Economic optimisation of multi layer flood safety

Applicability of the risk based optimisation process under sensitivity to uncertainties and budget constraints
Case study: Nyaungdon, Myanmar

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TU Delft

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by

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Preface

This thesis contains my research into the applicability of the risk based optimisation process of flood safety measures. The main goal is to explore its use when there has to be worked with data scarcity and measures have to be implemented with limited budget. It thereby mostly examines this approach for developing countries, where the above mentioned constraints are often present. The thesis is the final work of the Master programme of Hydraulic Engineering at the Delft University of Technology.

During the Bachelor of Civil Engineering and the current Master, I have become increasingly fascinated by flood risk related problems and solutions all over the world. What I find most interesting about this subject, is that flood risk solutions are not only technical tasks, but require an integrated approach. Humans have been living alongside rivers for as long as one can remember. Over time rivers have become connected to society, by offering means of transportation, recreation, fresh water and many more. Solutions must therefore be found within the constraints and opportunities that its surroundings have to offer. The multidisciplinary behaviour of flood risk problems makes dealing with them not only technically complicated, but also a complex assignment. I am therefore delighted that some of this integral approach could be covered in working on this thesis.

I would like to seize this opportunity to thank my graduation committee whose support and feedback have brought the value of this thesis to a higher level. In particular I would like to thank Matthijs Kok for chairing the committee. Due to his punctuality I now have a better understanding about the notions of risk and uncertainty than I have ever had before. I am also thankful to Saskia van Vuren, who has always critically reviewed my work. She was always available for feedback sessions and brought me into contact with experts of 'HKV Lijn in water' for extra information. Furthermore I would like to thank Martine Rutten, who brought up the subject and has introduced me to the students and researchers from Myanmar. Also her background in water management contributed in writing this research. Last but not least, I would like to thank Sander van Nederveen. His knowledge of integral design and infrastructure management has given me a broader view on engineering. Not only in this thesis, but also in previous projects.

All in all, I enjoyed working on this thesis. A final word of gratitude is dedicated to the fellow students that kept me motivated throughout the writing of this thesis. Because of them I succeeded in maintaining a regular working schedule over the total span of this research. Also my friends and family must not be forgotten, who have offered me the needed distractions to make a fresh start the next day. They have turned several years of studying into a pleasant, enjoyable and educational period of my life.

Maurits Kampen
Delft, June 2017

Summary

Living in the vicinity of rivers has many advantages, but also has one major drawback: fluvial flooding. People have been trying to reduce the risk of flooding for a long time. Risk is hereby divided into the product of probability of flooding and its consequences. This means that flood risk can not only be reduced by lowering the probability of floods, but also by reducing the consequences of a flood. This notion is captured in the multi layered safety approach, which classifies flood safety measures into three layers: prevention, spatial planning and crisis management. With the current computation power, optimal flood management systems can be designed so that the total costs of investments in measures and the remaining flood risk are as low as possible. This so called risk based economic optimisation is presently being implemented in the more developed countries, but offers potential for developing countries too. With a limited budget, every penny needs to be well spent. It is however questionable if this method fits the circumstances in developing countries. Sufficient data is needed to get reliable results, while developing countries are often data scarce. The sensitivity to uncertainties in the optimisation process due to working with limited data is explored by means of a case study concerning the area of Nyaungdon, Myanmar, which inundates regularly due to the Ayeyarwady River.

The risks of the case study area are mostly estimated on the basis of open source data. Only prerequisite is that a time series of the river is available to derive the probabilities of flooding. Inundation maps can be constructed based on NASA's Digital Elevation Model, after which they can be verified with Landsat images of historic flood events. Landsat images are furthermore used to construct land use maps. When these maps are combined in a geographic information system together with land use values and depth-damage curves, a spatial and quantitative estimation of the flood risk over the area is found. It is however essential that information about the current embankments is available, otherwise the probabilities of flooding cannot be determined with high confidence. The quantification of the risk is sensitive to the inclusion of data uncertainties. Within the case study the risk has a mean present value of $18.7 million with a standard deviation of $6 million. Especially the estimation of loss of life is a source of high uncertainty.

