do.

- *Do the MLS layers work like safety nets? How does MLS behave with regard to the failure of the flood protection? (Chapter 4.4)*

MLS is meant to introduce redundancy (safety nets) to flood risk management. In Chapter 4.4 it was found that redundancy is indeed an alternative to strengthening the strongest link, being the policy nowadays. But switching to a redundancy policy changes the flood risk management system fundamentally. In the Netherlands it is a serial system because it entirely relies on dike rings. MLS would make it a parallel system. Doing this makes it necessary to let go to the black- and white notion of floods: flood or not flooded. The performance of a parallel system would have to be measured in the degree of loss relative to the water level.

When looking at the so-called safety nets, or put differently MLS layers, individually, Prevention is the most and Crisis Management the least reliable.

Implementation of MLS (Chapter 5, 6)

- *Under which conditions does MLS lead to the reduction of the flood risk? Is MLS fit for Dordrecht?*

In areas with a flood protection that is concentrated on one measure, like the dikes in the Netherlands, it is not cost-efficient to use a concept like MLS to lower the flood risk substantially. Rather emotional values might justify further investments. MLS does provide the opportunity to implement flood management measures on a smaller geographical scale. This allows fine-tuning flood risk management to local characteristics. Thus, MLS is cost-efficient if it is used to address local differences in risk.
In countries with a less advanced flood protection the potential of MLS depends on the individual risk profile and the scale of the area in question. The risk profile is determined by the risk parameters described in the description of the theoretical framework above.
Chapter 7.3 discusses the potential of MLS in Dordrecht.

- *Is MLS cost-effective in Dordrecht?*

This objective is answered in a separate conclusion for Dordrecht (Chapter 7.3).

7.1.3 Discussion MLS: Review of Expectations for MLS

In Chapter 3.2.2 several objectives and expectations for Multilayered Safety were given. In the following these objectives will be discussed one by one in the light of the findings of this study. This discussion mainly applies to Dutch flood risk management.

- *Alternative*: It very much depends on the initial flood risk if MLS is a serious alternative to only Prevention. It matters with which frequency and severity extreme hydraulic conditions occur, how many objects and people are exposed to them and how vulnerable they are. In the Low Countries generally MLS is no cost-efficient alternative to Prevention due to the heavy implementation of the latter. MLS might act as a supplement to the Prevention policy to address high local risks or disadvantageous properties of flood defenses. However, the national government has not provided any legal basis to grasp this opportunity. Without a legal basis the funds would mainly have to be provided by private parties.

- *Diversification:* The flood protection in place in Dordrecht is based mainly on barrier measures (strategy 6): flood defenses. Thus, the flood protection becomes very dependent on relatively small dike sections (series). If looked at as a whole, flood safety is rather a parallel system though; MLS would make use of that property. According to Portfolio Theory this would be an advisable step. It is important though to follow the practical rule that the failure of the chosen MLS measures should be as little correlated as possible. This advice has a negative side-note though: Any additional flood management measures is less cost-efficient due to the improving safety level. This makes diversification an expensive commodity in the Netherlands.

- *Sustainability*: As concluded from both case studies (Chapters 5.8 and 6.6), MLS is a good instrument to play in on difference in local risk. Addressing the risk locally would indeed dampen the risk spiral. New building projects would be build at locations with a lower local risk or – if build at a location with high flood risk – would be adapted to be less vulnerable. Doing so the maximal loss would increase with a slower pace. The risk spiral would thus be less intense and the standards of Prevention would have to be increased less.

- *Efficiency*: As mentioned before, the cost-efficiency of flood management measures suffers when the safety level is increased. This is true for any flood management project in general and not only for MLS in particular. But combining Crisis Management measures with other measures does result in synergy as those organizational measures adapt to changing safety levels. Thus, the way in which MLS is implemented, matters a lot for the efficiency of it.

- *Acceptability*: This study has not considered acceptability in the public. It was found in Chapter 3.5.4 though that lower strategies are applied at a smaller scale. Usually a smaller scale means that measures affect people more in their daily lives. Furthermore, MLS is meant to introduce more safety nets to flood risk management. It was discussed in Chapter 4.4.2 that not each functioning safety net is also desirable for society.

- *Flexibility*: It was mentioned in Chapter 3.5.4 that the additional two layers of MLS, Spatial Solutions and Crisis Management set in on a low geographical scale, namely the individual person and building. It is therefore questionable if those measures would provide great flexibility in response to changes in the surrounding. A lot of people would have to agree and act coordinated to make changes happen fast.

- *Uncertainty:* Uncertainty can be answered with flexibility. For a discussion of that, see the last point discussed above. But uncertainty can also be answered by leaving the black- and white notion of loss due to flooding. If there was a legal basis to reduce the degree of flooding and the amount of damage, flood management measures would be effective in even unexpected circumstances. MLS would be an ideal way to achieve this. After all, it treats flood safety as a parallel system and is thus promoting more shades between the white of no loss and the black of total failure.

- *Financing*: As was mentioned before, in the Netherlands MLS is mainly appropriate for addressing locally high flood risk. Scenarios are thinkable where project developers put private money into flood risk management on a smaller scale, e.g. following the idea of MLS. Their benefit would be to be able to advertise new housing with less flood risk. On the one hand, it is certainly advantageous to attract private funds for flood risk management. On the other hand, it is unclear what effect it would have among the public if commercials highlight differences in local flood risk.

The following two bullets are a personal opinion formed during this study.

- *Multi-functionality*: This study has not looked into this point. A comment nonetheless: Multi-functionality of flood management measures decreases the opportunity to adapt the flood management measures to new circumstances and desires. MLS itself is an example for the realization that flood safety changes regularly, sometimes resulting in interesting contradictions. E.g. are overflow-resistant dikes very popular these days, especially because they could be used multi-functionally. But at the same time the Voorstraat in Dordrecht, an overflow-resistant dike par excellence, is considered to be the biggest threat to flood safety in that dike ring.

- *Loss*: From a (long-term) political point of view it might be beneficial to invest in loss-reduction, since the imbalance between probability and impact of flooding is growing. There will always be a probability left that a flood occurs and it will occur. The lower the probability of flooding, the more devastating its impact will be. Destruction approaches completeness. If a major flood occurs, it would be impossible to explain to the public why the areas behind the dikes were prepared poorly for such a disaster. This and the growing level of destruction itself might lead to precarious circumstances endangering the survival of the status quo of the administration. Since financial resources are usually limited, it is a political task to evaluate the value of preventing societal upset after a flood.

7.2 Comment on theoretical model

Both case studies showed that the measures are most cost-efficient at the geographical scale they are applied at. For many flood management measures the scale of application can only be chosen limitedly or not all. Flood-proofing e.g. is only possible for individual buildings.

It was observed in Chapter 3.5.4 that the scale of application decreases with along the ranking of Haddon's strategy. Prevention measures are usually applied at larger scale than measures altering the vulnerability. Thus the smaller the area of flood risk management is, and thus the smaller the overall-risk is, the lower the chosen strategy should lie in Haddon's ranking. This is in agreement of Haddon's idea that the larger the threat the higher the chosen strategy should be ranked.

Extending this thought to the practice of Dutch flood risk management it is found that applying measures different than Prevention, as does MLS, is mainly appropriate to address deviations in local risk at the scale of neighborhoods. Spatial Solutions and Crisis Management are not cost-efficient for scales larger than that (e.g. dike ring/delta).

7.3 Conclusion for Dordrecht

In the following it will first be discussed if it is a good idea to implement MLS in Dordrecht. Afterwards it is explained what the best way to implement MLS would be. The chapter closes with comments on other flood-prone areas.

7.3.1 Potential of MLS

As mentioned above on a conceptual basis introducing MLS does make sense. Introducing safety nets – the idea behind MLS – is indeed an alternative to strengthening the strongest link (e.g. heightening dike). But due to the high initial safety level any more safety measures are not cost-efficient. It is a political decision if additional measures, and thus MLS, are desirable due to other (emotional) societal benefits.

It is clear that right now MLS is not a good choice to live up to (national) standards. With the standards as they are today, MLS is not an option at all at national level. After all, there are only financial resources available to live up to those standards focusing on the probability of flooding. Since MLS mainly promotes supplementing Prevention with loss-reducing measures, its risk-reducing effect can only be captured with risk-based policies. E.g. Regional administrative bodies may decide to supplement their flood policy with risk-based elements. Thus, as of 2010 MLS is a good strategy for allocating additional resources and improving regional flood safety rather than basing national strategy for flood safety on it.

7.3.2 Application of MLS

In Dordrecht the existing flood safety system still offers many opportunities for improvement. Selective reinforcement of the primary and secondary dikes is among the possible cost-efficient measures. As there are already many flood defenses present this approach is also logical in terms of side-effects, failure and interaction. It was explained above that flood defenses have positive properties in terms of failure and do not facilitate combining other sorts of measures with them.

Because of Dike Ring 22 being a “bath tub” it is wise to keep the priority for the entire dike ring on Prevention. Nonetheless, there are some spots in Dordrecht where the local risk is higher than in the rest of the city (see Figure 6-18). Those areas are small enough to make Crisis Management and Spatial Solutions and thus implementation of MLS a serious option to lower the local flood risk. Especially in the industry park Dordtse Kil, in the West of the dike ring, MLS would be a good option. The local risk there is large, the area in question is relatively small and mainly material value is at danger there. Crisis Management combines best with the existing dike ring but scores not so well in reliability and saving material value. Thus, Spatial Solutions would be good choice if MLS is implemented. The application scale of Spatial Solution measures combines well with the size of the area, so it is expected that Spatial Solutions will be cost-efficient there.

7.4 Other flood-prone areas

A high flood safety level achieved by focusing on one type of protection is the most severe hindrance when wanting to apply MLS. In areas with a large diversity in flood management measures (not only dikes) and/or a higher flood risk, MLS might be a serious alternative. This is especially the case for smaller areas, the measures of Crisis Management and especially Spatial Solutions are most efficient on the scale of neighborhoods.

The way in which MLS should be implemented depends on the risk profile of the area in question (compare Appendix 9.1). The larger the area respectively the larger the overall-risk the higher the chosen strategy should rank in Haddon's sequence. A magnitude of the flood risk depends on the values of the risk parameters: the boundary conditions, the number of exposed, flood characteristics and vulnerability (compare Appendix 9.1).

Thus, if the risk is large, the priority should lie on changing the boundary conditions. This can best be done with Prevention. The other two layers are then useful to eliminate local differences in risk. If the risk is rather small to begin with, it might be wiser to address the exposure of even vulnerability with Spatial Solutions and Crisis Management. Finally, most findings as summarized in Chapter 7.1 apply for MLS anywhere.

7.5 Recommendations for further research

This study has been done within in limited time and with limited resources. Below a number of aspects are listed that are recommended to look into if this study was to be extended.

Level of detail/accuracy

- To reduce calculation time not all available flooding scenarios have been included in this study. Instead of the three scenarios chosen all twelve should be included.
- The investment costs are rough estimates. Before actually deciding to implement MLS those cost estimates should be refined with more consideration for the local conditions.
- If MLS is used to address local deviations of risk it is advisable to increase the resolution of the computational models used. The level of detail using a grid size of 100x100m^2 is not sufficient to implement measures such as flood-proofing accurately enough.

Extension of study

- As mentioned in the recommendations for the case study, it would be worth researching which measures' cost-efficiency suffers more or less under the changing initial safety levels. This would show which measures are respond well to changing boundary conditions such as for example climate change.

- Sustainable policy should also take into account long-term effects. Therefore it is recommended to study long-term effects of flood management measures such as migration and level of preparation and experience.
- It would be interesting to see how MLS performs in other areas than treated in the case studies. Those areas should not only have different geographic characteristics (e.g. size) but also feature different kinds of flood management.
- The risk approach used in flood risk management should be extended to be able to study units of different scale. Right now the risk approach relies too much on dike rings which make it difficult to appreciate the risk reductions in smaller or larger areas such as neighborhoods or deltas. This is especially important if this risk approach is to be used everywhere in Europe.
- When developing risk-based policies or even standards, long-term effects of flood management measures and long-term processes such as climate change should be integrated.

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9 Appendix

9.1 Appendix: Models in Safety Science

This appendix describes the four models from Safety Science mentioned in Chapter 3.4.4. These models were considered as potential foundations for the theoretical framework of this study. Nonetheless, they have not been chosen.

For better understanding it should be noted that all of these models are based on the following notion: It is assumed that the hazard harms the target by uncontrolled release of energy or by disturbing the normal level of energy (Leveson 1995: 186). In the case of flood safety this energy would have the form of kinetic energy due to flow velocity and other kinds of energy such as the temperature of the water. This is does not cover the entire load of harm done by water. But it does describe the way of thinking in safety science.

9.1.1 Domino Model

In many cases an accident is caused by a chain of events. To prevent an accident it is merely necessary to remove one domino and the chain will be interrupted. Furthermore, the failure of a domino is dependent on the failure of the piece in front of it. This is a very linear model that only looks at prevention and not loss reduction (Ale 2009: 23).

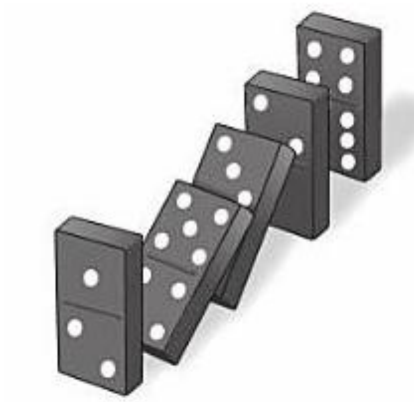


Figure 9-1: Domino Model (Ale 2009: 24)

The description already suggests that this model is only sufficient to model prevention and can therefore not be applied to more than the first layer of MLS. Still there is a lesson to be learned from the domino model. Prevention can happen at different levels and stages of the calamity. It encourages looking beyond traditional flood defenses, to realize prevention.

9.1.2 Hazard-Barrier-Target Model

As the name already suggests the hazard-barrier-target (HBT) model assumes that the target is protected by a barrier from the hazard. The hazard is thought to be present continuously. Similar to the domino model there can be more than one barrier. The difference is that a domino represents failure causing another failure whereas the barriers in the HBT model prevent the accident from happening. Each barrier is seen as a system that has to be managed and maintained. As a consequence these barriers usually are imperfect barriers because they might fail due to technical or human errors and faults (Ale 2009: 25).

A more extended version of the HBT model allows including impact reduction and makes a difference between prevention and protection. This is done by defining different kinds of barriers. *Control barriers* are used to describe prevention. These barriers keep an event from occurring. Once this event does occur nonetheless *safety barriers* will provide protection. They are meant to mitigate or deflect the impact of the hazard being released by an initiating event. Finally there is a third kind of barrier that minimizes the consequences of the accident by applying boundaries to the accident happening. A last notion separates active from passive barriers (Guldenmund 2009). According to Leveson passive barriers should be preferred since they rely on for example physical principles such as gravity. Active barriers need supplements as hazard detection etc. before they come into action and therefore are much more likely to fail or dysfunction (Leveson 1997: 154-155).

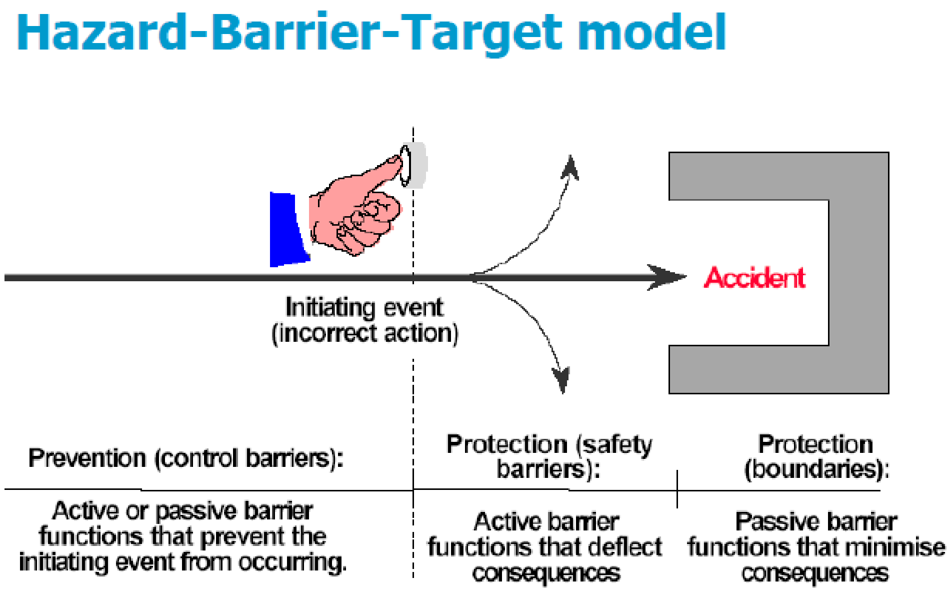


Figure 9-2: Hazard-Barrier-Target Model (Guldenmund 2009: slide 28)

Parallels between the HBT model and MLS are that the barriers are imperfect. In the reality of flood management it is almost always the case that barriers can fail due to the complexity and diversity of the society living in the system dike ring. It has to be noted that each flood management measure would be a barrier if flood safety was tried to be captured in a HBT model. The HBT model suggests that there are different kinds of barriers but it does not capture the diversity of measures possible in flood management yet. When looking at the reliability of a flood management system the idea of passive barriers being more desirable over active barriers should be adopted.

9.1.3 Swiss Cheese Model

Originally introduced by James Reason in the early nineties the Swiss cheese model has gone through different versions. In general they are all based on the same notion: Each slice of cheese represents a defensive layer. Compared to the models introduced above this model not only includes unsafe acts and other failures but also latent conditions that are necessary (but not sufficient) to cause an accident. In this way also human and organizational contributions can be captured.

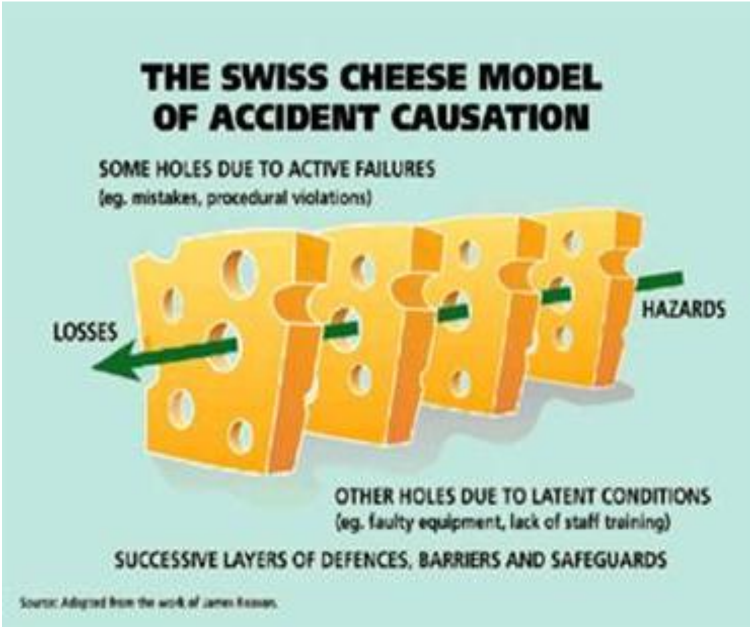


Figure 9-3: Swiss Cheese Model

The gaps in the cheese slices are assumed to be in continuous motion. They open, shut and move around. Only if each slice happens to have a gap in line with the other slices an accident will take place and losses will be suffered (Reason 2008: 101ff.).

The most fruitful notion of the Swiss cheese model for flood management is the idea that the barriers show different imperfections during time. This captures the dynamic of the society and the dike ring. It shows that imperfections are not necessarily fatal but also indicates the difficulty of predicting when they do lead to accidents. With each cheese layer the probability that all of them will have gaps in line will decrease and the reliability and safety of the system will increase.

9.1.4 Bow Tie Model

The bow tie model examines the causes and the consequences of an accident. The knot in the middle is the actual accident that links the fault tree on the left side with the event tree on the right side. The fault tree indicates the causes that lead to an accident. The event tree describes the consequences of the event and therefore inventories the losses. As this model includes the causes as well as the consequences it is a widely used model in risk reduction. Similar to the models introduced above the bow tie pictures multiple lines of defense. Each of these lines is an opportunity for risk reduction measures to set in. Usually running through several scenarios is necessary to make a bow tie complete.

Leveson criticizes that fault and event trees, just as other event chain models, are based too strongly on linear causality relationships and encourage moving away from non-linear relationships and feedback mechanisms. Furthermore, social factors as management commitment to safety and the safety culture cannot be included (Leveson 2004: 240).