The risk reducing measures that are chosen for this case study are dike heightening of the current dike, placing poles under the dwellings located in the floodplain and construct shelters to reduce the loss of life. While the uncertainties in risk and investment costs are large, the choice for optimal design remained the same. Lowest total costs are found when dike heightening is used. This layer also corresponds to the lowest needed investments. Dike heightening can be combined with shelters, which become especially attractive when a high statistical valuation of life is used. Within the case study, the spatial planning layer is not only more receptive to the influence of uncertainties, from economic perspective it is also least attractive due to its high investment costs. The amount of dike heightening also remained stable under the inclusion of uncertainties. The shape of the curve that relates dike heightening to Total Costs was as such that its minimum value will always be located around the same location, irrespective the uncertainties: one meter dike heightening, corresponding to a new danger level of 8.5m +MSL. It must however be noted that there is worked with symmetrical uncertainty distributions, other shapes will have more effect on the optimal dike heightening. The optimisation results can still serve as a good indicator of economically most appropriate designs.

The robustness of the optimisation process within the case study does not necessarily offer conclusions for other cases as well, as this is situation and measure specific. It is expected that the outcomes will be robust under uncertainties as long as the Total Costs curve has the same shape as in the case study: fast declining at first, before slowly rising again. With respect to the allocation of resources over different safety layers under budget constraints, it is advisable to invest first in those measures that have the steepest declining Total Costs curve. These measures have the highest ratio between risk reduction and needed investments. The derived risk assessment method is nevertheless executable for other areas that are comparable in size, due to its use of information that is openly available.

Contents

List of Figures

List of Tables

Glossary

Design specifications	Quantitative characteristics of measures, in this case dike height, pole height and number of shelters
Economic optimisation	Endeavour to minimise the total costs of investments and flood risk
Flood management system	Combination of measures to reduce the flood risk
Flood risk	Product of flood probabilities and corresponding consequences
Frequency	Expected number of occurrences of a particular event
Multi layered safety	Flood safety approach based on the combination of prevention, spatial planning and crisis management
Present value	Current worth of a future sum of money
Probability	Chance of occurrence of a particular event
Return period	Estimated recurrence interval of a particular event
Risk based assessment	Examination of flood dangers based on probabilities and consequences
Uncertainty	Unsureness of variables and functions due to lack of knowledge or natural randomness

List of Symbols

B_t	[$]	Benefits in year t
C_t	[$]	Costs in year t
D	[$]	Flood damage
$E(D)$	[$]	Expected flood damage
F_D		Mortality rate
F_E		Evacuation rate
F_S		Shelter rate
h	[m]	Inundation depth
h_{dike}	[m]	Dike heightening
I	[$]	Investment costs
I_0	[$]	Initial investment costs
I_x	[$]	Marginal investment costs
K_p		Gumbel frequency factor
L_{dike}	[m]	Dike length
n		Sample size
N		Extreme flood events per year
N_F		Number of fatalities
N_{PAR}		Population at risk
p		Probability
P		Cumulative probability
P_{exc}		Probability of exceedance
r	[%]	Discount rate
s		Standard deviation of measurements
SE		Standard error
t	[year]	Time period
T	[year]	Return period
V_{extra}	[m^3]	Extra dike heightening volume
z_p		Critical value
α		Tail probability
β		Gumbel scale parameter
γ		Euler-Mascheroni constant
μ		Gumbel location parameter
μ_N		Mortality rate mean
σ		Standard deviation
σ_N		Mortality rate standard deviation
τ	[year]	Time interval
Φ_N		Cumulative standard normal distribution

1

Introduction

People have a complicated relationship with rivers. Despite the dangers, we have been living in the vicinity of them since the beginning of human history. Living in floodplains offers arable and fertile land, nearby means of transportation and abundant supply of fresh water. However, fluvial floods are also among the world's most fatal natural disasters. In the course of history, people have been trying to combat this disadvantage of living near a river by means of embankments, weirs and sluices. In doing so, the science behind this so called flood management developed as well. Over the last centuries, dealing with river floods has changed from implementing measures by trial and error towards comprehensive assessments of costs and benefits. The state of the art of flood management concepts are mostly used in developed countries, although it seems that they might be helpful for developing countries as well. The thoughts behind this and the issues it brings are introduced below to elaborate on the relevance of this research.

1.1. Introduction to flood management

Flood management strategies are not based on one single approach. Rivers are connected to society; their physical behaviour and the impact of human interventions should be handled together (Sayers et al., 2015). Effective flood management requires therefore input from multiple sciences like geography, hydrology, environment, economy and social knowledge. However, most assessments and plans lead back to an economic decision problem (Jonkman et al., 2004). Using an economic rationale in flood management, the endeavour is to increase the economic benefits and lower the costs of riverine flooding with appropriate measures. Although real life policies cannot solely be based on an economic motive, this concept allows for an integrated approach and hands decision makers quantified options to choose from.

1.1.1. Determining safety

Underlying principles

Three methods are in use today to determine the specifications of measures against floods (Tariq, 2011): element design standards, probability based standards and risk based assessment. When element design standards are used, protective structures are designed through minimum standards that are derived from experiments or experiences. Following this method, dikes can for instance be designed to withstand the highest known water level. Compared to the other two methods, little analysis is required, but the design of measures is not economically optimised. A more elaborate method is the probability based assessment, which is most frequently used worldwide. The degree of flood control depends on the return period of the flood that is tried to be prevented. For example, the USA designs its protection structures against a flood with a 100-years probability. In other words, they protect against the situation that statistically will occur on average once every 100 years (Holmes and Dinicola, 2010). The level of failure probability that is chosen depends on the socio-economic situation of the protected area and the aversion against flood risks. Due to its high economic value, large number of inhabitants and their high susceptibility, the coastal defence system of part of the Netherlands has long been designed for a 10,000-years storm.

Although the derivation of this optimal probability for the Dutch coast was already in the direction of the fully risk based approach, the lack of knowledge and computing power forced them to simplified calculations of economic optimisation. Compared to the element design method, the probability based approach already shows that there is a residual chance of failure when a less likely event than the standardised event will occur. However, also this method cannot be used to fully economically optimise the protection system.

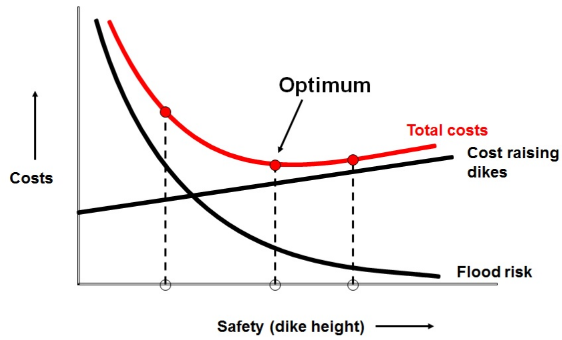


Figure 1.1: *Economic optimisation of dike height Source: Jonkman and Schweckendiek (2015)*

The method that can do this is the risk based assessment. Main difference with the previous two methods is its focus on flood impacts in combination with the probability of flooding. With this approach, all possible flood risks are defined as the product of the probability of occurrence and the flood damages. So, as already proposed by Kaplan and Garrick (1981), this quantitative risk analysis implies answering the following three questions: *What can happen? How likely is it that this will happen? If it does happen, what are the consequences?* Damages are not necessarily economic, they can also be social or environmental and loss of human life. When all damages are expressed in monetary terms, the risk assessment can be extended with a cost-benefit analysis. By investing in safety measures the possible damages can be reduced, which is the benefit in this case. The total costs of floods are now given by the investment costs and the expected residual flood damages. By playing with the safety levels and design specifications, the total cost can be minimised. This kind of economic optimisation and its corresponding calculations can have several results. It can represent the optimal failure probabilities of safety measures, the distribution of investments over several measures and the design specifications of measures. All three are closely related and follow almost immediately from the same process. The idea of minimising total costs is visualised in Figure 1.1. It depicts the achieved safety by means of dike heightening versus the costs, but this could have been any measure or combination of measures. Dike heightening will cost money, but it increases the safety level and thus reduces the residual risk. The optimal dike height and safety level corresponds to the lowest total costs.

Risk based assessments in practice

Improved understanding in the science of flood risks has lead to many countries reassessing their flood management approach. The risk based economic optimisation as described in the previous paragraph is used for determining the new safety standards in the Netherlands, implemented in 2017. All flood control measures will be adapted to meet the new requirements (Kind, 2014b). Risk based assessments are also used in the United Kingdom, United States and Japan for varying purposes, although the frequency and scale of possible flooding is different compared to the Netherlands. The aim of the Environment Agency in the UK is to understand the risks of flooding from rivers and sea, which are translated into risk maps. They thereby support decision making in possible investments and policy of flood insurance companies (Alphen et al., 2011). The U.S. Army Corps of Engineers has shifted from engineering standards to impact assessments to ensure that their large amount of dams and levee systems are operated and maintained in a way that no intolerable risk of life is present. The drafted portfolio classifies the dams on their failure probability and potential consequences (USACE, n.d.). In Japan, the risk based approach is a result of their concern of climate change. The change of risks due to the more intense precipitation are determined to maintain a certain target level of safety of flood control measures (Alphen et al., 2011).