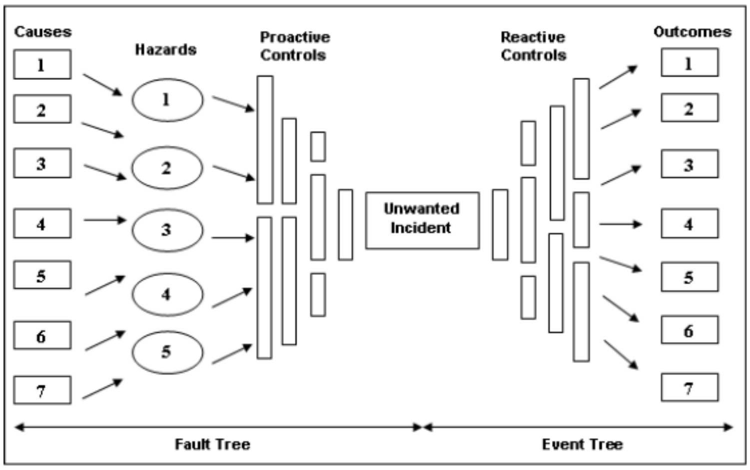


Figure 9-4: Bow Tie Model (Guldenmund 2009: slide 44)

Fault trees and event trees are useful tools to analyze what actually causes a flood and what the consequences are. This method makes it possible to identify the nature of the system (series or parallel system) and the probability and severity of consequences. Fault trees are often used to determine the reliability of systems that are being designed probabilistic. Indeed the fault tree method will be used to analyze the effect of MLS on failure of the flood safety system in Chapter 4.4.

The criticism on the exaggerated linearity of fault and event trees can also be recognized in the complex of problems in relation to flood safety. Indeed it is common practice to ignore or only mention on the side, feedback mechanisms as the risk spiral. Reducing the frequency of flooding will encourage building more houses. The increasing value to be protected then requires better protection and so forth (Seo 2006: 43). Another feature of flood management that often is studied separately concerns the cost of flood management measures. In reality those costs actually do interact with the state of the flood protection system. For a long-term view this interaction should not be ignored. Thus, the extreme linearity of fault and event trees makes them less suitable to serve as the foundation of a theoretical framework for MLS.

9.2 Appendix: Link theoretical framework and risk-based approach

9.2.1 Parallels risk-based approach and theoretical framework

To calculate the risk the following *risk parameters* have to be calculated (compare Chapter 2.3):

- probability of flooding P_{flood}
- number of affected $n_{eff}(x,y)$
- inundation depth $h(x,y)$ as a function of ground level $z(x,y)$ and water level WL

- damage factor Dam(x,y) as a function of inundation depth h(x,y)

Those four parameters are sufficient to calculate the three dimensions of risk as introduced in Chapter 2.2 (Economic Risk, Individual Risk and Group Risk). If one of those parameters increases, the risk grows as well. Put differently, **these are the four buttons with which the risk profile can be tuned**.

One of the ways to visualize flood risk is shown in Figure 9-5. In this figure loss can stand for material damage (FS-curve) or fatalities (FN-curve) respectively a combination of both.

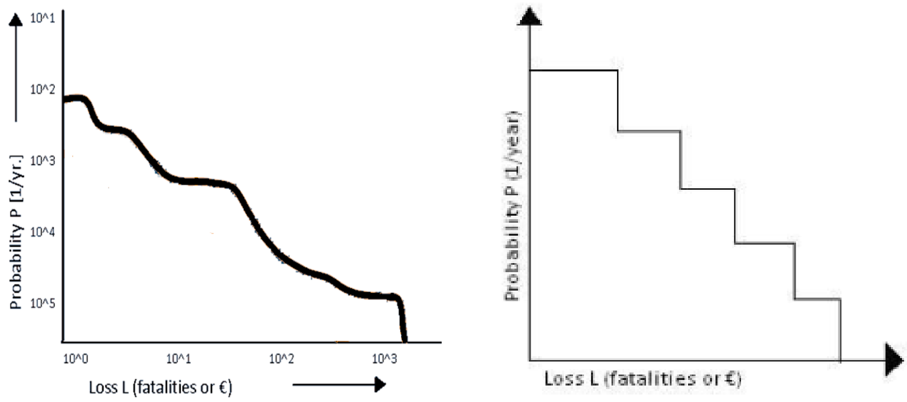


Figure 9-5: Two examples of a FN/FS-curve for a random risk

9.2.2 Differences risk-based approach and theoretical framework

In the risk-based approach a flood equals a dike breach. Thus the probability of flooding equals the probability of a dike breach. The theoretical framework from Chapter 3.5 is meant for all flood-prone areas, not only those that are surrounded by a dike. Therefore, in the theoretical framework a flood is defined as the situation when water covers ground that is normally dry (compare Figure 2-13). The aim of flood risk management is then decreasing the probability of loss due to a flood.

As a result of those different definitions of flood the definition of the probability of flooding differs as well. The risk-based approach assumes that the probability of flooding is equal to the probability of a dike breach. Thus the probability is split in two: The probability that a high water load occurs and the probability that the dike is not strong enough. The new theoretical framework understands the probability of flooding as the probability of certain water levels to occur. This is equal to the first part of the probability of flooding according to the risk-based approach.

In the theoretical framework the dike ring is not used as basis to define respectively calculate risk. A dike ring and the heightening of it, is rather seen as just another flood management measure. If a dike ring is already there, it is assumed that one flood management measures has already been taken. In other areas the houses might already be elevated or flood-proof. Thus, in such a situation measures should be chosen that combine well with the measure already taken.

Another difference between the two approaches is the notion of failure. The risk-based approach follows a black-and white notion of a flood: flooded or dry. The theoretical framework is based on degrees of flooding that cause degrees of losses between *no loss* and *total loss*.

Yet another difference is the fact that in the risk-based approach a measure failed if water reaches the vulnerable object. Thus as soon as a house becomes wet, the measure, e.g. a terp, has failed. In the theoretical framework from Chapter 3.5 a measure fails (partially) if it does not live up to its design capacity. A terp that is flooded still reduces the inundation depth for the houses on top of it and thus still reduces the flood risk. It is considered to fail if e.g. it is eroded away. In the theoretical framework the correlation between inundation depth and failure is thus much smaller than in the risk-based approach.

9.2.3 Deeper analysis of risk

The theoretical framework is based on a number of strategies, derived from a theory of Haddon (Chapter 3.4.4). The theoretical framework indicates the physical functioning of the flood management measures. It indicates which buttons, identified in Chapter 9.2.1, a measures turns to tune the risk profile. To understand the way in which the measures turn those buttons better, first a deeper analysis of risk is given here.

An area is characterized by the values the risk parameters from Chapter 9.2.1. Those parameters can have endless combinations of values. Thus the flood risk profile in different areas will never be the same, even if the total flood risk is the same. E.g. flood risk can be a consequence of a large number of exposed objects or of a high frequency of flooding or a certain combination of both. Thus each FN-/FS-diagram is based on a different structure of risk.

The risk structure is mainly characterized by the fact that the risk parameters are closely related to each other. For example an object is only effected by the flood if the inundation depth h>0. The ground level determines if h>0 depending on the water level WL. The relationship between the risk parameters is different for each area and determines which value combinations of the risk parameters occur in an area. Successful flood management anticipates these characterizing relationships of the flood parameters

Table 9-1 introduces the characterizing relationships between the risk parameters. The shown functions are used later to visualize the effect of flood management measures on the flood risk. Additionally, those functions make it possible to study the interaction flood management measures have.

Table 9-1: Functions characterizing area at risk

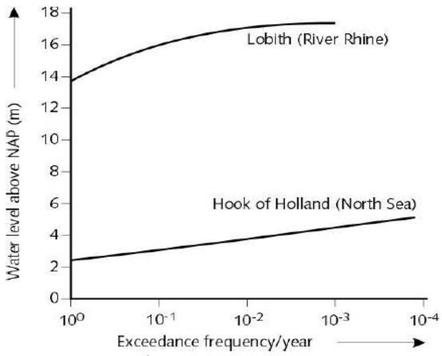
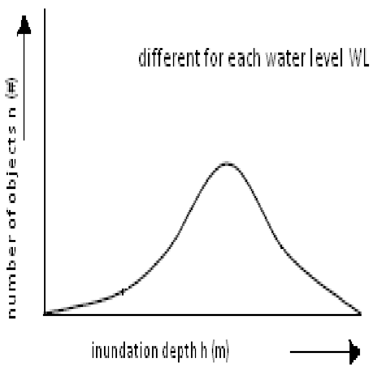
<table>
<tr><th>Visualization</th><th>Explanation</th></tr>
<tr><td>Hazard Source</td><td></td></tr>
<tr><td>
</td><td>The boundary conditions represent the hazard sources. The diagram shows which water levels occur with which probability in the river or at sea. It is also possible to combine two hazard sources into one function. In this study it is assumed that the water level in the flooded areas equals the water level resulting from the combined hazard sources, thus the water level in the supplying body of water (e.g. in the river). The frequency of exceeding is the inverse of the probability of occurrence per year.</td></tr>
<tr><td>Exposure</td><td></td></tr>
<tr><td>

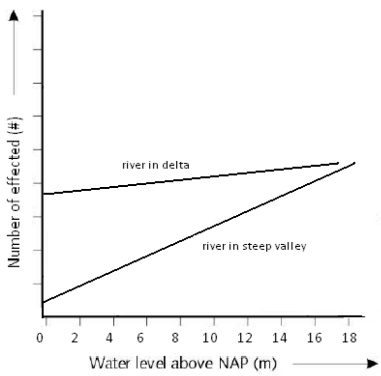
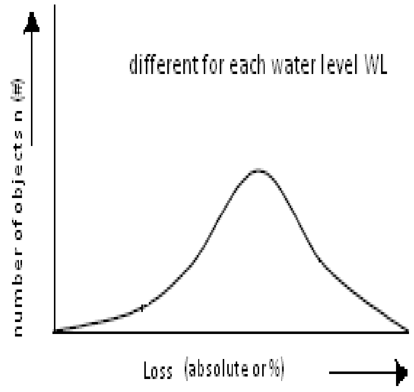
Figure 9-7: Exposure diagram

</td><td>The exposure is quantified by the number of affected objects and the degree with which they are affected, thus the inundation depth (see Figure 9-7). Each inundation depth occurs with a certain probability, as defined by the boundary conditions.
The number of effected objects n depends on how much area is flooded given a certain water level and how densely populated that area is (Figure 9-6).

Figure 9-7 and Figure 9-6 can be combined to a 3D-diagram.

How much area is flooded is strongly influenced by the landscape. In a river or at a coast with steep shores, like in a narrow valley or at a bold coast, higher water levels do not flood much more area surface. The diagram thus will show an only slightly sloped line. In river delta's though the landscape usually is rather flat, so that a small increase in water level results in a much bigger area being flooded. The function in Figure 9-6 will then be steep. If at all, in this case only the amount of water in the flood peak and the distance from the river have limiting influence on the extent of the flooded area. If the area is flooded from the sea, there are virtually no limits; there will just be a delay in time until the flood arrives.</td></tr>
</table>

Vulnerability	The vulnerability function
 **Figure 9-8: Loss diagram**	Each object has its own vulnerability function. The vulnerability function expresses how much loss the object suffers when coming in contact with water. To calculate the loss, additionally the value of the object has to be known. For human lives there are no degradations in value. The vulnerability function transforms the exposure diagram (Figure 9-7) to the loss diagram in Figure 9-8. An area is characterized by this diagram because every area has different objects with different vulnerability functions in it. So even if the exposure diagram is the same for two areas, the loss diagram can differ. Again this diagram can be extended to a 3D diagram by including the Water Level or the probability of certain Water Levels as a third axis (compare above).

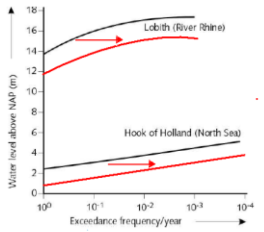
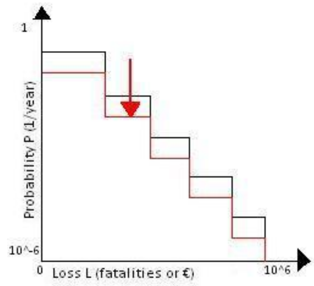
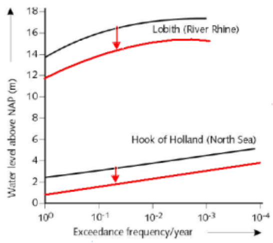
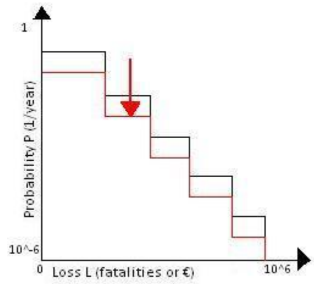
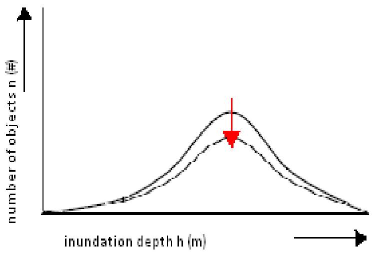
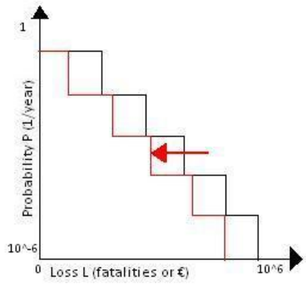
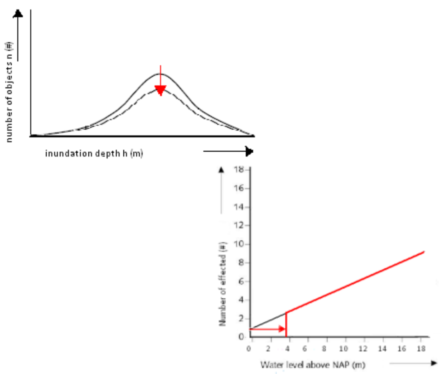
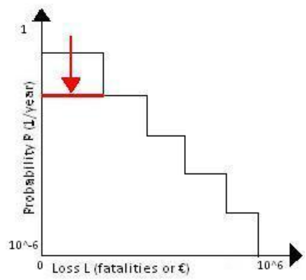
9.2.4 Strategies in the theoretical framework and the risk-based approach

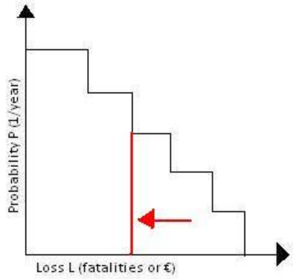
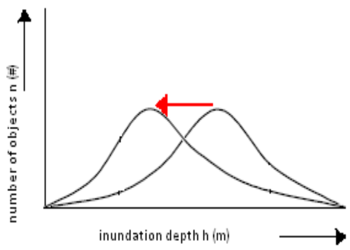
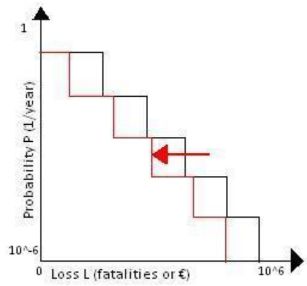
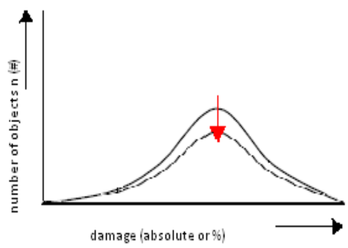
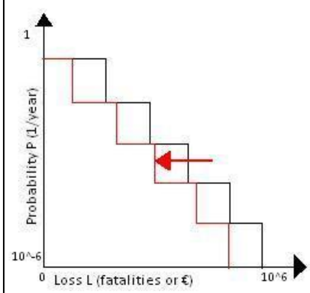
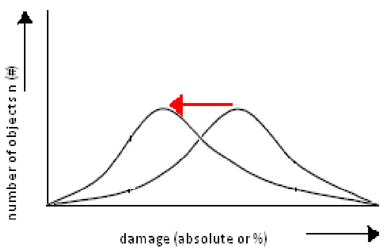
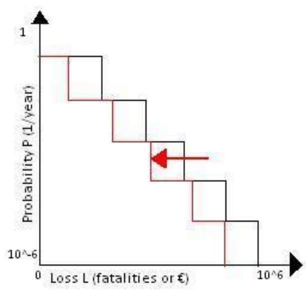
Haddon's strategies, introduced in Chapter 3.5, can be used to categorize flood management measures by their physical way of functioning. This means that Haddon's strategies describe what actually happens in real-life terms, e.g. are vulnerable objects adapted or are they protected by a barrier. In the following those strategies are therefore translated to flood management.

As mentioned in Chapter 3.4.4 Haddon introduced his sequence of strategies to give a full account of the available strategies to protect a target from a hazard. It is expected that flood risk management is no exception, so that the Haddon's approach will give a comprehensive cover of all actions thinkable. Furthermore Haddon stated that the larger the energy that threats the target, the higher a chosen strategy should ideally lay in his sequence (compare Chapter 3.4.4). Translated to flood risk management, this means the larger the absolute value of risk, the higher strategies should be chosen in Haddon's sequence. Nonetheless, Haddon does note that practicability does limit this approach (see p.60).

The first column of Table 9-2 shows Haddon's strategy and the second column translates them to flood management. In the previous subchapter (Chapter 9.2.3) an in-depth description of the risk parameters was given. Those parameters can be understood as buttons that tune the risk profile. The second last column of Table 9-2 shows the way that the flood management measures actually turn these buttons. The last column indicates the way of functioning according to the risk-based approach. Chapter 9.2.5 discusses the link between the theoretical framework and the labels probability- and risk-reducing. Note that in the used version of the risk-based approach a probability of exeedance (*overschrijdingskans*), rather than a probability of flooding (*overstromingskans*) (see Chapter 2.5.2) is assumed.

Table 9-2: Haddon's safety strategies translated to flood risk management

	Haddon	Practical way of functioning	Theoretical way of functioning		
			Dimension effected	Visualization effect on characterizing functions	Visualization effect on overall risk
3	Prevent release of hazard	Prevent extreme amounts of water in system	Boundary conditions		
4	Modify rate of release of hazard source	Relief extreme hydraulic situation			
5	Separate in space and time hazard source and object	Reduce number of objects in flood-prone area	Exposure		
6	Use a barrier between the hazard and the objects	Reduce number of effected using a **barrier**			

	Haddon	Practical way of functioning	Theoretical way of functioning		
			Dimension effected	Visualization effect on characterizing functions	Visualization effect on overall risk
					
7	Modify contact surface of hazard source	Decrease degree by which objects are effected			
8	Strengthen objects against hazard	Prevent that effected objects suffer damage			
9	Mitigation	Reduce occurring damage among effected	Vulnera-bility		
10	Reparative strategies/stabilization	*Make damage undone*	*Increase Resilience*		

While the strategies aimed at the boundary conditions change the flood characteristics, the exposure and vulnerability oriented strategies reduce the consequences of those water levels. Strategy 5 and 7 do so by reducing the number of affected respectively the inundation depth. As an object is affected if the inundation depth h is h > 0m, both strategies come down to the same process, namely reducing the exposure. The integrated exposure function shows where the difference lies: Strategy 5 shifts the function to the side while strategy 7 causes a downward shift. Strategies 8-9 reduce the suffered damage.

9.2.5 Translation of theoretical approach to probability- or loss-reducing

In the risk-based approach the distinction between probability- or loss-reducing is crucial. This paragraph examines if measures would be probability- or loss reducing according to the new theoretical framework.

Strategies that set in on reducing the hydraulic load by lowering the boundary conditions are understood to reduce the probability of those hydraulic loads to occur. It follows that in terms of risk (= probability*loss) the strategies 3 and 4 lead to probability reduction. Those strategies shift the risk diagram downwards. The strategies 5-9 (except strategy 6) on the other hand reduce the loss suffered by either decreasing the exposure (strategies 5-7) or the vulnerability (strategies 8-9). Those consequence-reducing strategies shift the risk diagram to the side. It is disputable if strategy 6, barriers, reduces the occurrence of a hydraulic load somewhere or reduces the exposure to a hydraulic load. According to the first vision, barriers would have to be probability-reducing. If the reduce the exposure they are loss-reducing though.

See Table 3-4 to Table 3-6 and Figure 3-8 in Chapter 3.5.3 to see the flood management measures sorted by strategy. Table 3-7 in the same chapter indicates if those measures are probability- or loss-reducing. That table is based on this paragraph.

9.3 Appendix: Parameter analysis

This parameter analyzes and discusses the parameters that are needed for to calculate the risk. Since this parameter analysis is done in preparation for examining the interaction between flood management measures, the relationships between the parameters will be given attention as well.

For this study the parameters are clustered in four classes (see Figure 9-9):

- (Flood) scenarios
- Location and it's characteristics
- Flood characteristics
- Object characteristics

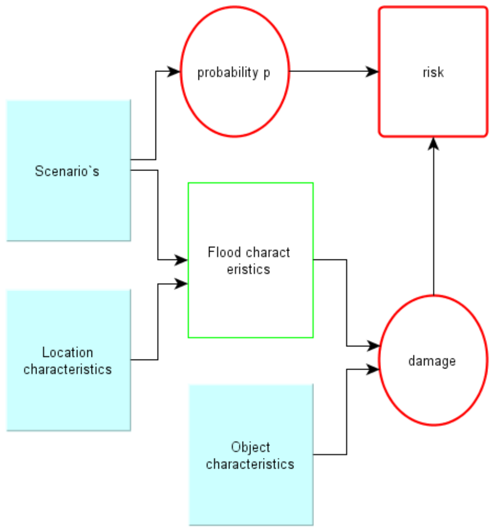


Figure 9-9: Schematization of groups of parameters used in the computational model

These four categories will be elaborated in the following based on the practice of calculating risk (see Chapter 2.3).