1.1.2. Multi layer flood safety

Managing risks in multiple ways

Hand in hand with the risk based approach comes the principle of multi layer safety (MLS) against floods, recently formalised in the the Dutch water policy (Rijkoverheid, 2009). One of the notions of the risk based assessment is that the occurrence of a flood can never be fully excluded. The general idea of this integrated multi layer approach is that lowering the flood probability is not the only way to reduce flood risk, reducing the consequences or damages if a flood may occur is a possibility as well.

Of course this concept is not new, especially countries that have to deal with floods on regular basis have developed ways of coping with the consequences of floods. An example of this are the flood warning systems and evacuation plans in the United States (PrepareAthon, n.d.). However, coupling this approach to risk based flood management is relatively new. This multi layer principle of achieving safety contains three layers: prevention, spatial planning and crisis management, as visualised in Figure 1.2. The first layer is meant to reduce the probability of flooding to prevent a flood from happening in the first place. Corresponding actions are for example the building of dikes and dams or lowering the hydraulic loads on the protective structures by measures that increase the flood conveyance capacity. The second layer is concerned with the mitigation of losses in case of flooding. Examples of spatial planning solutions are making assets flood proof or moving assets to areas that are less prone to flooding. The purpose of the third layer is also to mitigate the consequences, but focussing on reducing the loss of human life by means of warning systems and evacuation planning (Rijkoverheid, 2009).

Economic efficiency

Although the concept of multi layered safety is clear, doubts exist about whether investing in other layers than prevention is cost efficient. After all, the other two layers only become effective after a flood has occurred. The question is whether investments in the mitigating layers could not better be spend to avoid a disaster in the first place. The only way to answer this question is by quantitative risk analysis and probabilistic reasoning for every situation, instead of relying on intuition (Vrijling, 2013). An important concept in this analysis is the marginal cost, which is the change in total cost of a product when the produced quantity is incremented with one unit. Relating this to flood risk, marginal costs are for example the change in total costs of increasing a dike with a certain height or the change in total costs for increasing the piles of a house on stilts with a certain length to achieve a higher safety level.

In literature, several findings with respect to the attractiveness of single versus multi layered safety are derived on the basis of simple example calculations. It is for example likely that MLS is preferable over solely prevention if the marginal costs of mitigating measures are lower than that of the preventive measures (Tsimopoulou, 2015). Furthermore, if the economic value of the land decreases, investing in multiple layers becomes more attractive (Kolen and Kok, 2012).This can also be noticed from the Dutch focus on prevention, where most areas are of high economic value and dike heightening often has lower marginal costs for achieving the same risk reduction as compared to, for example, the adaptation of assets (Kolen, 2013). Furthermore, it appeared that when the available budget for flood management is getting lower, it becomes more likely that investing in multiple layers is economically more attractive. It must however be noticed that uncertainty in the used variables affects the likelihood of multi layered safety being the optimal solution. Especially uncertainty in the marginal costs of layer 3 (crisis management) appeared to have a large influence on the optimality results (Kolen and Kok, 2012). Interestingly, the robustness not only increased with a decrease of uncertainty, the results became also more robust when the available budget was reduced (Tsimopoulou, 2015).

Figure 1.2: *Multi layer safety. At the top: crisis management, middle: spatial planning, bottom: prevention. Source: Rijkoverheid (2009)*

1.2. Problem description

As has been said above, multi layer safety might offer potential for regions with a limited available budget for flood management. Such regions are often developing countries, which have increasing value to protect, but lack the resources to implement appropriate measures. However, conducting a full risk assessment and proposing suitable plans for these kind of areas brings some issues, which are first elaborated in this section. After that, the location which will be used as case study in this research is presented briefly.

1.2.1. Flood management in developing countries

The amount of people worldwide exposed to a devastating flood scenario is estimated to have doubled to 2 billion in 2050, if no further efforts are taken (UN University, 2004). One of the reasons is climate change, which will lead to rising sea levels and more extreme events of precipitation, resulting in higher river discharges. Another issue is the deforestation of mountainous regions, which normally act as buffer for extreme precipitation. Furthermore, the population in areas prone to flooding is increasing. Especially Asia is among the regions that suffers under great potential hazards. Not only does this continent experience most of the world's floods, its economic activities have also rapidly developed over the past decades. Despite this growth, most people still live from agriculture, often situated in low lying floodplains. Moreover, some growing economies in Asia like Cambodia, Laos, Bangladesh and Myanmar are fragile and remain vulnerable to external shocks such as floods (ADPC, 2005). Even when flood damages are comparable in absolute values, developing countries suffer relatively higher damages compared to their national income. On top of their enhanced vulnerability, developing countries often lack proper flood management. Among the causes are limited resources, lack of research capacity and failing to integrate structural and non-structural measures, which synergy could reduce risks significantly (Petry, 2002). Flood management is often implemented with the financial and technical aid of developed countries. The problem is that they often bring their own methodologies and safety standards that do not fit the conditions of less developed countries. For instance, the high safety standards that are derived in developed countries will not bring the desired efficiency in countries where the social and economical situation is different, also keeping in mind the possible technical constraints (Tariq, 2011). There is need for a fit-for-purpose flood management methodology that considers these boundaries and constraints of the specific area.

Risk based assessments could be an outcome to draft economically effective flood management systems for developing countries. This is however easier said than done, since even the most comprehensive models have embedded uncertainty and decisions have to be made under a certain reliability. An important source of uncertainty is lack of data. This is the case for any area, but especially in data scarce regions, what developing countries often are. The reliability of the risk assessments decreases with insufficient information about rainfall series, river dimensions, land use, damage functions, current protection levels and other sources of uncertainty. By not acknowledging this reduced reliability, false conclusions might be drawn from economic optimisation calculations. This issue poses challenges for the use of risk based flood management in developing countries.

1.2.2. Case study: Nyaungdon

Research into cost effective flood management in developing countries based on risk assessments will be conducted on the basis of a case study. As stated before in section 1.2.1, Asia suffers under great hazards of flooding. The case study that will therefore be used for this research is located in the Republic of the Union of Myanmar, mostly abbreviated to Myanmar. The location that is chosen to investigate the applicability of optimisation of measure is Nyaungdon. Nyaungdon is a town located at the junction of the Pan Hlaing River and the Ayeyarwady River. Especially the latter is a highly dynamic river. The town has around 40.000 inhabitants of which the main work sectors are fishery and agriculture. This area has experienced floods in the past. Therefore a dike around the town is in place of which a part is recently heightened. However, flood safety is still seen as an issue here. The dike consists of different sections of earthen dikes and dikes covered with brick works. Furthermore, objects such as houses and trees are located on and near the dike, influencing its functioning. The second safety layer is also in place, mostly by means of houses on stilts on the riverside of the dikes (Blom et al., 2016). The area around the town consists primarily of rice fields in the Ayeyarwady floodplain, which is not protected by any dike for the biggest part.

1.2.3. Knowledge gaps and research focus

Floods are likely to occur more often in the future. Especially for developing countries, including Myanmar, the effects of floods can be disastrous. However, the control of flood risks in developing countries is often based on crude element design standards or unsuitable probability standards from wealthier countries (Tariq, 2011). Combining this with the fact of limited available budgets, implies that such areas are in need of more efficient flood management. Summarising the previous sections, risk based assessments in combination with economic optimisations make it possible to design cost efficient flood

Figure 1.3: *Case study location, location within Myanmar (left) and zoomed in (right)*
Source underlying map: Google Maps (2016)

management plans. Not only the specification of measures can be determined, it should also be possible to economically optimise the distribution of investments over the three layers of safety against floods. Tsimopoulou (2015) and Kolen and Kok (2012) already derived promising results of the capability of multi layer safety in developing countries from simplified examples, but it is still unknown how this works out in real life situations. In short, risk based design optimisation appears to offer potential as appropriate flood management approach in such areas, but the question is whether this method suits the circumstances in developing countries. Uncertainties in the modelled system might give an optimal specification of measures that differs from how it will work out in the actual situation. Economic optimisations are therefore most valuable if there is sufficient data available to get reliable results. Unfortunately, developing countries often lack this data. How valuable the optimisation is depends on the degree of influence of uncertainties caused by the lack of data. The answer will lie between two extremes. The first extreme corresponds to a reliable outcome of the economic optimisation, meaning that the uncertainties have little effect in the design specifications and ideal distribution of the budget over the three layers of safety. The other extreme represents a situation where the spread in optimal design values due to uncertain inputs is so wide, that the derived values are not meaningful at all. An intermediate result is that it might only serve as preliminary assessment of measures.