Scenarios

There are different scenarios thinkable for the social and physical surroundings such as the climate, the management of water systems, political and economical developments. Most types of scenarios influence the physical properties of the system. Social factors determine how many people live where in what kind of houses and how much value there is to be protected in general. The physical surroundings point to processes as climate change but also land subsidence and others. As for the computational model the flooding scenarios are of special importance; this type of scenario is further explained in the following.

Flooding scenario

Each scenario consists of the external hydraulic load S (“solicitation”) and the breach location B depending on the strength of the flood defense R (“resistance”). Depending on those characteristics each scenario has a probability of occurring attached to it. Note that a breach can also be of controlled origin.

Location and its characteristics

The location is identified by the parameters x,y. Each location has an altitude respectively ground level z. The location is modeled as a grid with $\Delta x, \Delta y$ = 100m.

Flood characteristics

These characteristics are indicated by the rise rate r and the flow velocity v of the water as well as the inundation depth h and the duration of inundation t. The flood characteristics depend on the scenario, more specifically on where water enters in which manner. This is indicated by the scenario parameters breach location and external hydraulic load. Furthermore these flood characteristics are dependent on some characteristics of the location, namely [x,y] and z(x,y). The location x&y is taken separately because it matters how far a location is situated from the breach.

Object characteristics

The type of object at risk is indicated by assigning a land use Lu to each location. The number of people at risk is based on the number of registered citizens per postcode. Depending on its infrastructure and position in the dike ring each location has an evacuation factor Ef attached to it. A national database of all buildings is used to determine the number and type of the real estate etc.

The actual loss caused is calculated using the flood characteristics and the damage factor d respectively mortality factor m. These two factors are a point on damage respectively mortality functions (D resp. M) depending on the flood characteristics. Each land use Lu is linked to another damage function. Furthermore the maximal damage D_{max} of the objects is relevant. In case of humans the maximal damage is naturally death. These three parameters are labeled vulnerability in this study.

Each land use has at least one damage function assigned to it. The land use but also the probability of flooding influences how many buildings are in the area and how many people live there. The number of dead is further compromised by the evacuation factor Ef indicating the number of people being subject to preventive evacuation. This factor depends in physical terms mainly on the infrastructure of the area and the warning time. It is further influenced by the number of people to be evacuated.

Link to the notions exposure and vulnerability

When recalling the difference made between exposure of a flood and the vulnerability, as introduced in Chapter 3.4.3 it is interesting to note that the flood, location and object characteristics excluding the vulnerability parameters determine the exposure. With exposure it is meant who or what is exposed to flooding in what manner. More concretely the exposure indicates which number of people and objects are exposed to which flood characteristics. When combining the exposure with the vulnerability the extent of the loss can be derived. Together with the probability of the scenario the flood risk can be computed. At this point it is assumed that flood, location and object characteristics are deterministic parameters.

Overview

The parameters identified above and their dependencies among each other are schematized in the Figure 9-10, for both objects and human lives. That scheme is based on the flow chart in Figure 4-3. In the schematization in Figure 9-10 the arrows point to the parameters that depend on the parameter from which the arrow is departing. The red arrows represent the interdependencies which the computational model is based on. The black arrows indicate any further interdependencies. The interdependencies are summed up in Table 9-3.

Table 9-3: Overview of interdependencies of the parameters

Classes	Parameters	Dependent on:	
Flooding scenario	• (Probability of flooding p) • breach location B, depending on strength R • external hydraulic load S	*Probability:* breach location external hydraulic load	p=(B, S)
Location characteristics	• *Location [x,y]* • Altitude z(x,y)		
Flood characteristics	• Rise rate r • flow velocity v • inundation duration t • inundation depth h	*All flood characteristics:* • Breach location B • External hydraulic load S • Location x,y • altitude z	Flood characteristics = f(x,y,z,B,S)
Object characteristics	• Land use Lu • number of units n_i • Evacuation factor Ef • mortality function M • damage function D	*Number of units:* land use Lu probability n *Evacuation factor:* number of units n_i location x,y *Damage factor:* land use Lu	Lu = f(-) n=f(Lu, p) Ef=f(x,y,n_i) D= f(Lu) M=f(-)

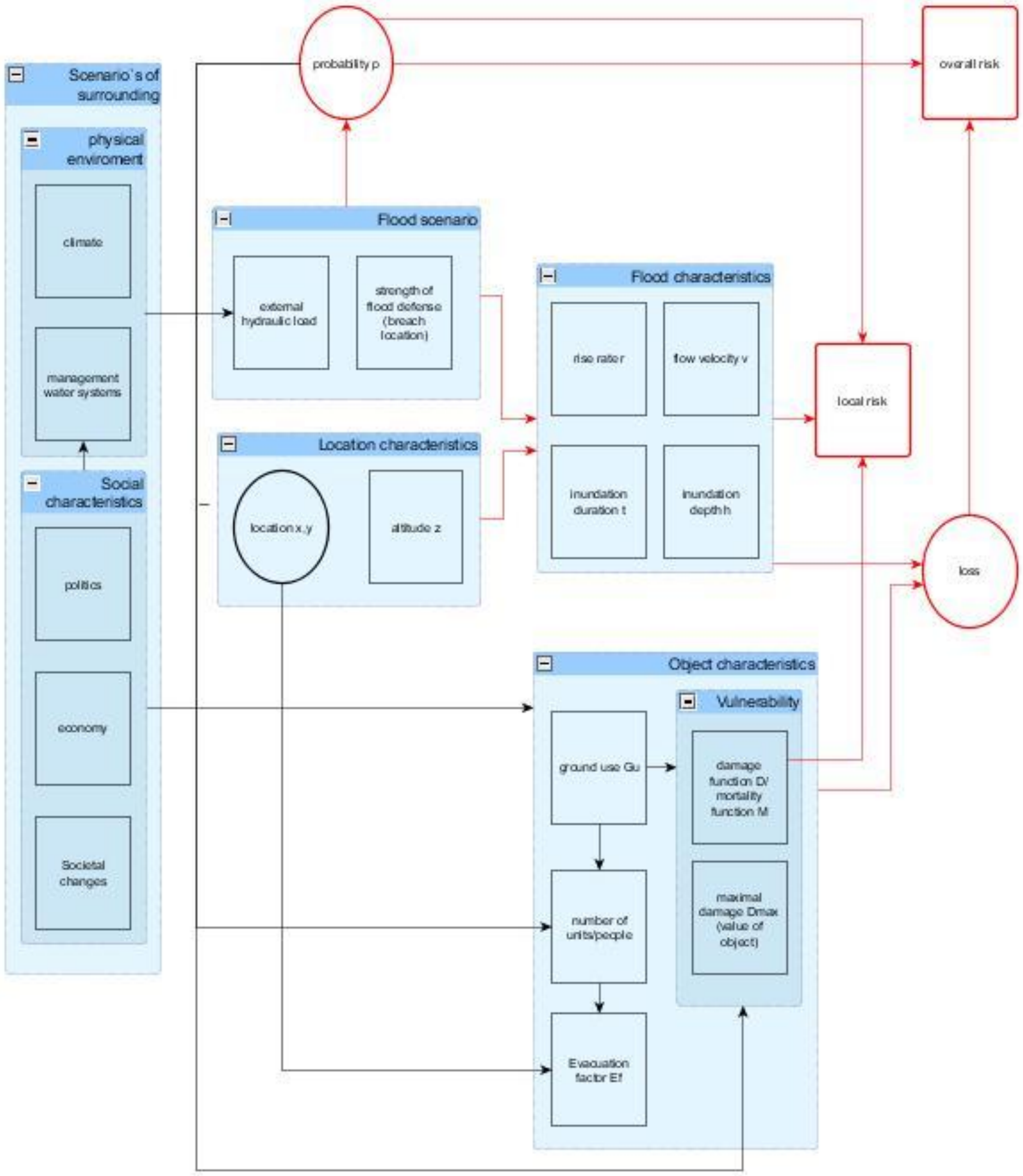


Figure 9-10: Parameter Analysis

Discussion of parameters

When looking at the schematization of the parameter analysis in Figure 9-10, a few things can be noticed. First of all, it is interesting to observe that the classes of parameters *Scenario* and *Location characteristics* are not depending on any of the other parameters. The *Flood characteristics* on the contrary depend on some of the parameters representing the Scenario and Location characteristics. The *Object characteristics* depend on some of the location characteristics and in one case on the probability of flooding. Taking a step back, it can be said that there is little interaction between the parameter classes apart from the interactions which the computational models are based upon. Only the object parameters show some interdependence among each other.

- *Probability:* Reviewing the discussion above a few conclusions to be used for flood management can be derived. Starting from a risk perspective the probability can only be changed if scenario properties such as boundary conditions or the strength of the flood defenses are influenced. It has to be remembered though that the scenario parameters also influence the flood characteristics. Another tricky interaction lies in the fact that the probability of flooding has influence on how many people settle in the area. So changing those parameters would not only alter the probability but also the loss, thus resulting in a more complex effect on the overall risk.

- *Exposure:* The exposure can be influenced by changing the flood and location characteristics. Doing this one has to be aware that the flood characteristics depend on the location characteristics, possibly resulting in adverse effects. A strategy to get around this interdependence would be to alter the flood characteristics without affecting the location characteristics.

- *Object characteristics/vulnerability:* Leaving the location characteristics unchanged would prevent unintended effects on the object characteristics. The vulnerability does show one interaction that is not captured by the computational models: Investing in a lower vulnerability means increasing the value of the object in question. Consequently the maximal damage of this object and thus the vulnerability increases. Thus there is an optimum for the vulnerability.

Summing up, it can be said that concentrating on flood characteristics and object characteristics makes it possible to directly manage exposure and loss. In case of manipulating the flood characteristics, their dependency on the probability has to be considered. This leaves the object parameters as the ones with the best-predictable effects. On the other side of the coin, measures adjusting the location characteristics skillfully might have an extraordinary positive effect since they influence most classes of parameters.

Finally, it should be noted that the effects all parameters have on the costs of flood protection are not considered in this parameter analysis.

9.4 Results *Mouillé*

9.4.1 Appendix: Calculation Results Hypothetical Case Study Mouillé

		Neighborhood					Dike ring			
RISK										
		total costs	ER	IR	GR		total costs	ER	IR	GR
	REF1	0	1	0.000004	0.0000	REF1	0	469,950	0.000004	0.0730
	REF2	0	132,550	0.000004	0.0207	REF2	0	602,500	0.000004	0.0938
	1 – 3	60,000,000	66,275	0.000002	0.0104	1 – 3	60,000,000	301,250	0.000002	0.0469
	1 – 4	30,000,000	88,367	0.000003	0.0138	1 – 4	30,000,000	401,667	0.000003	0.0625
	1 – 6a	60,000,000	26,510	0.000001	0.0041	1 – 6a	60,000,000	120,500	0.000001	0.0188
	1 – 6b	90,000,000	13,255	0.000000	0.0021	1 – 6b	90,000,000	60,250	0.000000	0.0094
	1 – 7	110,000,000	84,350	0.000003	0.0131	1 – 7	110,000,000	313,300	0.000002	0.0468
	2 – 5	60,000,000	84,350	0.000003	0.0131	2 – 5	60,000,000	554,300	0.000004	0.0861
	2 – 6	100,000,000	42,175	0.000001	0.0072	2 – 6	100,000,000	530,200	0.000003	0.0835
	2 – 7	10,000,000	84,350	0.000003	0.0131	2 – 7	10,000,000	554,300	0.000003	0.0861
	2 – 8a	6,000,000	132,550	0.000004	0.0207	2 – 8a	6,000,000	602,500	0.000004	0.0938
	2 – 8b	16,000,000	1	0.000004	0.0207	2 – 8b	16,000,000	469,950	0.000004	0.0938
	3 – 5a	7,500,000	132,550	0.000004	0.0176	3 – 5a	7,500,000	602,500	0.000004	0.0907
	3 – 5b	40,000,000	132,550	0.000004	0.0041	3 – 5b	40,000,000	602,500	0.000004	0.0772
	3 – 6	3,691,588	106,040	0.000003	0.0166	3 – 6	3,691,588	482,000	0.000003	0.0750
	3 – 8	2,768,691	119,295	0.000004	0.0187	3 – 8	2,768,691	589,245	0.000004	0.0917

		Neighborhood					Dike ring	dike ring		
RISK REDUC.			neighborh.							
(fraction)		total costs	Economic Ris	Inidvidual Ris	Societal Risk reduction		total costs	Economic Risl	Inidvidual Risk	Societal Risk reduction
	REF1	*0*	*0.00*	*0.00*	*0.00*	*REF1*	*0*	*0.00*	*0.00*	*0.00*
	REF2	*0*	*0.00*	*0.00*	*0.00*	*REF2*	*0*	*0.00*	*0.00*	*0.00*
	1 – 3	60,000,000	0.50	0.50	0.50	1 – 3	60,000,000	0.50	0.50	0.50
	1 – 4	30,000,000	0.33	0.33	0.33	1 – 4	30,000,000	0.33	0.33	0.33
	1 – 6a	60,000,000	0.80	0.80	0.80	1 – 6a	60,000,000	0.80	0.80	0.80
	1 – 6b	90,000,000	0.90	0.90	0.90	1 – 6b	90,000,000	0.90	0.90	0.90
	1 – 7	110,000,000	0.36	0.37	0.37	1 – 7	110,000,000	0.48	0.41	0.50
	2 – 5	60,000,000	0.36	0.37	0.37	2 – 5	60,000,000	0.08	0.00	0.08
	2 – 6	100,000,000	0.68	0.65	0.65	2 – 6	100,000,000	0.12	0.19	0.11
	2 – 7	10,000,000	0.36	0.37	0.37	2 – 7	10,000,000	0.08	0.10	0.08
	2 – 8a	6,000,000	0.00	0.00	0.00	2 – 8a	6,000,000	0.00	0.00	0.00
	2 – 8b	16,000,000	1.00	0.00	0.00	2 – 8b	16,000,000	0.22	0.00	0.00
	3 – 5a	7,500,000	0.00	0.00	0.15	3 – 5a	7,500,000	0.00	0.00	0.03
	3 – 5b	40,000,000	0.00	0.00	0.80	3 – 5b	40,000,000	0.00	0.00	0.18
	3 – 6	3,691,588	0.20	0.20	0.20	3 – 6	3,691,588	0.20	0.20	0.20
	3 – 8	2,768,691	0.10	0.10	0.10	3 – 8	2,768,691	0.02	0.03	0.02

		Neighborhood						Dike ring				
abs. Risk reduc.		total costs	ΔER (NPV)	I/Δ(IR)	CSX neighborhood	I/NCW(dER)		total costs	ΔER (NPV)	I/Δ(IR)	CSX dike ring	I/NCW(dER)
	REF1	*0*	0	*0*	0	Neighborhood	*REF1*	*0*	0	*0*	0	Dike Ring
	REF2	*0*	0	0	0		*REF2*	*0*	0	0	0	
	1 – 3	60,000,000	3,313,750	2.89E+13	5,788,371,969	18.1	1 – 3	60,000,000	15,062,500	3.19E+13	1,279,624,907	4.0
	1 – 4	30,000,000	2,209,167	2.17E+13	4,341,278,976	13.6	1 – 4	30,000,000	10,041,667	2.39E+13	959,718,680	3.0
	1 – 6a	60,000,000	5,302,000	1.81E+13	3,617,732,480	11.3	1 – 6a	60,000,000	24,100,000	1.99E+13	799,765,567	2.5
	1 – 6b	90,000,000	5,964,750	2.41E+13	4,823,643,307	15.1	1 – 6b	90,000,000	27,112,500	2.66E+13	1,066,354,089	3.3
	1 – 7	110,000,000	2,410,000	7.19E+13	14,374,469,107	45.6	1 – 7	110,000,000	14,460,000	7.13E+13	2,341,303,922	7.6
	2 – 5	60,000,000	2,410,000	NA	7,840,619,513	24.9	2 – 5	60,000,000	2,410,000	NA	7,840,619,513	24.9
	2 – 6	100,000,000	4,518,750	3.70E+13	7,399,507,795	22.1	2 – 6	100,000,000	3,615,000	1.37E+14	9,683,774,407	27.7
	2 – 7	10,000,000	2,410,000	6.53E+12	1,306,769,919	4.1	2 – 7	10,000,000	2,410,000	2.61E+13	1,306,769,919	4.1
	2 – 8a	6,000,000	0	NA	0	0.0	2 – 8a	6,000,000	0	NA	0	0.0
	2 – 8b	16,000,000	6,627,450	NA	0	2.4	2 – 8b	16,000,000	6,627,500	NA	0	2.4
	3 – 5a	7,500,000	0	NA	2,411,821,654	NA	3 – 5a	7,500,000	0	NA	2,411,821,654	NA
	3 – 5b	40,000,000	0	NA	2,411,821,654	NA	3 – 5b	40,000,000	0	NA	2,411,821,654	NA
	3 – 6	3,691,588	1,325,500	4.45E+12	890,345,194	2.8	3 – 6	3,691,588	6,025,000	4.90E+12	196,827,000	0.6
	3 – 8	2,768,691	662,750	6.68E+12	1,335,517,792	4.2	3 – 8	2,768,691	662,750	2.67E+13	1,335,517,792	4.2

Table 9-4: Computation results *Mouillé*, all measures compared

Table 9-5: CEA for MLS layers

CBA	NEIGHBORHOOD							DIKE RING		
			I/NPV(dER)	I/Δ(IR)	CSX			I/NPV(dER)	I/Δ(IR)	CSX
Prevention	1 – 3		18.1	2.89E+13	5.79E+09		1 – 3	4.0	3.19E+13	1.28E+09
	1 – 4		13.6	2.17E+13	4.34E+09		1 – 4	3.0	2.39E+13	9.60E+08
	1 – 6a		11.3	1.81E+13	3.62E+09		1 – 6a	2.5	1.99E+13	8.00E+08
	1 – 6b		15.1	2.41E+13	4.82E+09		1 – 6b	3.3	2.66E+13	1.07E+09
	1 – 7		45.6	7.19E+13	1.44E+10		1 – 7	7.6	7.13E+13	2.34E+09
	Average		20.7	3.29E+13	6.59E+09		Average	4.1	3.47E+13	1.29E+09
Spatial Solutions	2 – 5		24.9	NA	7.84E+09		2 – 5	24.9	NA	7.84E+09
	2 – 6		22.1	3.70E+13	7.40E+09		2 – 6	27.7	1.37E+14	9.68E+09
	2 – 7		4.1	6.53E+12	1.31E+09		2 – 7	4.1	2.61E+13	1.31E+09
	2 – 8a		NA	NA	NA		2 – 8a	NA	NA	NA
	2 – 8b		2.4	NA	NA		2 – 8b	2.4	NA	NA
	Average		13.4	6.53E+12	5.52E+09		Average	14.8	2.61E+13	6.28E+09
Crisis Management	3 – 5a		NA	NA	2.41E+09		3 – 5a	NA	NA	2.41E+09
	3 – 5b		NA	NA	2.41E+09		3 – 5b	NA	NA	2.41E+09
	3 – 6		2.8	4.45E+12	8.90E+08		3 – 6	0.6	4.90E+12	1.97E+08
	3 – 8		4.2	6.68E+12	1.34E+09		3 – 8	4.2	2.67E+13	1.34E+09
	Average		3.5	5.6E+12	1.76E+09		Average	2.4	1.6E+13	1.59E+09

9.4.2 Appendix: Diagrams *Mouillé;* effectiveness of measures

Table 9-6: FS-/FN-curve for Prevention measures

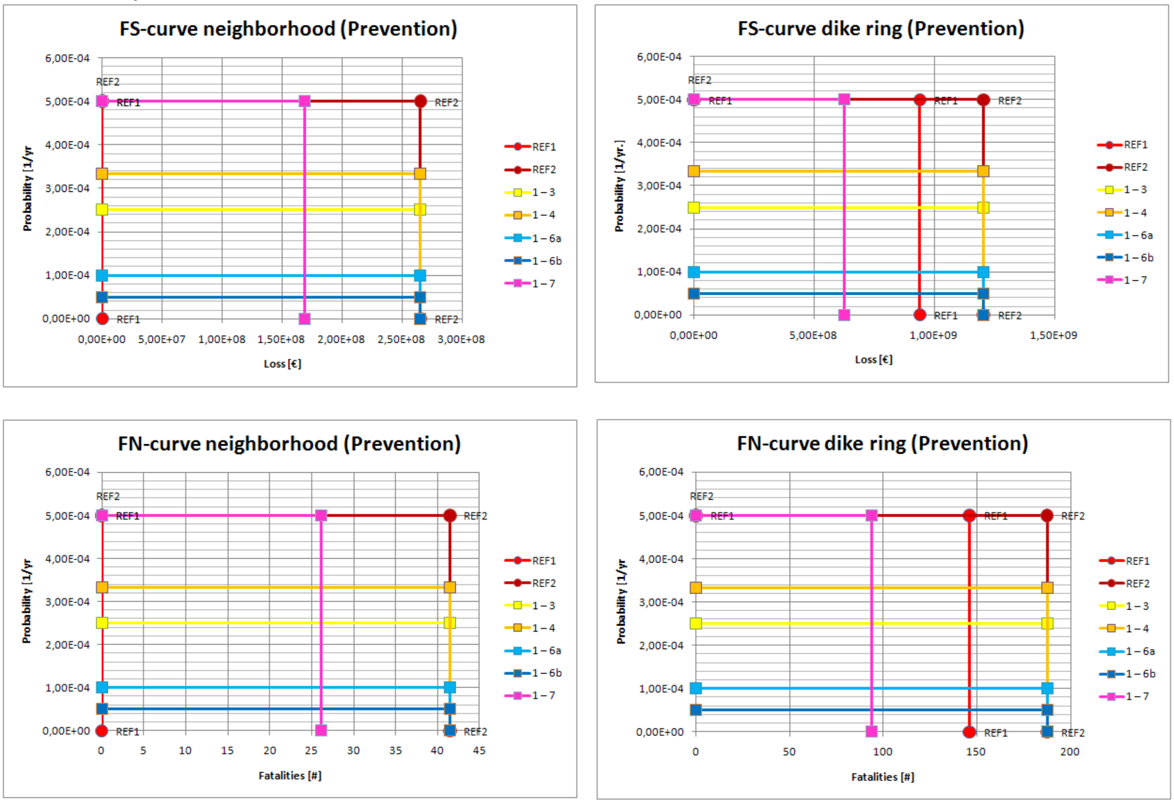


Table 9-7: FS-/FN-curve for Spatial Solution measures

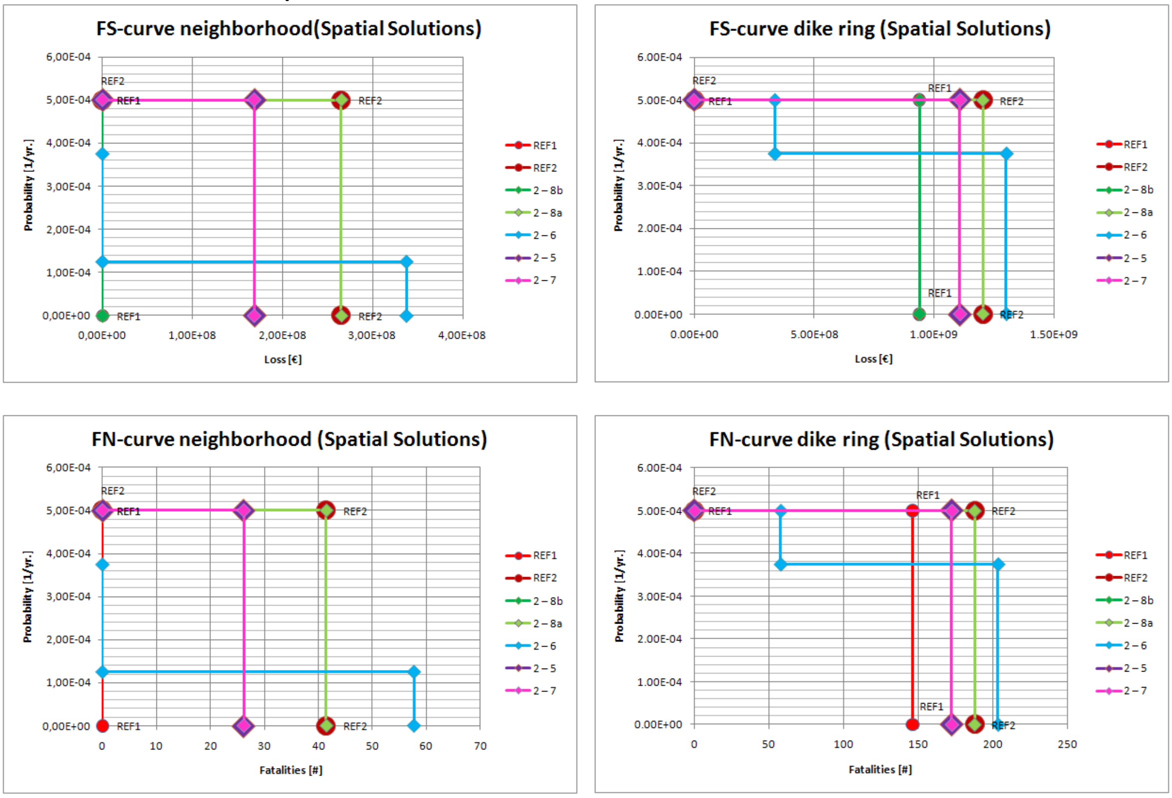
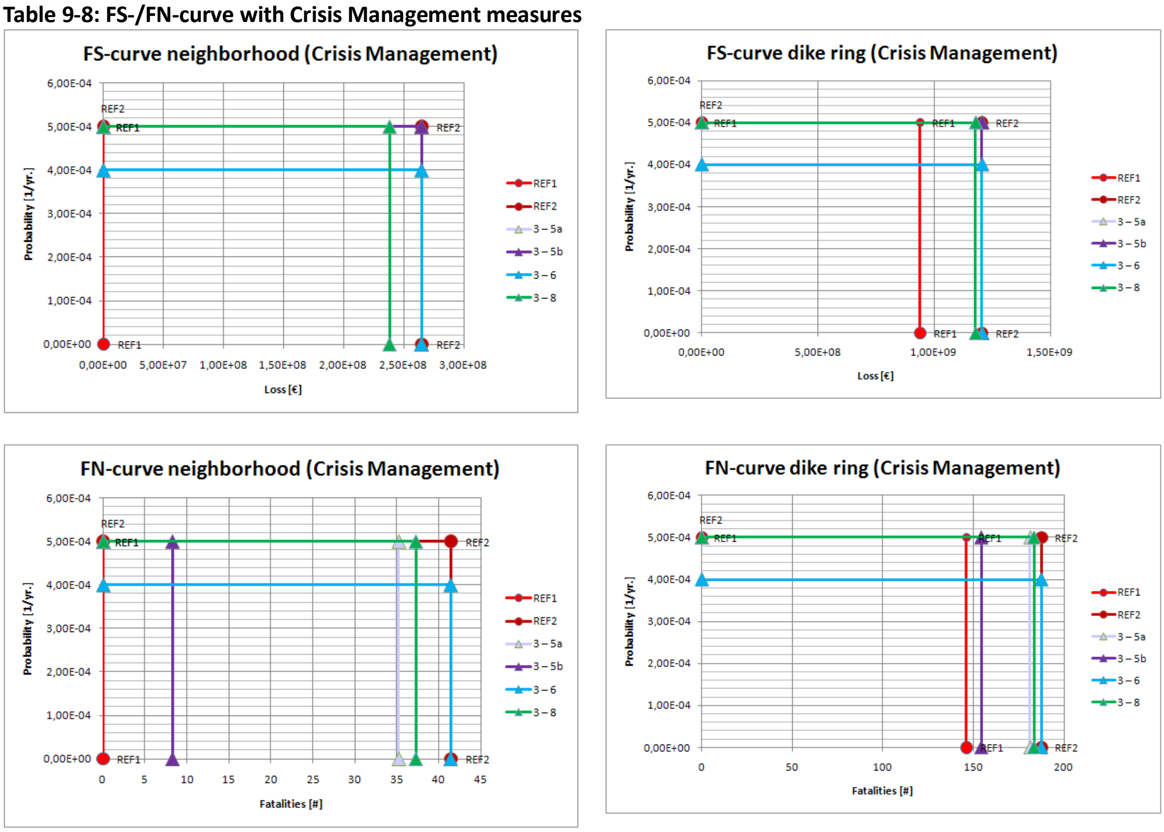


Table 9-8: FS-/FN-curve with Crisis Management measures

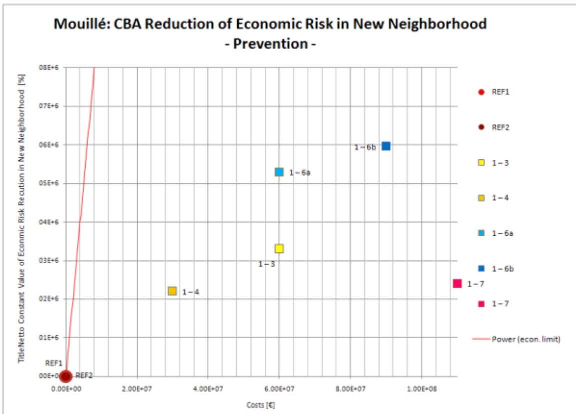


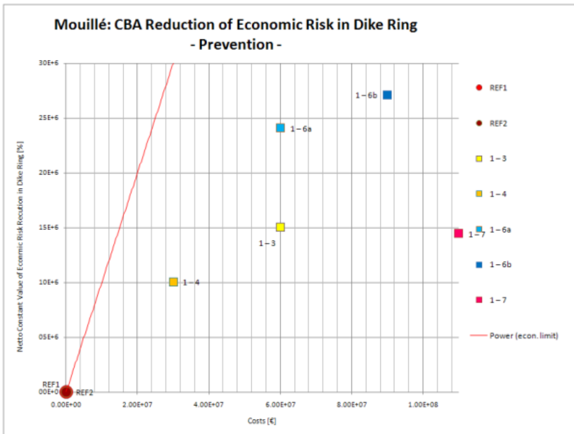
9.4.3 Appendix: Diagrams *Mouillé;* cost-efficiency of measures

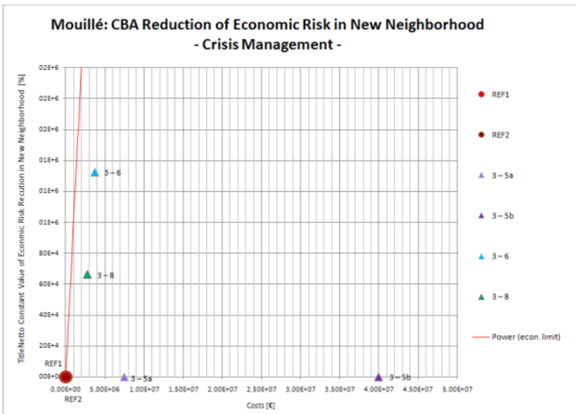
The following diagrams show this cost-benefit-relation for the individual measures. Each diagram stands for another MLS layer. The red line represents the justifying rule that was just reviewed. Measures on the right of that red line are not economically wise investments. The measures situated on the left of the line do fulfill the rule above.

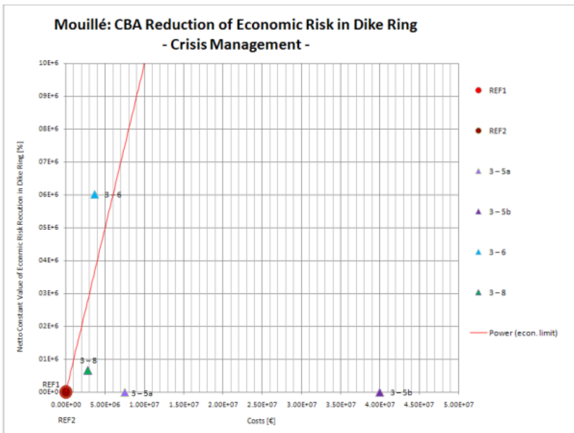
Each data point represents one measure. Data points with the same form belong to the same MLS layer. If the data points have the same color they belong to the same strategy and thus have the same way of functioning. After the diagrams for each layer, a summarizing diagram follows. It is meant to show all the measures in relation to each other on the same axes.

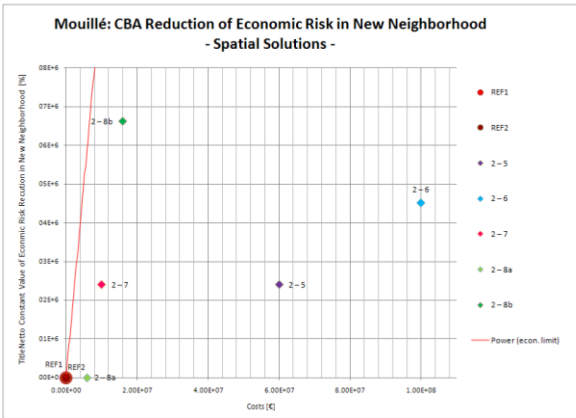
Economic Risk per layer

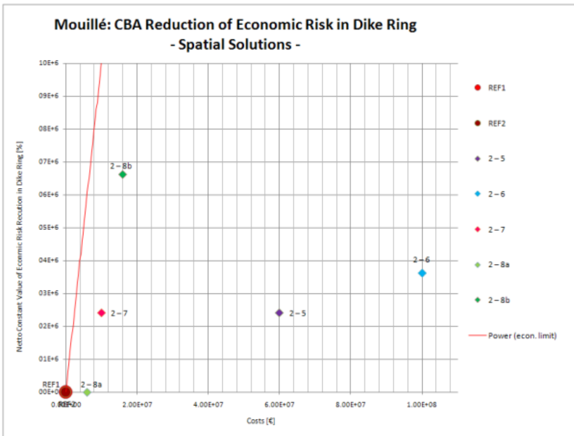


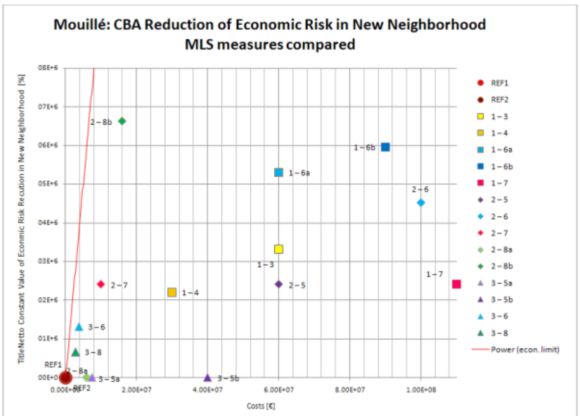


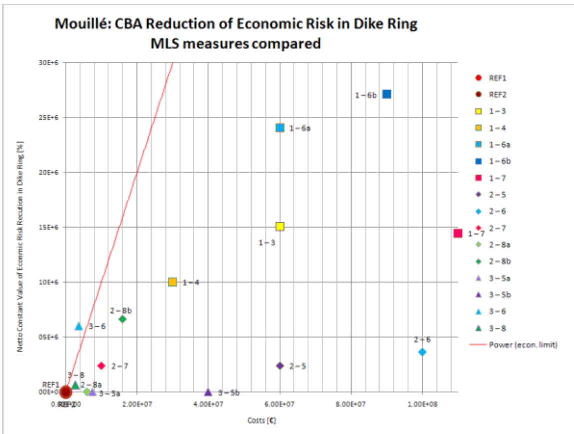


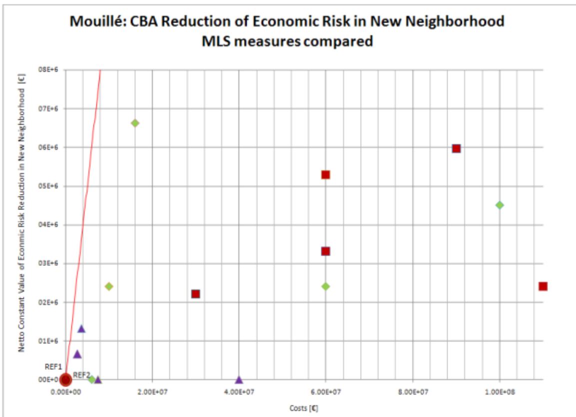


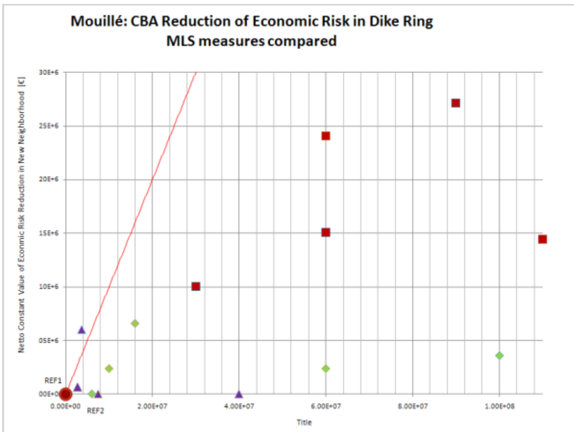

Mouillé: CBA Reduction of Economic Risk in New Neighborhood
- Spatial Solutions -
Costs [€]


Mouillé: CBA Reduction of Economic Risk in Dike Ring
- Spatial Solutions -
Costs [€]

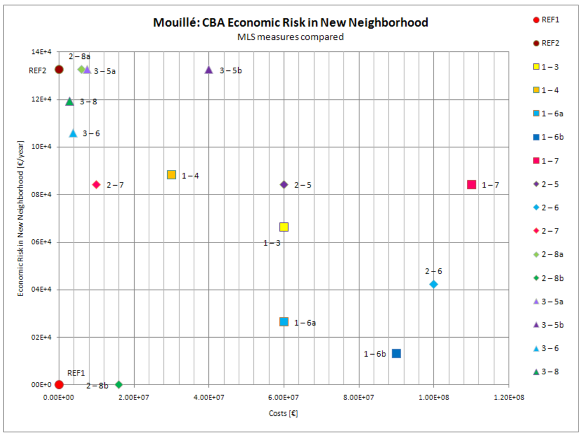

Mouillé: CBA Reduction of Economic Risk in New Neighborhood
MLS measures compared
Costs [€]

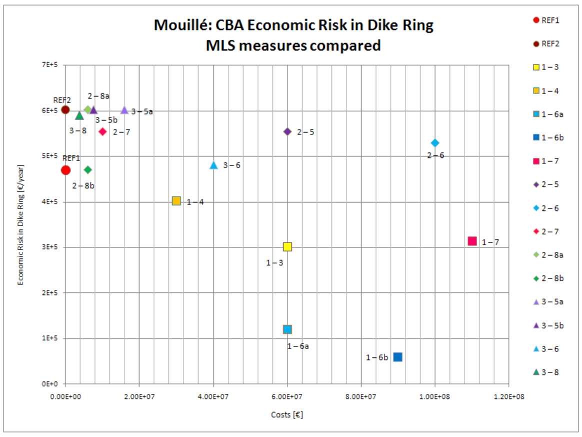

Mouillé: CBA Reduction of Economic Risk in Dike Ring
MLS measures compared
Costs [€]

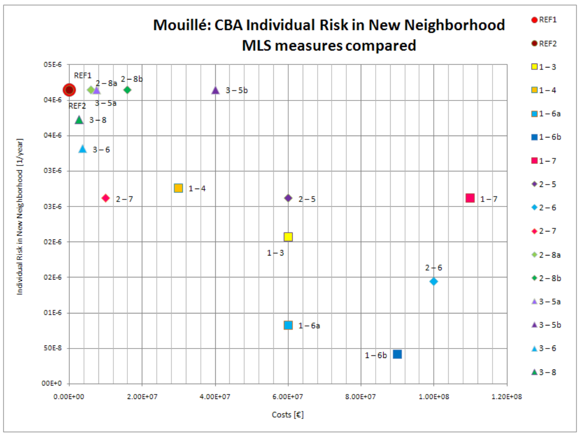

Mouillé: CBA Reduction of Economic Risk in New Neighborhood
MLS measures compared
Costs [€]

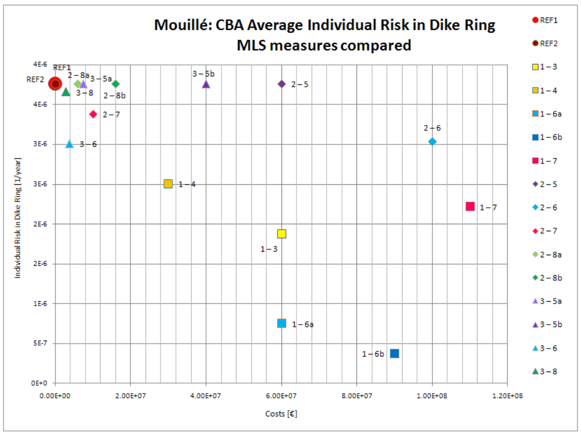

Mouillé: CBA Reduction of Economic Risk in Dike Ring
MLS measures compared
Title

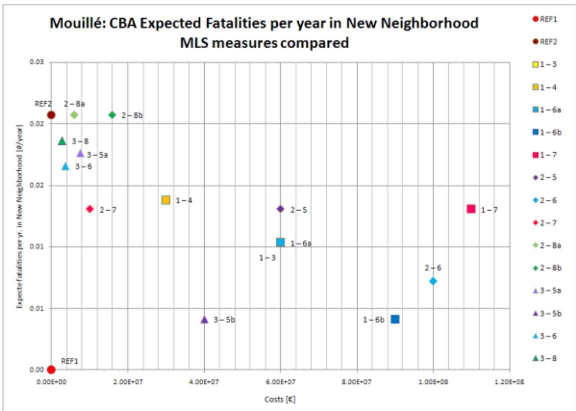
All risk dimensions compared

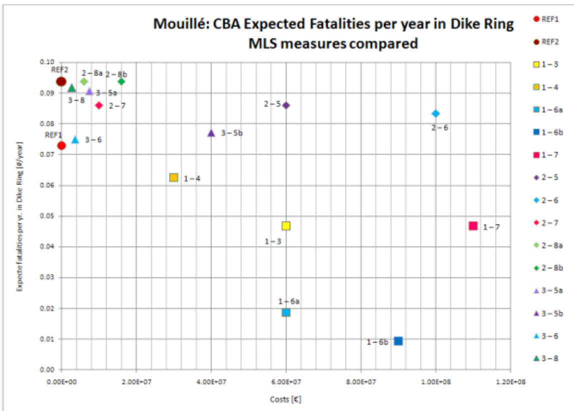












9.5 Appendix: Policy regarding insufficient dike ring parts in dike ring 22

dijkvak			mechanisme	score (1)	indicatieve maatregel / nader onderzoek
begin..m	eind..m	lengte [m]			
0	1100	1100	macro-stab. binnenw./ piping	(-)	nadere toetsing bebouwing
1100	1600	500	macro-stab. buitenw.	(-)	nader onderzoek met (steen)bekleding
1600	2000	400	macro-stab. buitenw.	(-)	herberekening stabiliteit met stortsteen
5200	5500	300	macro-stab. binnenw.	o	verbreding berm / verlegging waterpartij
6600	7700	1100	macro-stab. binnenw.	o	verbreding berm / verlegging watergang
7500	8600	1100	piping	o	verbreding berm / verlegging watergang
14840	15800	960	hoogte	(-)	nader onderzoek grasbekleding (afschuiving binnentalud)
16300	18700	2400	piping	o	verbreding berm / verlegging watergang
17750	17850	100	steenbekleding	o	bekleding vernieuwen
21800	23400	1600	zettingsvloeiing	(-)	Lopend onderzoek: geavanceerde risicoanalyse
21800	23400	1600	afschuiving voorland	(-)	nader onderzoek
22800	23400	600	macro-stab. binnenw.	o	verbreding berm / verlegging watergang
24600	25800	1200	macro-stab. binnenw.	o	verbreding berm / verlegging watergang
25000	26100	1100	zettingsvloeiing	(-)	Lopend onderzoek: geavanceerde risicoanalyse
25000	26100	1100	afschuiving voorland	(-)	nader onderzoek
25800	27500	1700	macro-stab. binnenw.	o	verbreding berm / verlegging watergang
26100	29000	2900	zettingsvloeiing	(-)	Lopend onderzoek: geavanceerde risicoanalyse
26100	29000	2900	afschuiving voorland	(-)	nader onderzoek
27200	27400	200	steenbekleding	o	bekleding vernieuwen
27500	28000	500	macro-stab. binnenw.	o	verbreding berm / verlegging watergang
28200	29000	800	macro-stab. binnenw.	o	verbreding berm / verlegging watergang
33300	33800	500			
34100	36300	2200	macro-stab. binnenw./ piping	(-)	nadere toetsing bebouwing
34300	34350	50	piping	(-)	nader onderzoek damwanden Zuidersluisdam+grondlichaam
34560	36160	1600	hoogte	v	Voorstraat c.a. visieontwikkeling middellange termijn
36300	36540	240	macro-stab. binnenw./ piping	(-)	nadere toetsing bebouwing
36300	36540	240	macro-stab. buitenw.	(-)	nadere toetsing (o.a. oude kademuur)

(1)
o = onvoldoende
(-) = geen oordeel
v = voldoende

Table 9-9: Planned flood safety measures per part of dike ring

Figure 9-11: Dike reinforcement program

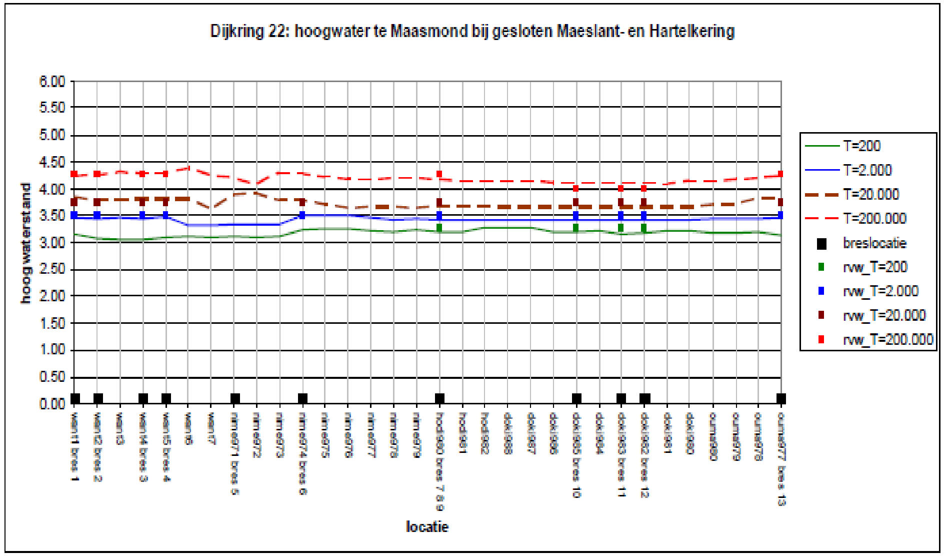
9.6 Appendix: Boundary Conditions and Dike Breaches as Input for Sobek1D2D model

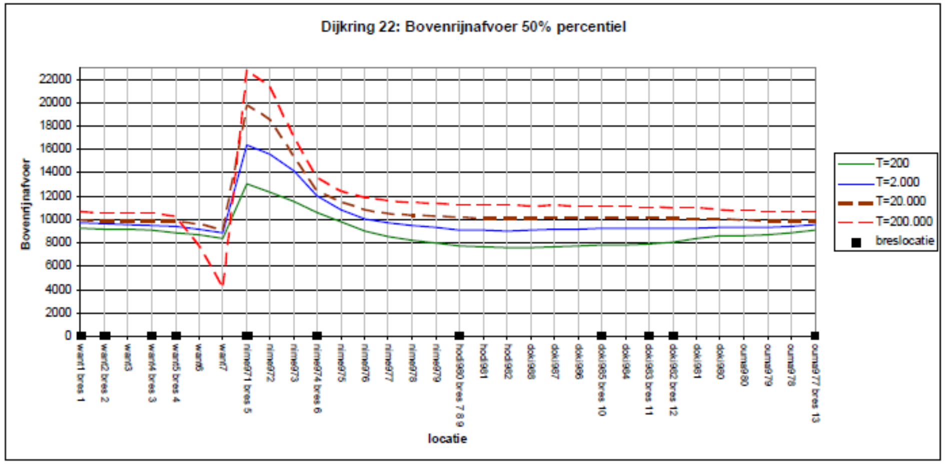
(Source: Piek 2007)

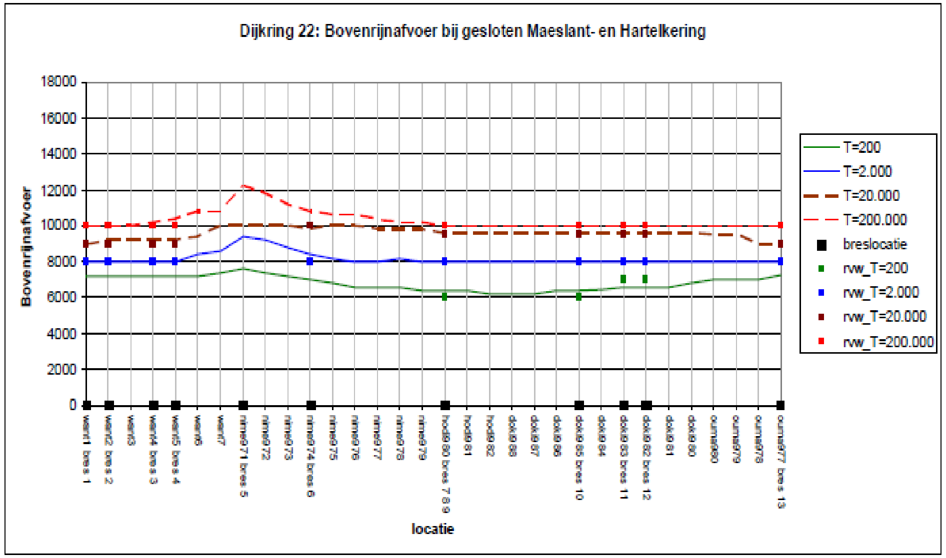
9.6.1 Appendix: Breach locations in Sobek Model of Dike Ring 22:

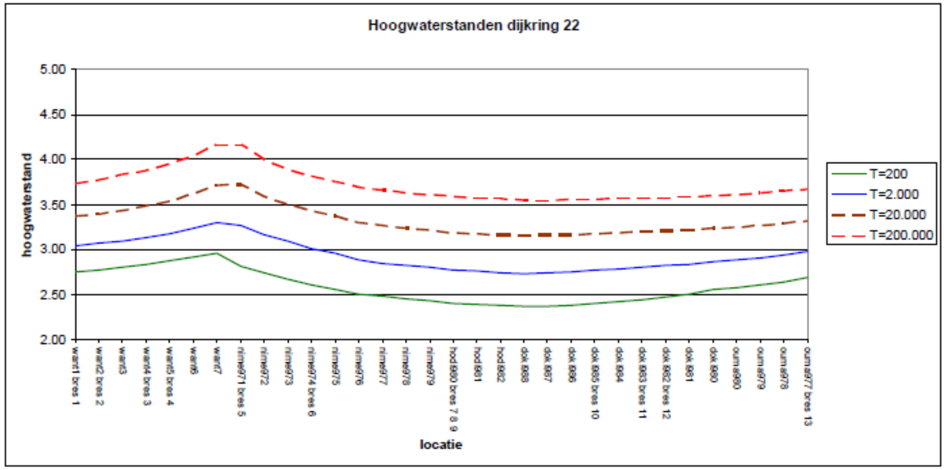
locatie	cases met zandbres	cases met kleibres		km-raai
want1 bres 1	Bres22-01_TP-1D_O_bresUc02	Bres22-01_TP-1D_O_bresUc05		Wantij km 1
want2 bres 2	Bres22-02_TP-1D_O_bresUc02	Bres22-02_TP-1D_O_bresUc05		Wantij km 2
want4 bres 3	Bres22-03_TP-1D_O_bresUc02	Bres22-03_TP-1D_O_bresUc05		Wantij km 4
want5 bres 4	Bres22-04_TP-1D_O_bresUc02	Bres22-04_TP-1D_O_bresUc05		Wantij km 5
nme971 bres 5	Bres22-05_TP-1D_O_bresUc02	Bres22-05_TP-1D_O_bresUc05	ndb_R74_25	Nieuwe Merwede km 971
nme974 bres 6	Bres22-06_TP-1D_O_bresUc02	Bres22-06_TP-1D_O_bresUc05	tussen ndb_R74 26 en 27	Nieuwe Merwede km 974
hod 980 bres 7	Bres22-07_TP-1D_G_bresUc02	Bres22-07_TP-1D_G_bresUc05		Hollandsch Diep km 980 Splitsingspunt
hod 980 bres 8	Bres22-08_TP-1D_G_bresUc02	Bres22-08_TP-1D_G_bresUc05		Hollandsch Diep km 980 Splitsingspunt
hod 980 bres 9	Bres22-09_TP-1D_G_bresUc02	Bres22-09_TP-1D_G_bresUc05		Hollandsch Diep km 980 Splitsingspunt
dok 985 bres 10	Bres22-10_TP-1D_G_bresUc02	Bres22-10_TP-1D_G_bresUc05		Dordtsche Kil km 985
dok 983 bres 11	Bres22-11_TP-1D_G_bresUc02	Bres22-11_TP-1D_G_bresUc05	node 9	Dordtsche Kil km 983
dok 982 bres 12	Bres22-12_TP-1D_G_bresUc02	Bres22-12_TP-1D_G_bresUc05		Dordtsche Kil km 982
ouma977 bres 13	Bres22-13_TP-1D_O_bresUc02	Bres22-13_TP-1D_O_bresUc05		Oude Maas km 977
want1 bres 1	Bres22-01_TP_G_bresUc02	Bres22-01_TP_G_bresUc05	node 3	Wantij km 1
want2 bres 2	Bres22-02_TP_C_bresUc02	Bres22-02_TP_G_bresUc05	node 3	Wantij km 2
want4 bres 3	Bres22-03_TP_G_bresUc02	Bres22-03_TP_G_bresUc05	node 2	Wantij km 4
want5 bres 4	Bres22-04_TP_G_bresUc02	Bres22-04_TP_G_bresUc05	node 2	Wantij km 5
nme971 bres 5	Bres22-05_TP_C_bresUc02	Bres22-05_TP_O_bresUc05	ndb_R74_25	Nieuwe Merwede km 971
nme974 bres 6	Bres22-06_TP_C_bresUc02	Bres22-06_TP_O_bresUc05	tussen ndb_R74 26 en 27	Nieuwe Merwede km 974
nme974 bres 6	Bres22-06_TP_G_bresUc02	Bres22-06_TP_G_bresUc05		Nieuwe Merwede km 974
hod 900 bres 7	Bres22-07_TP_G_G_bresUc02	Bres22-07_TP_G_G_bresUc05		Hollandsch Diep km 900 Splitsingspunt
hod 980 bres 8	Bres22-08_TP_G_G_bresUc02	Bres22-08_TP_G_G_bresUc05		Hollandsch Diep km 980 Splitsingspunt
hod 980 bres 9	Bres22-09_TP_G_G_bresUc02	Bres22-09_TP_G_G_bresUc05		Hollandsch Diep km 980 Splitsingspunt
dok 905 bres 10	Bres22-10_TP_G_G_bresUc02	Bres22-10_TP_G_G_bresUc02		Dordtsche Kil km 905
dok 983 bres 11	Bres22-11_TP_G_bresUc02	Bres22-11_TP_G_bresUc02	node 3	Dordtsche Kil km 983
dok 982 bres 12	Bres22-12_TP_G_bresUc02	Bres22-12_TP_G_bresUc05		Dordtsche Kil km 982
ouma977 bres 13	Bres22-13_TP_G_bresUc02	Bres22-13_TP_G_bresUc05		Oude Maas km 977
want1 bres 1	Bres22-01_TP+1D_G_bresUc02	Bres22-01_TP+1D_G_bresUc06		Wantij km 1
want2 bres 2	Bres22-02_TP+1D_G_bresUc02	Bres22-02_TP+1D_G_bresUc06		Wantij km 2
want4 bres 3	Bres22-03_TP+1D_G_bresUc02	Bres22-03_TP+1D_G_bresUc06		Wantij km 4
want5 bres 4	Bres22-04_TP+1D_G_bresUc02	Bres22-04_TP+1D_G_bresUc06		Wantij km 5
nme971 bres 5	Bres22-05_TP+1D_O_bresUc02	Bres22-05_TP+1D_O_bresUc06	ndb_R74_25	Nieuwe Merwede km 971
nme974 bres 6	Bres22-06_TP+1D_G_bresUc02	Bres22-06_TP+1D_G_bresUc06		Nieuwe Merwede km 974
hod 900 bres 7	Bres22-07_TP+1D_G_bresUc02	Bres22-07_TP+1D_G_bresUc06		Hollandsch Diep km 900 Splitsingspunt
hod 980 bres 8	Bres22-08_TP+1D_G_bresUc02	Bres22-08_TP+1D_G_bresUc06		Hollandsch Diep km 980 Splitsingspunt
hod 980 bres 9	Bres22-09_TP+1D_G_bresUc02	Bres22-09_TP+1D_G_bresUc06		Hollandsch Diep km 980 Splitsingspunt
dok 985 bres 10	Bres22-10_TP+1D_G_bresUc02	Bres22-10_TP+1D_G_bresUc06		Dordtsche Kil km 985
dok 983 bres 11	Bres22-11_TP+1D_C_bresUc02	Bres22-11_TP+1D_C_bresUc06		Dordtsche Kil km 983
dok 982 bres 12	Bres22-12_TP+1D_G_bresUc02	Bres22-12_TP+1D_G_bresUc06		Dordtsche Kil km 982
ouma977 bres 13	Bres22-13_TP+1D_G_bresUc02	Bres22-13_TP+1D_G_bresUc06		Oude Maas km 977
want1 bres 1	Bres22-01_TP+2D_G_bresUc02	Bres22-01_TP+2D_G_bresUc06		Wantij km 1
want2 bres 2	Bres22-02_TP+2D_G_bresUc02	Bres22-02_TP+2D_G_bresUc06		Wantij km 2
want4 bres 3	Bres22-03_TP+2D_G_bresUc02	Bres22-03_TP+2D_G_bresUc06		Wantij km 4
want5 bres 4	Bres22-04_TP+2D_G_bresUc02	Bres22-04_TP+2D_G_bresUc06		Wantij km 5
nme971 bres 5	Bres22-05_TP+2D_O_bresUc02			Nieuwe Merwede km 971
nme974 bres 6	Bres22-06_TP+2D_G_bresUc02			Nieuwe Merwede km 974
hod 900 bres 7	Bres22-07_TP+2D_G_bresUc02	Bres22-07_TP+2D_G_bresUc06		Hollandsch Diep km 900 Splitsingspunt
hod 980 bres 8	Bres22-08_TP+2D_G_bresUc02	Bres22-08_TP+2D_G_bresUc06		Hollandsch Diep km 980 Splitsingspunt
hod 980 bres 9	Bres22-09_TP+2D_G_bresUc02	Bres22-09_TP+2D_G_bresUc06		Hollandsch Diep km 980 Splitsingspunt
dok 985 bres 10	Bres22-10_TP+2D_G_bresUc02	Bres22-10_TP+2D_G_bresUc06		Dordtsche Kil km 985
dok 983 bres 11	Bres22-11_TP+2D_C_bresUc02	Bres22-11_TP+2D_C_bresUc06		Dordtsche Kil km 983
dok 982 bres 12	Bres22-12_TP+2D_G_bresUc02	Bres22-12_TP+2D_G_bresUc06		Dordtsche Kil km 982
ouma977 bres 13	Bres22-13_TP_2D_G_bresUc02	Bres22-13_TP_2D_G_bresUc05		Oude Maas km 977
ouma977 bres 13	Bres22-13_TP+2D_G_Voorstraat_300m_overlaat			

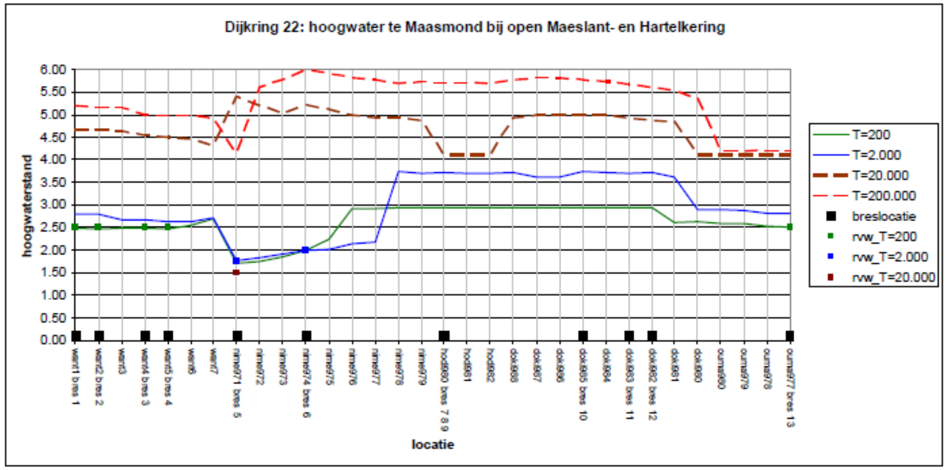
9.6.2 Appendix: Hydraulic boundary conditions in Sobek Model of Dike Ring 22

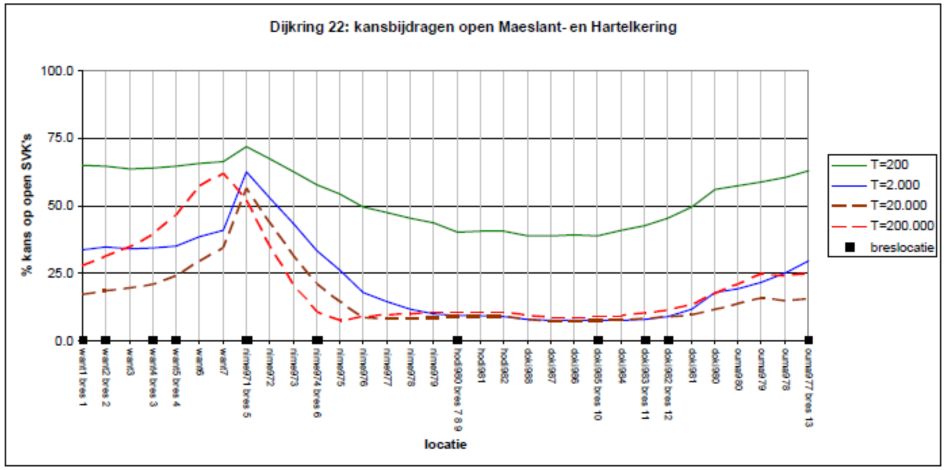


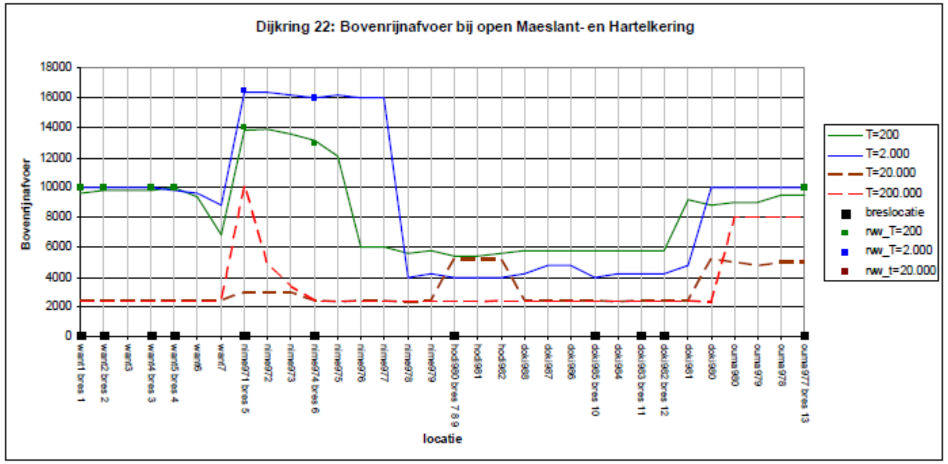





Hoogwaterstanden dijkring 22
hoogwaterstand
locatie
T=200
T=2.000
T=20.000
T=200.000


Dijkring 22: hoogwater te Maasmond bij open Maeslant- en Hartelkering
hoogwaterstand
locatie
T=200
T=2.000
T=20.000
T=200.000
breslocatie
rvw_T=200
rvw_T=2.000
rvw_T=20.000


Dijkring 22: kansbijdragen open Maeslant- en Hartelkering
% kans op open SVK's
locatie
T=200
T=2.000
T=20.000
T=200.000
breslocatie


Dijkring 22: Bovenrijnafvoer bij open Maeslant- en Hartelkering
Bovenrijnafvoer
locatie
T=200
T=2.000
T=20.000
T=200.000
breslocatie
rvw_T=200
rvw_T=2.000
rvw_t=20.000

9.7 Appendix: Results second case study

9.7.1 Appendix: Computational Results on Wielwijk

		WW	Probability	P		ER (mil. €)	SR	ER (NPV, m	SR (NPV)	ΔER (%)	ΔSR (%)	ΔER (abs)	ΔSR (abs)	ΔER (NPV)	ΔSR	CBA ER	CSX	Costs total	
REF	TP		1/2000	0.0005		0.070	0.017	3.49	0.017	0.00	0.00	0	0.000	0	0.000			0	REF
1 - 3	TP plus		1/4000	0.00025		0.035	0.008	1.74	0.008	0.50	0.50	30,000	0.008	1,500,000	0.008	133.3	23,734,200,687	200,000,000	1 - 3
1 - 6a	TP plus		1/20000	0.00005		0.009	0.002	0.43	0.002	0.88	0.89	60,000	0.015	3,000,000	0.015	30.0	6,020,968,357	90,000,000	1 - 6a
1 -7	TP whole-1m		1/2000	0.0005		0.045	0.008	2.25	0.008	0.36	0.52	20,000	0.009	1,000,000	0.009	110.0	12,603,814,373	110,000,000	1 -7
2-6	TP Comp		1/2000	0.0005		0.009	0.001	0.46	0.001	0.87	0.96	60,000	0.016	3,000,000	0.016	30.0	5,559,587,973	90,000,000	2-6
2 - 7a	TP min1m	x	1/2000	0.0005		0.045	0.008	2.25	0.008	0.36	0.52	25,000	0.010	1,250,000	0.010	16.0	2,000,000,000	20,000,000	2 - 7a
2 - 7b	TP WW50	x	1/2000	0.0005		0.053	0.008	2.63	0.008	0.24	0.51	20,000	0.010	1,000,000	0.010	4.2	420,000,000	4,200,000	2 - 7b
2 - 7c	TP WW100	x	1/2000	0.0005		0.044	0.006	2.22	0.006	0.36	0.63	30,000	0.010	1,500,000	0.010	5.6	840,000,000	8,400,000	2 - 7c
3 - 5a	TP 15 woonwijk		1/2000	0.0005		0.070	0.014	3.48	0.014	0.00	0.15	0	0.003	0	0.003	0.0	7,911,235,933	20,000,000	3 - 5a
3 - 5b	TP 80 woonwijk		1/2000	0.0005		0.069	0.003	3.43	0.003	0.02	0.80	0	0.013	0	0.013	0.0	7,416,939,548	100,000,000	3 - 5b
3 - 5c	TP 15	x	1/2000	0.0005		0.070	0.014	3.48	0.014	0.00	0.15	0	0.003	0	0.003	0.0	65,267,696,446	165,000,000	3 - 5c
3 - 5d	TP 80-15	x	1/2000	0.0005		0.069	0.003	3.43	0.003	0.02	0.80	0	0.013	0	0.013	0.0	18,171,501,893	245,000,000	3 - 5d
3 - 6	TP 2500		1/2500	0.0004		0.056	0.013	2.79	0.013	0.20	0.20	10,000	0.003	500,000	0.003	7.4	1,097,706,782	3,700,000	3 - 6
3 - 8	TP 90%		1/2000	0.0005		0.063	0.015	3.14	0.015	0.10	0.10	10,000	0.002	500,000	0.002	25.0	7,416,937,715	12,500,000	3 - 8
1 -6c	TP min	x	1/200	0.005		0.505	0.072	25.23	0.072	-6.23	-3.25	-430,000	-0.055	-21,500,000	-0.055	0.0	-18,282	1,000	1 -6c
AVERAGE										0.30	0.52	20,385	0.009	1,019,231	0.009	27.8	12,189,276,131	82,215,385	
Number of inhabitants wielwijk			13700	interest rate	0.02														

		Costs total	Costs WW	ER	SR	ΔER (NPV)	ΔSR	CBA ER	CSX	
Prevention										Prevention
1 - 3	TP plus	200,000,000	14,599	34,899	0.008	1,500,000	0.008	133.3	23,734,200,687	1 - 3
1 - 6a	TP plus	90,000,000	6,569	8,601	0.002	3,000,000	0.015	30.0	6,020,968,357	1 - 6a
1 -7	TP whole-1m	110,000,000	8,029	44,968	0.008	1,000,000	0.009	110.0	12,603,814,373	1 -7
1 -6c	TP min	1,000	0	504,603	0.072	-21,500,000	-0.055	0.0	-18,282	1 -6c
average		133,333,333	9,732			1,833,333	0.011	91.1	14,119,661,139	
Spatial Planning										Spatial Planning
=C6	TP Comp	90,000,000	6,569	9,171	0.001	3,000,000	0.016	30.0	5,559,587,973	=C6
2 - 7a	TP min1m	20,000,000	1,460	44,968	0.008	1,250,000	0.010	16.0	2,000,000,000	2 - 7a
2 - 7b	TP WW50	4,200,000	307	52,698	0.008	1,000,000	0.010	4.2	420,000,000	2 - 7b
2 - 7c	TP WW100	8,400,000	613	44,325	0.006	1,500,000	0.010	5.6	840,000,000	2 - 7c
average		30,650,000	2,237			1,687,500	0.012	14.0	2,204,896,993	
Crisis Management										Crisis Management
3 - 5a	TP 15 woonwi	20,000,000	1,460	69,580	0.014	NA	0.003	NA	7,911,235,933	3 - 5a
3 - 5b	TP 80 woonwi	100,000,000	7,299	68,636	0.003	NA	0.800	NA	7,416,939,548	3 - 5b
3 - 5c	TP 15	165,000,000	12,044	69,580	0.014	NA	0.003	NA	65,267,696,446	3 - 5c
3 - 5d	TP 80-15	245,000,000	17,883	68,636	0.003	NA	0.013	NA	18,171,501,893	3 - 5d
3 - 6	TP 2500	3,700,000	270	55,838	0.013	500,000	0.200	7.4	1,097,706,782	3 - 6
3 - 8	TP 90%	12,500,000	912	62,818	0.015	500,000	0.100	25.0	7,416,937,715	3 - 8
average		91,033,333	6,645			500,000	0.186	16.2	17,880,336,386	

9.7.2 Appendix: Computation Results of DR22

Table 9-10: Computational Results for all Measures in DR22

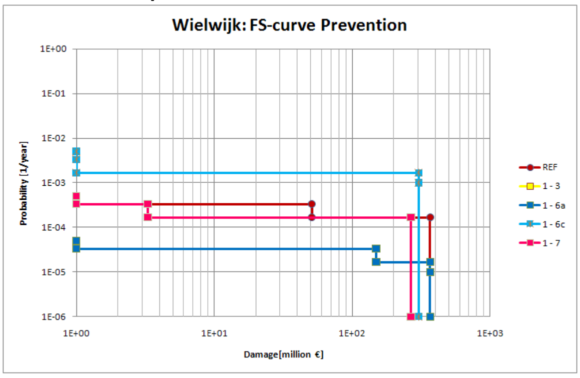
		WW	Probability	P		ER (mil. €)	SR	ER (NPV)	SR	ΔER (%)	ΔSR (%)	ΔER (abs)	ΔSR (abs)	ΔER (NPV)	ΔSR	CBA ER	CSX		Costs total	
REF	TP		1/2000	0.0005		1.78	0.86	89	0.86	0.00	0.00	0	0.00	0	0.00				0	REF
1 - 3	TP plus		1/4000	0.00025		0.89	0.43	45	0.43	0.50	0.50	890,000	0.43	44,500,000	0.43	4.49	465,116,279		200,000,000	1 - 3
1 - 6a	TP plus		1/20000	0.00005		0.19	0.09	10	0.09	0.89	0.89	1,590,000	0.77	79,500,000	0.77	1.13	116,883,117		90,000,000	1 - 6a
1 -7	TP whole-1m		1/2000	0.0005		0.99	0.24	50	0.24	0.44	0.72	790,000	0.62	39,500,000	0.62	2.78	177,419,355		110,000,000	1 -7
2-6	TP Comp		1/2000	0.0005		0.33	0.02	17	0.02	0.81	0.97	1,450,000	0.84	72,500,000	0.84	1.24	107,142,857		90,000,000	2-6
2 - 7a	TP min1m	x	1/2000	0.0005		1.75	0.85	88	0.85	0.02	0.01	30,000	0.01	1,500,000	0.01	13.33	2,000,000,000		20,000,000	2 - 7a
2 - 7b	TP WW50	x	1/2000	0.0005		1.76	0.85	88	0.85	0.01	0.01	20,000	0.01	1,000,000	0.01	4.20	420,000,000		4,200,000	2 - 7b
2 - 7c	TP WW100	x	1/2000	0.0005		1.75	0.85	88	0.85	0.02	0.01	30,000	0.01	1,500,000	0.01	5.60	840,000,000		8,400,000	2 - 7c
3 - 5a	TP 15 woonwijk		1/2000	0.0005		1.78	0.86	89	0.86	0.00	0.00	0	0.00	0	0.00	0.00	10,000,000,000		20,000,000	3 - 5a
3 - 5b	TP 80 woonwijk		1/2000	0.0005		1.78	0.85	89	0.85	0.00	0.02	0	0.01	0	0.01	0.00	10,000,000,000		100,000,000	3 - 5b
3 - 5c	TP 15	x	1/2000	0.0005		1.78	0.73	89	0.73	0.00	0.15	0	0.13	0	0.13	0.00	1,269,230,769		165,000,000	3 - 5c
3 - 5d	TP 80-15	x	1/2000	0.0005		1.78	0.72	89	0.72	0.00	0.16	0	0.14	0	0.14	0.00	1,750,000,000		245,000,000	3 - 5d
3 - 6	TP 2500		1/2500	0.0004		1.42	0.69	71	0.69	0.20	0.20	360,000	0.17	18,000,000	0.17	0.21	21,764,706		3,700,000	3 - 6
3 - 8	TP 90%		1/2000	0.0005		1.602	0.78	80	0.78	0.10	0.10	178,000	0.09	8,900,000	0.09	1.40	138,888,889		12,500,000	3 - 8
1 -6c	TP min	x	1/200	0.005		13.86	2.70	693	2.70	-6.79	-2.13	-12,080,000	-1.84	-604,000,000	-1.84	0.00	-543		1,000	1 -6c
AVERAGE										0.23	0.29	410,615	0.25	20,530,769	0.25	4.00	2,100,495,844		82,215,385	
Number of inhabitants wielwijk			13700	interest rate	0.02															
Number of inhabitants Dordt			110000				Dike ring 22, Economic Risk reduction													
							Dike ring 22, Societal Risk reduction													

Table 9-11: Computational Results on MLS Layers in DR22

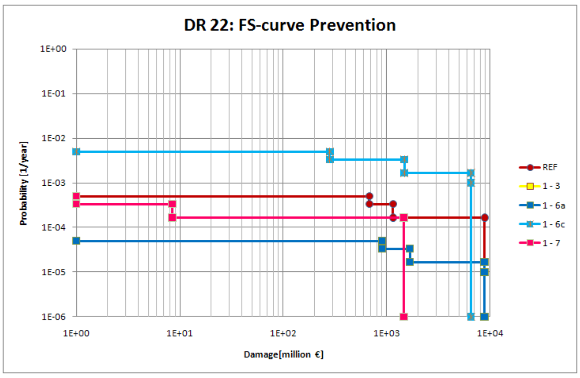
		Costs total	Costs WW	Costs DR22		ER	SR		ΔER (NPV)	ΔSR		CBA ER	CSX		
Prevention														Prevention	
1 - 3	TP plus	200,000,000	14,599	1,818		890,000	0.43		44,500,000	0.43		4.49	465,116,279	1 - 3	
1 - 6a	TP plus	90,000,000	6,569	818		190,000	0.09		79,500,000	0.77		1.13	116,883,117	1 - 6a	
1 -7	TP whole-1m	110,000,000	8,029	1,000		990,000	0.24		39,500,000	0.62		2.78	177,419,355	1 -7	
average		133,333,333	9,732	1,212					54,500,000	0.61	average	2.80	253,139,584		
Spatial Planning														Spatial Planning	
=C6	TP Comp	90,000,000	6,569	818		330,000	0.02		72,500,000	0.84		1.24	107,142,857	=C6	
2 - 7a	TP min1m	20,000,000	1,460	182		1,750,000	0.85		1,500,000	0.01		13.33	2,000,000,000	2 - 7a	
2 - 7b	TP WW50	4,200,000	307	38		1,760,000	0.85		1,000,000	0.01		4.20	420,000,000	2 - 7b	
2 - 7c	TP WW100	8,400,000	613	76		1,750,000	0.85		1,500,000	0.01		5.60	840,000,000	2 - 7c	
average		30,650,000	2,237	279					19,125,000	0.22	average	6.09	841,785,714		
Crisis Management														Crisis Management	
3 - 5a	TP 15 woonwi	20,000,000	1,460	182		1,780,000	0.86		0	0.00		NA	10,000,000,000	3 - 5a	
3 - 5b	TP 80 woonwi	100,000,000	7,299	909		1,780,000	0.85		0	0.01		NA	10,000,000,000	3 - 5b	
3 - 5c	TP 15	165,000,000	12,044	1,500		1,780,000	0.73		0	0.13		NA	1,269,230,769	3 - 5c	
3 - 5d	TP 80-15	245,000,000	17,883	2,227		1,780,000	0.72		0	0.14		NA	1,750,000,000	3 - 5d	
3 - 6	TP 2500	3,700,000	270	34		1,420,000	0.69		18,000,000	0.17		0.21	21,764,706	3 - 6	
3 - 8	TP 90%	12,500,000	912	114		1,602,000	0.78		8,900,000	0.09		1.40	138,888,889	3 - 8	
average		91,033,333	6,645	828		1,690,333	0.77		13,450,000	0.09	average	0.81	3,863,314,061		

9.7.1 Appendix: Diagrams of DR22 and Wielwijk; effectiveness of measures

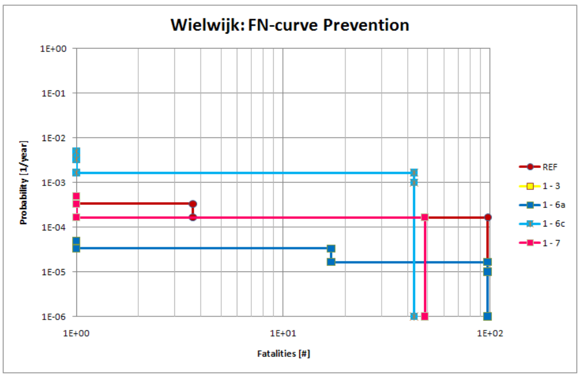
Table 9-12: FN-/FS-curve for Prevention measures



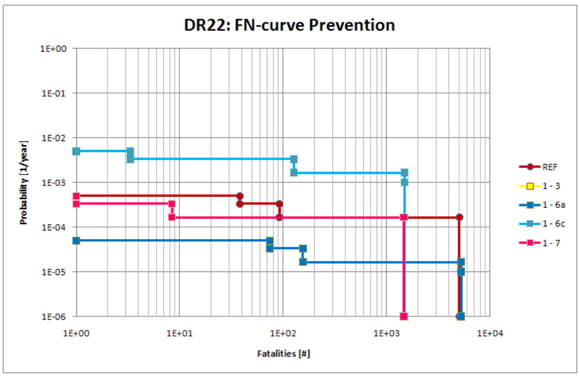
1-3 =1-6a



1-3 =1-6a

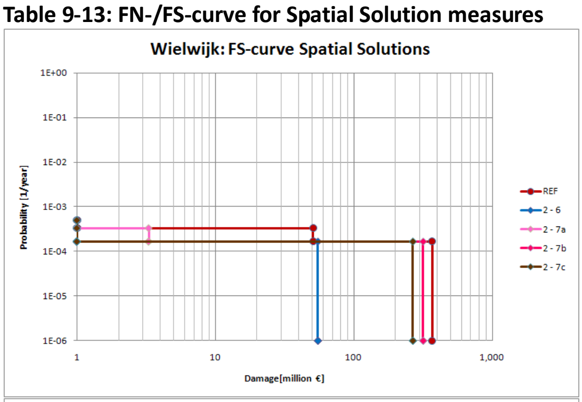


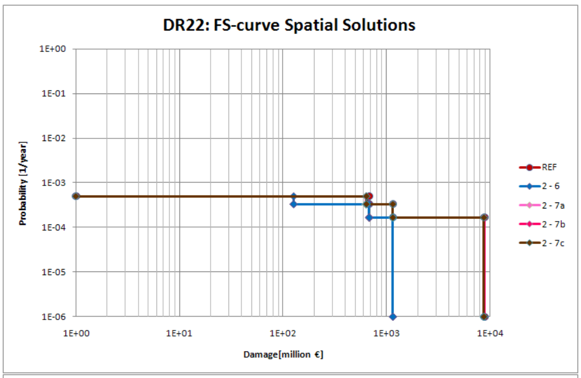
1-3 =1-6a

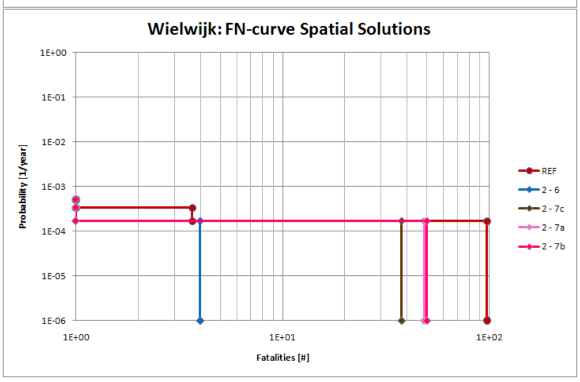


1-3 =1-6a

Table 9-13: FN-/FS-curve for Spatial Solution measures







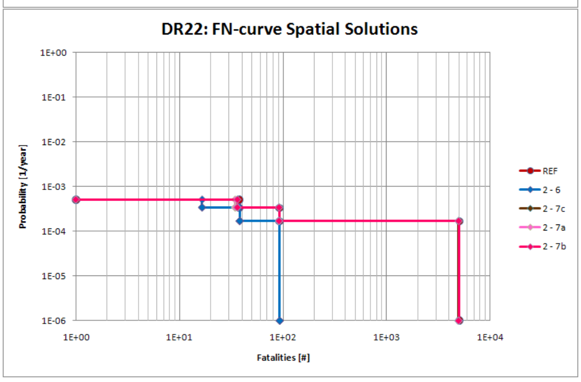


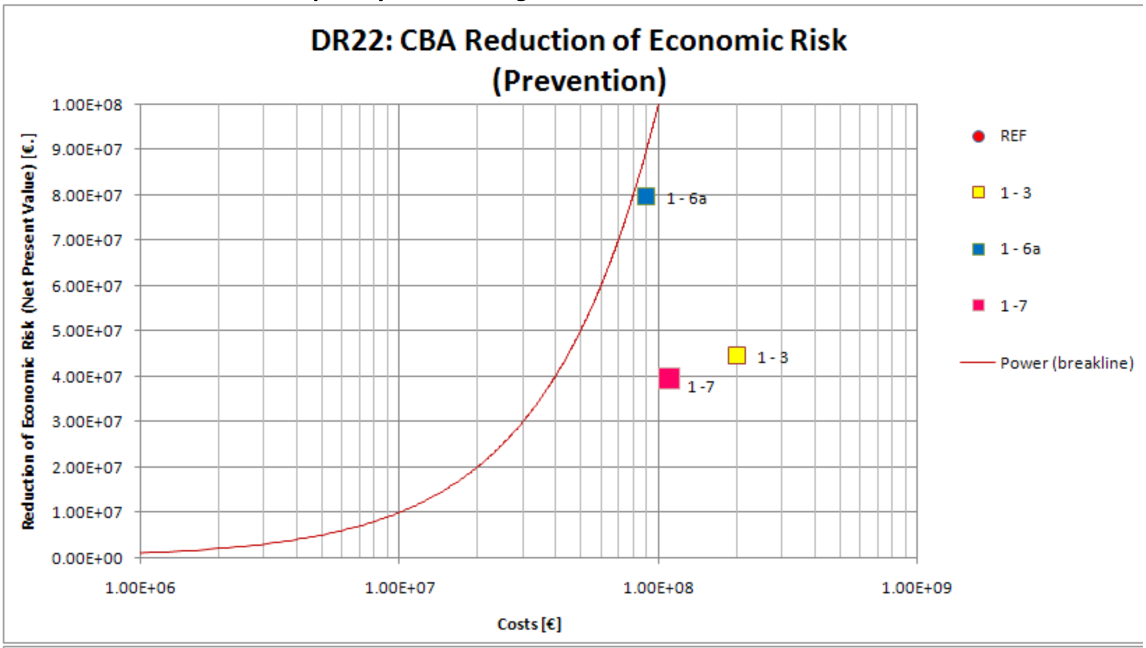
Table 9-14: FN-/FS-curve for Crisis Management measures

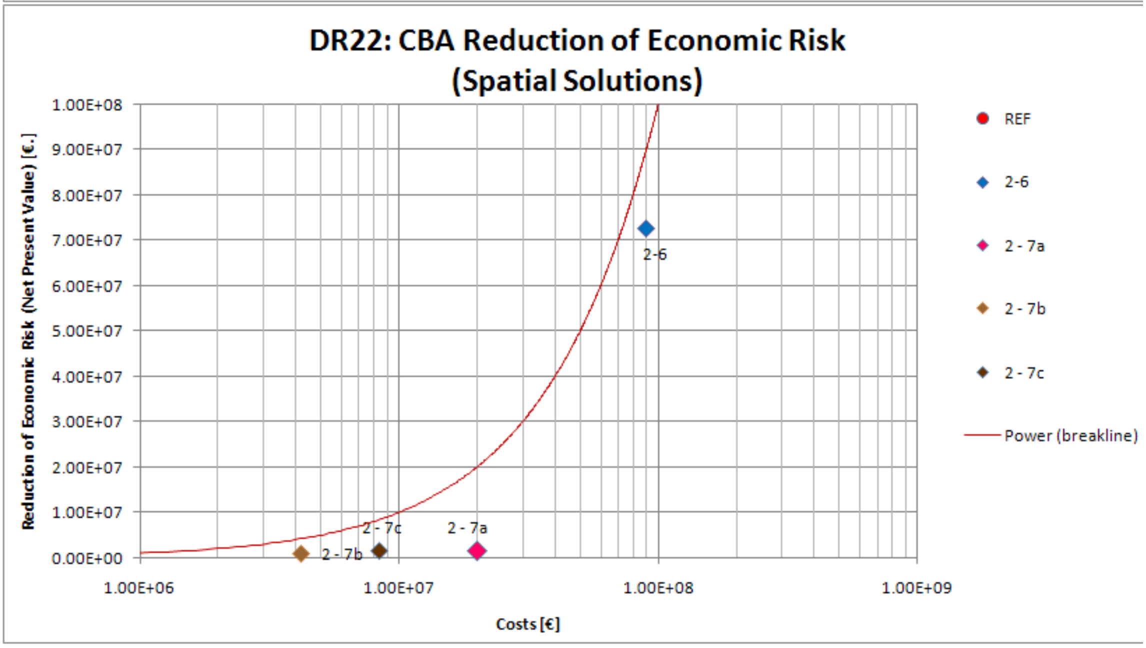
9.7.2 Appendix: Diagrams of DR22 and Wielwijk; cost-efficiency of measures

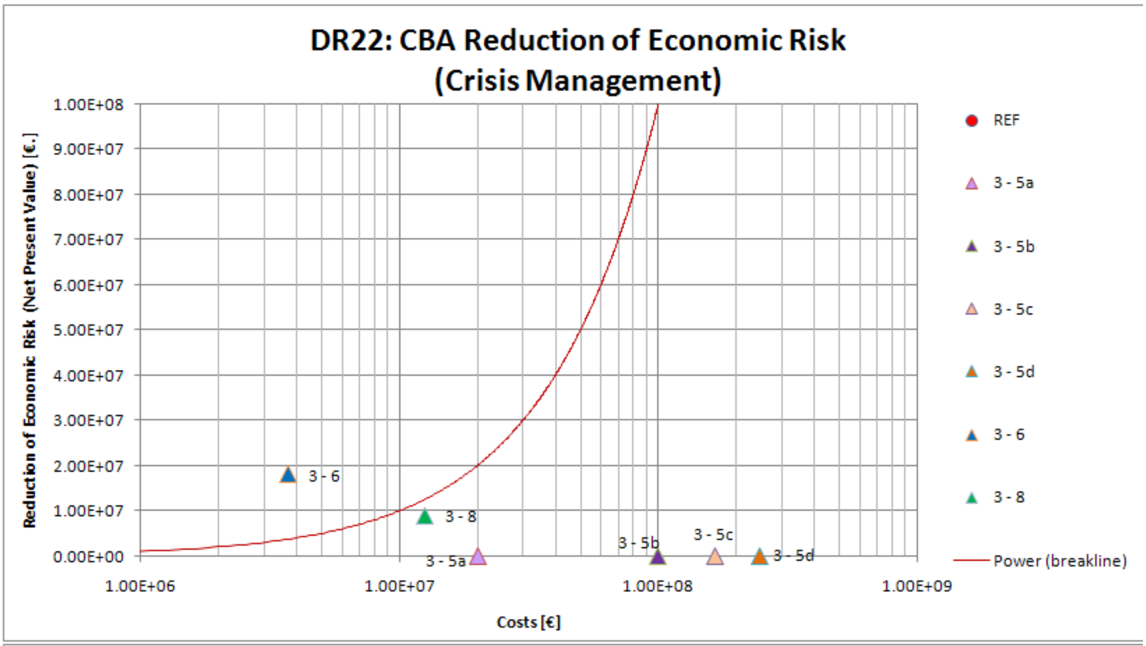
The following diagrams show this cost-benefit-relation for the individual measures. Each diagram stands for another MLS layer. The red line represents the justifying rule that was just reviewed. Measures on the right of that red line are not economically wise investments. The measures situated on the left of the line do fulfill the rule above.

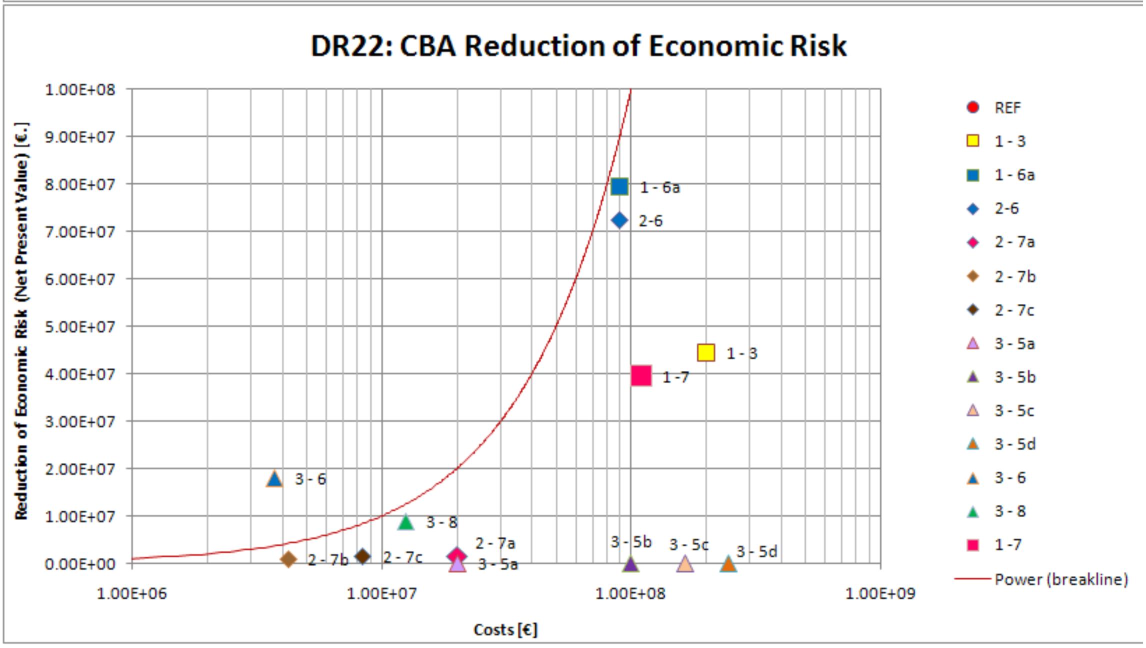
Each data point represents one measure. Data points with the same form belong to the same MLS layer. If the data points have the same color they belong to the same strategy and thus have the same way of functioning. After the diagrams for each layer, a summarizing diagram follows. It is meant to show all the measures in relation to each other on the same axes.

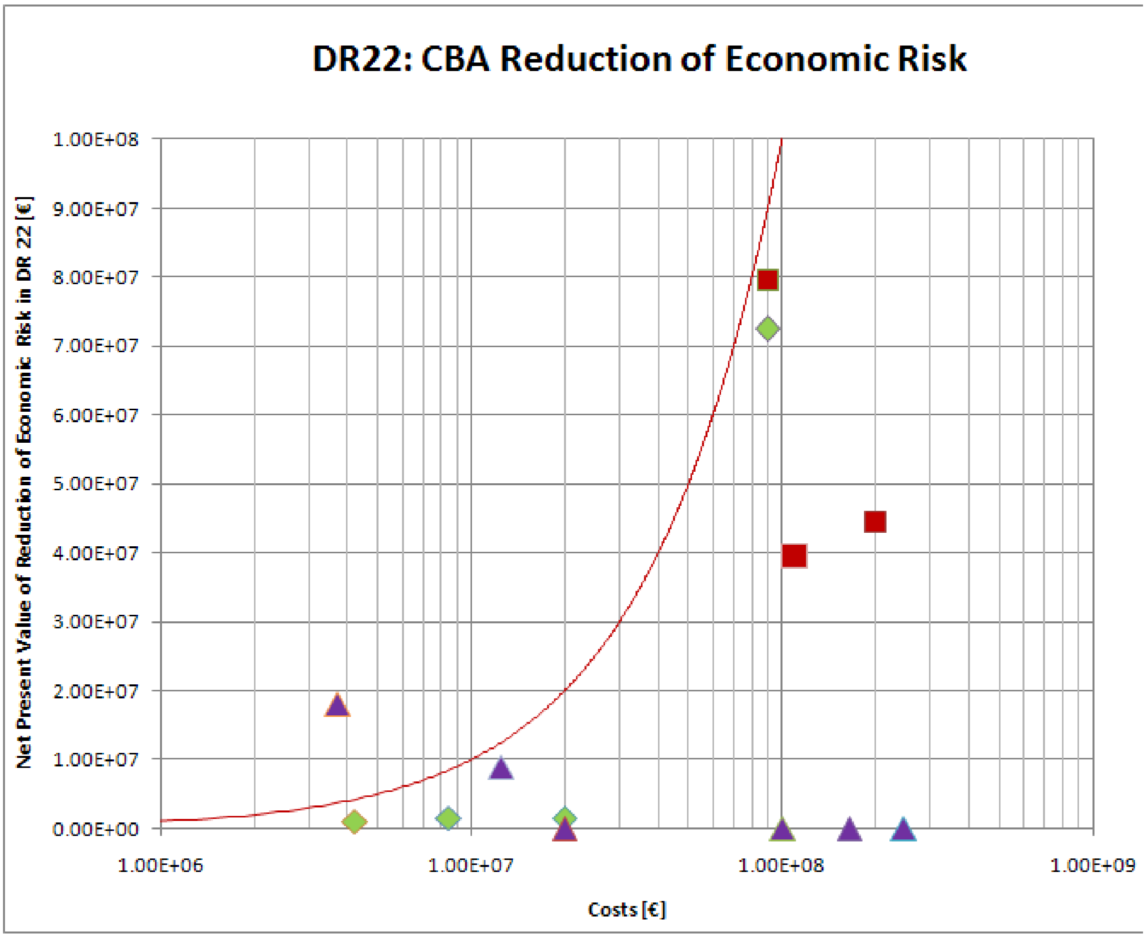
Reduction of Economic Risk per layer*: Dike Ring 22*



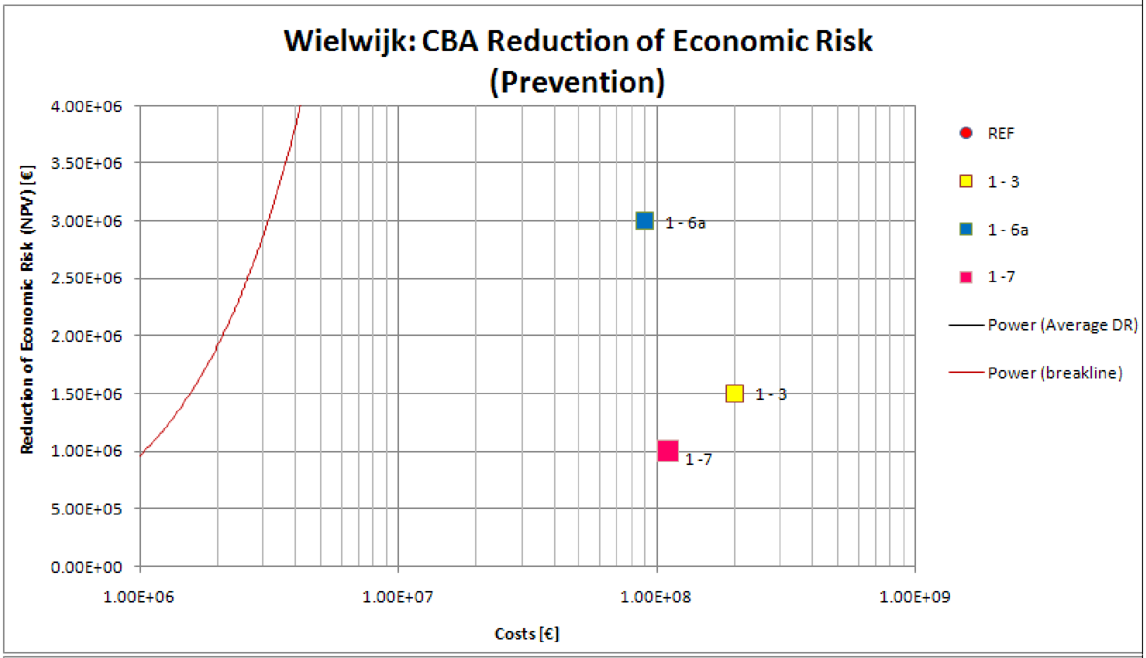


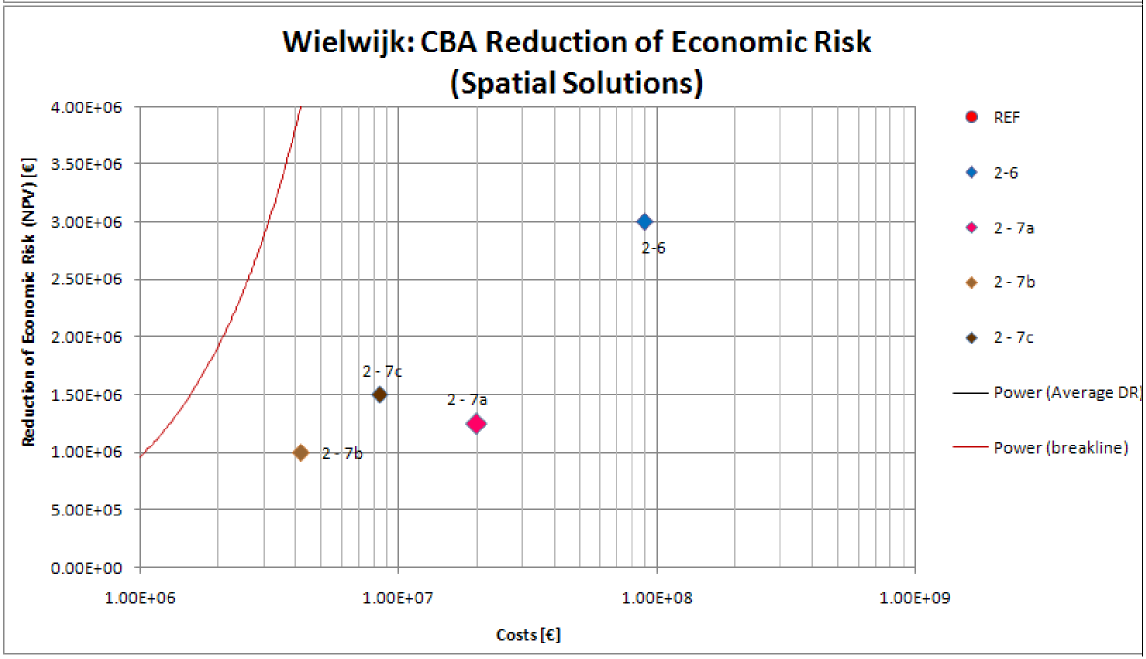

DR22: CBA Reduction of Economic Risk
(Crisis Management)
Reduction of Economic Risk (Net Present Value) [€.]
1.00E+08
9.00E+07
8.00E+07
7.00E+07
6.00E+07
5.00E+07
4.00E+07
3.00E+07
2.00E+07
1.00E+07
0.00E+00
1.00E+06
1.00E+07
1.00E+08
1.00E+09
Costs [€]
3 - 6
3 - 8
3 - 5a
3 - 5b
3 - 5c
3 - 5d
REF
3 - 5a
3 - 5b
3 - 5c
3 - 5d
3 - 6
3 - 8
Power (breakline)

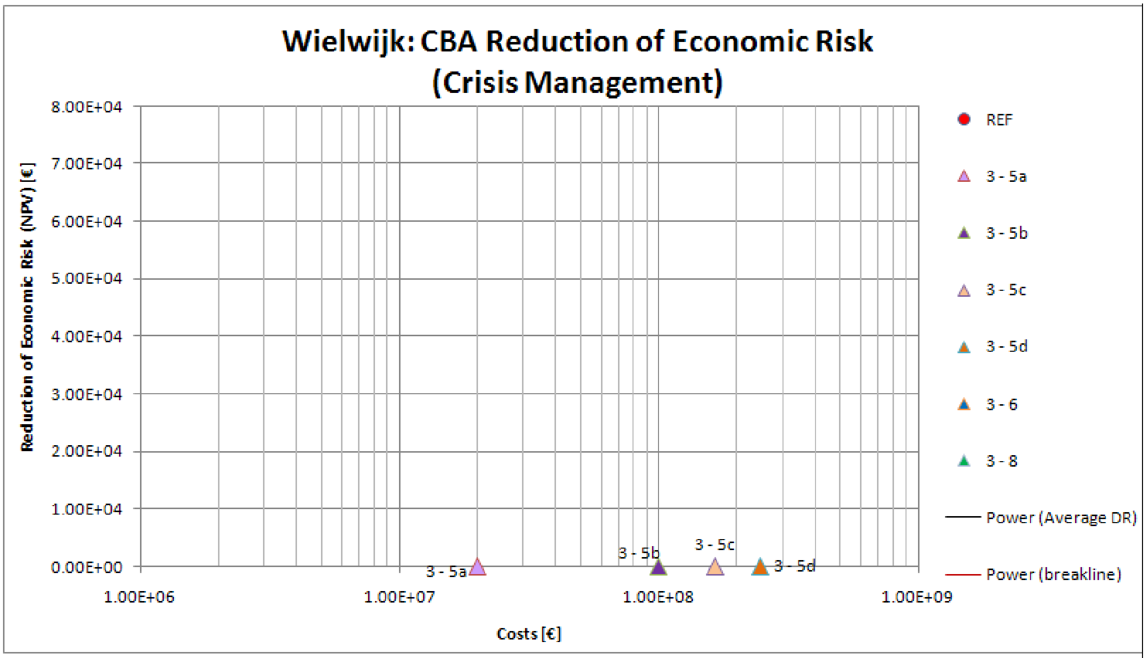

DR22: CBA Reduction of Economic Risk
Reduction of Economic Risk (Net Present Value) [€.]
1.00E+08
9.00E+07
8.00E+07
7.00E+07
6.00E+07
5.00E+07
4.00E+07
3.00E+07
2.00E+07
1.00E+07
0.00E+00
1.00E+06
1.00E+07
1.00E+08
1.00E+09
Costs [€]
1 - 6a
2-6
1 - 3
1 - 7
3 - 6
3 - 8
2 - 7a
2 - 7b
2 - 7c
3 - 5a
3 - 5b
3 - 5c
3 - 5d
REF
1 - 3
1 - 6a
2-6
2 - 7a
2 - 7b
2 - 7c
3 - 5a
3 - 5b
3 - 5c
3 - 5d
3 - 6
3 - 8
1 - 7
Power (breakline)

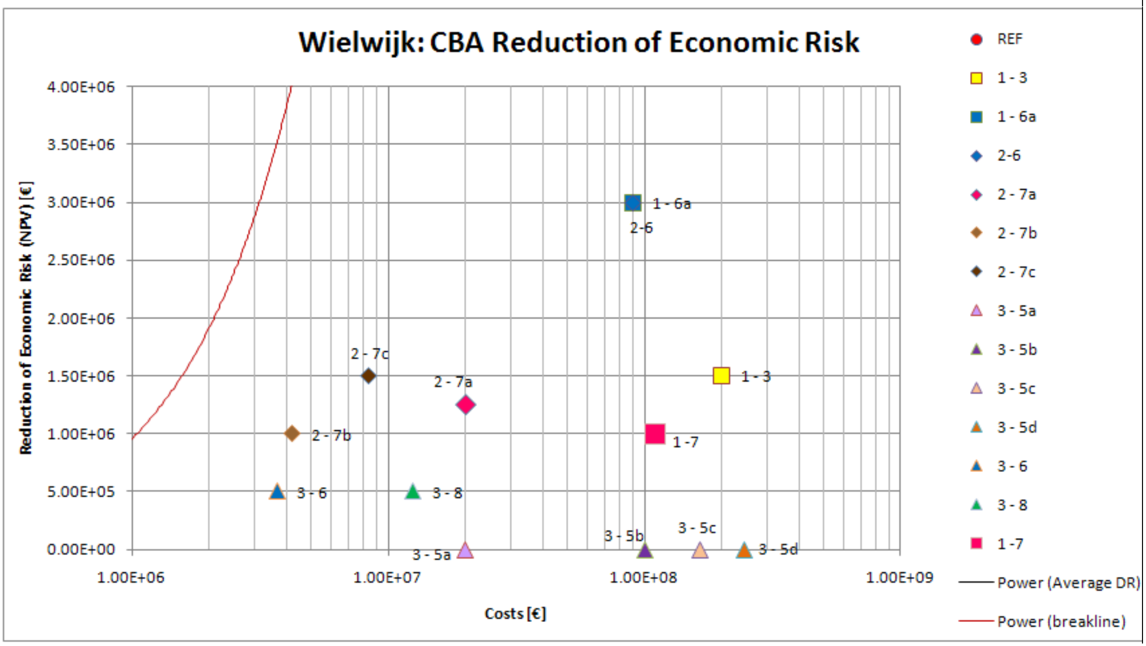

DR22: CBA Reduction of Economic Risk
1.00E+08
9.00E+07
8.00E+07
7.00E+07
6.00E+07
5.00E+07
4.00E+07
3.00E+07
2.00E+07
1.00E+07
0.00E+00
Net Present Value of Reduction of Economic Risk in DR 22 [€]
1.00E+06
1.00E+07
1.00E+08
1.00E+09
Costs [€]

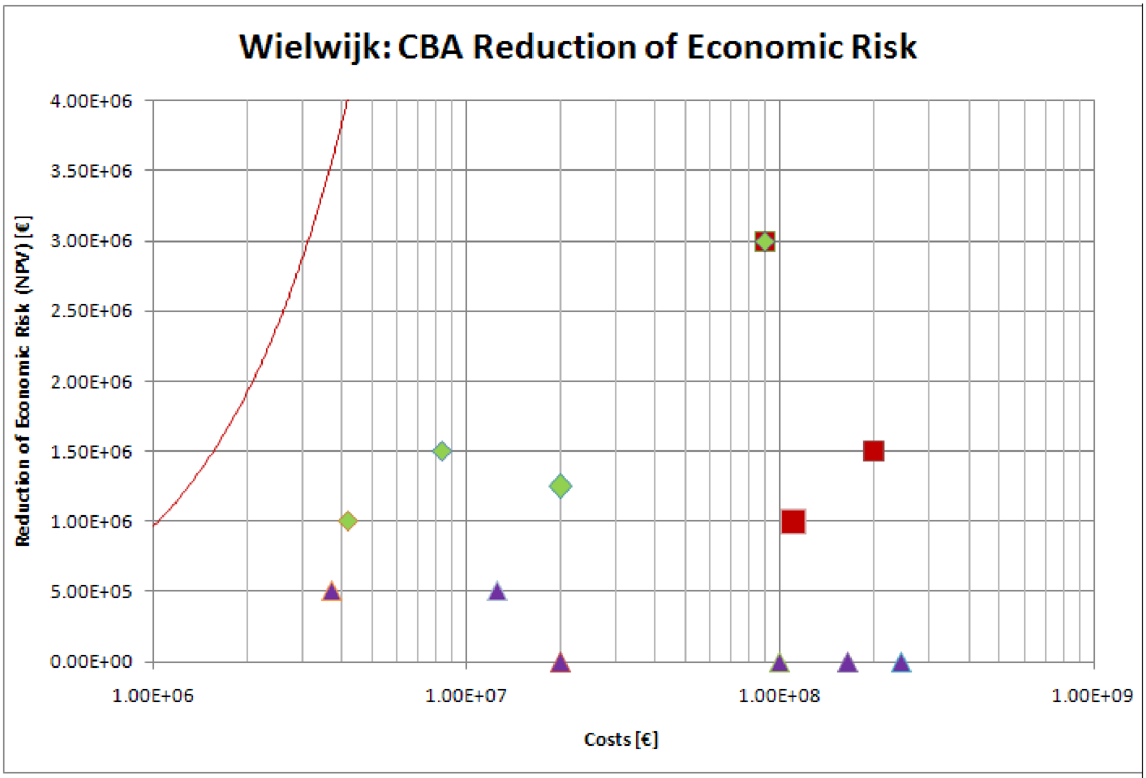
Reduction of Economic Risk per layer: *Wielwijk*



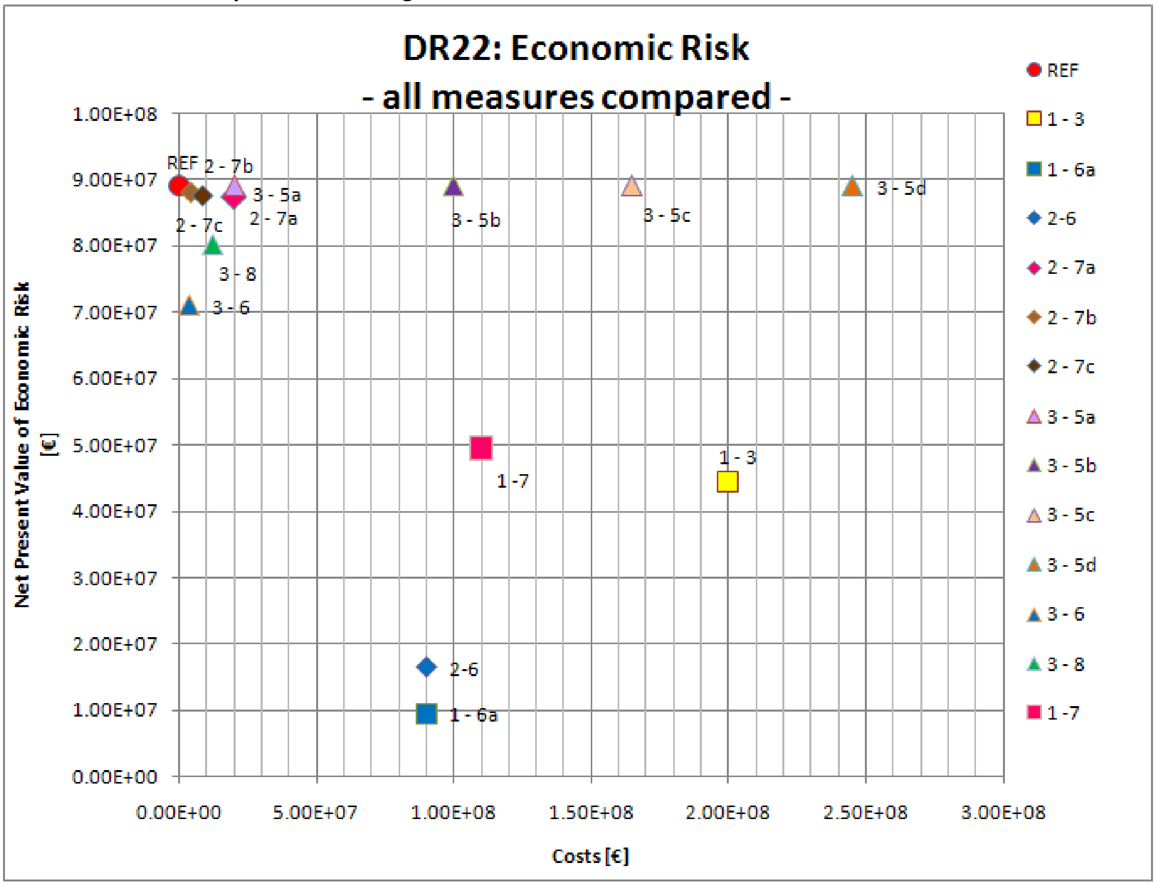


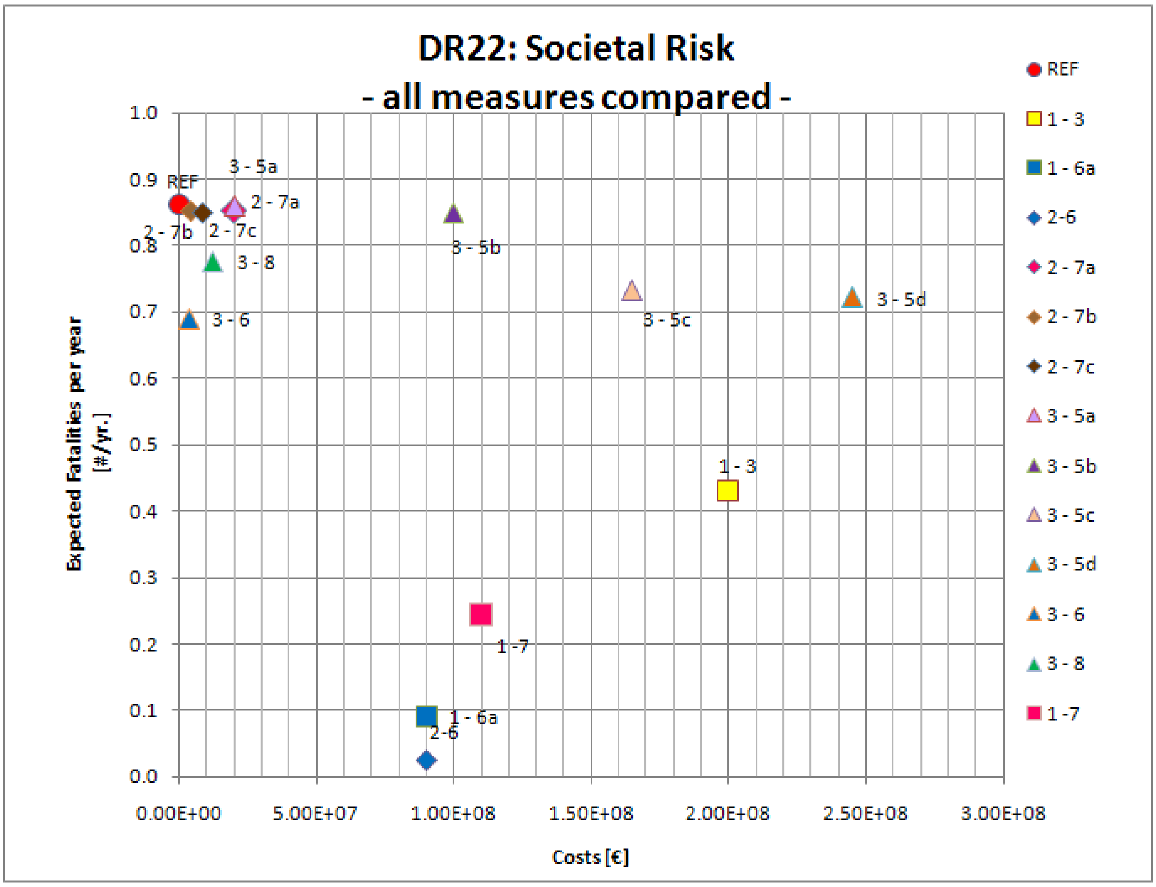

Wielwijk: CBA Reduction of Economic Risk (Crisis Management)
Reduction of Economic Risk (NPV) [€]
Costs [€]
8.00E+04
7.00E+04
6.00E+04
5.00E+04
4.00E+04
3.00E+04
2.00E+04
1.00E+04
0.00E+00
1.00E+06
1.00E+07
1.00E+08
1.00E+09
3 - 5a
3 - 5b
3 - 5c
3 - 5d
REF
3 - 6
3 - 8
Power (Average DR)
Power (breakline)


Wielwijk: CBA Reduction of Economic Risk
Reduction of Economic Risk (NPV) [€]
Costs [€]
4.00E+06
3.50E+06
3.00E+06
2.50E+06
2.00E+06
1.50E+06
1.00E+06
5.00E+05
0.00E+00
1.00E+06
1.00E+07
1.00E+08
1.00E+09
1 - 6a
2-6
2 - 7c
2 - 7a
1 - 3
2 - 7b
1 - 7
3 - 6
3 - 8
3 - 5b
3 - 5c
3 - 5a
3 - 5d
REF
1 - 3
1 - 6a
2-6
2 - 7a
2 - 7b
2 - 7c
3 - 5a
3 - 5b
3 - 5c
3 - 5d
3 - 6
3 - 8
1 - 7
Power (Average DR)
Power (breakline)



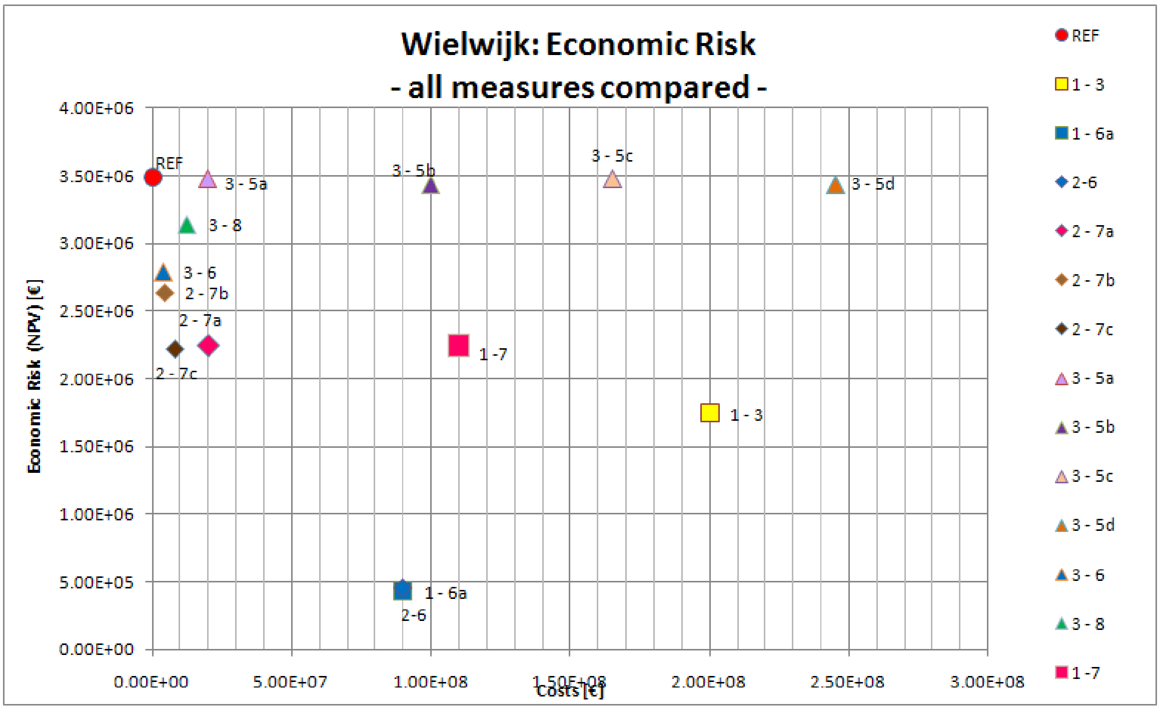
Risk dimensions compared: ***Dike Ring 22***

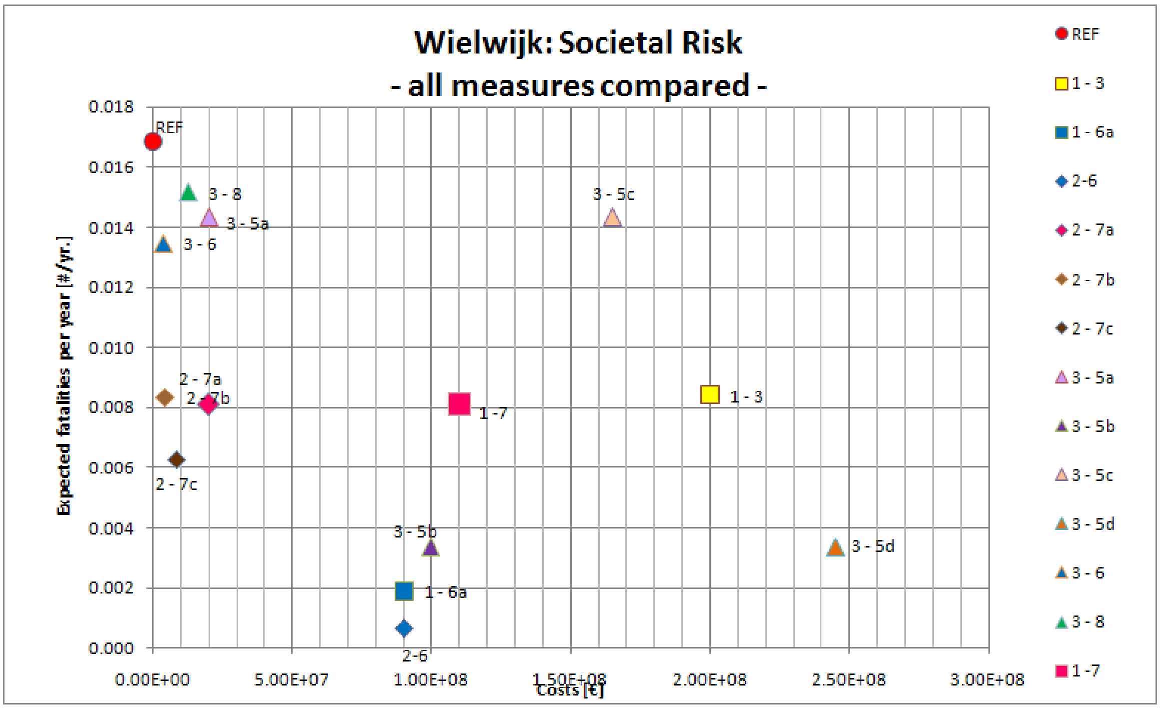




Wielwijk

Risk dimensions compared: *Wielwijk*




Wielwijk: Societal Risk
- all measures compared -
Expected fatalities per year [#/yr.]
Costs [€]
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0.00E+00
5.00E+07
1.00E+08
1.50E+08
2.00E+08
2.50E+08
3.00E+08
REF
3 - 8
3 - 5a
3 - 6
3 - 5c
2 - 7a
2 - 7b
2 - 7c
1 - 7
1 - 3
3 - 5b
1 - 6a
2-6
3 - 5d
REF
1 - 3
1 - 6a
2-6
2 - 7a
2 - 7b
2 - 7c
3 - 5a
3 - 5b
3 - 5c
3 - 5d
3 - 6
3 - 8
1 -7

9.8 Appendix: Software used

The following software has been used for this study:

- Microsoft Office 2007, notably Excel 2007
- Sobek12 (1D,2D)
- HIS-SSM
- HIS-SSM scenario viewer
- RisicoTool (HKV Lijn in Water)
- ArcView