Summarising, the focus of this research is determining the sensitivity to uncertainties of the risk based economic optimisation of multi layer safety and therefore examining the applicability of this approach. The case study in Myanmar will be used to make sure that the uncertain variables of a real life case are included. The conclusions that are drawn from this case may be generalised to comparable situations. It must however be noticed that the economic motive is not the only factor contributing to appropriate flood management in real life situations. Some social and political limitations cannot be incorporated in this approach, but are still important in finding the most suitable solution and have to be examined in every situation. Nonetheless, the added value of the economic rationale is that it provides decision makers with quantified options. It is therefore important to investigate if an economic optimisation is possible in the first place.

1.3. Research question

The research is aimed at answering the main research question, derived from the knowledge gaps and research focus from the previous section. The main question is divided into several subquestions which make it possible to provide a reasoned conclusion of the main question.

Main question
Based on the problem description, referring to the problems within the case study and the issues with respect to the applicability of economic optimisation in data scarce areas, the following research question is formulated:

How can risk based economic optimisation in multi layer flood safety be applied under budget constraints and uncertainty due to data scarcity?

The case study is used to investigate the applicability of economic optimisations in real life situations. The safety measures that are included in the optimisation process are chosen to fit the social and economic situation in the case studies. It is however not the goal of this research to present a suitable combination of measures for each case study, but to test the applicability of optimisation. The multi layers of safety might therefore be simplified in order to accommodate the purpose of this research.

Subquestions
The main question is divided into several subquestions. The sub questions are primarily answered for the situation within the case study, but lessons learned are generalised to wider applications if possible.

1. How can the economically optimal design be determined, assuming certainty in used variables and functions and fixed budget?
   (a) How can the level of risk be determined with the available data?
   (b) How can the three layers of safety be schematised to facilitate optimisation calculations?
2. What effect do the uncertainties have on the optimal distribution of investments?
   (a) Which uncertainties arise due to lack of data and how can their effect be quantified?
   (b) Which uncertainties arise due to the used models and methods and can their effect be quantified?
   (c) Which uncertainties arise due to unsure future developments and how can their effect be quantified?
   (d) What is the effect of the size of the available budget?
   (e) Which uncertainties affect the optimised outcome the most?
3. Can the expected uncertainty in optimal design specifications be reduced?
   (a) Can the uncertainty be reduced by extra measurements?
   (b) Can the uncertainty be reduced by developments in open data?
4. Which learned lessons with respect to the applicability of risk based economic optimisation can be generalised to other data scarce areas?

1.4. Reading guide

The information that is needed for answering the main question is gathered throughout a series of chapters. After this introduction, the report continues with a theoretical background in Chapter 2. It will explain the notions of flood risk, system analysis, economic optimisation and the influence of uncertainty within all this. The theory from literature is combined into a coarse methodology that will be followed in the chapters to come. In Chapter 3 the current flood risk is determined for the Nyaungdon case study area. The theory is shaped into a workable method with the use of open source data and software. After that, suitable measures to reduce this flood risk are defined in Chapter 4. Subsequently, the design of these measures is economically optimised in the same chapter. Since this research explores the multi layer flood safety, not only the individual measures, but every combination of measures is optimised. The analyses in Chapter 3 and 4 are performed with single parameters. Chapter 5 explores the effects of uncertainty within these parameters. The input variables and functions are changed into uncertainty distributions and the optimality calculations are performed again. It is here that the effect of data scarcity and budget constraints is investigated. The applicability of the risk based assessment and economic optimisation of measures will depend on the influence of the uncertainties.

Before entering the discussion and conclusion of the main report, the derived method is summed up in Chapter 6, which can serve a concise recipe for other cases. All the results of the above are examined in Chapter 7, the discussion. It assesses the method as it is used in Chapters 3 and 4 and the reliability of the outcomes. It furthermore explores the possibilities of the method to be generalised to other data scarce areas around the world. The main report ends with the conclusions and recommendations in Chapter 8. Based on all previous chapters, the research question is answered here. The back end of the report consists of appendices that complement the elaborations in the main report.

2
Literature

To answer the main question and its subquestions a certain methodology is followed. The case study is conducted by a sequence of four main actions. These actions are the flood risk determination, analysis of possible measures, economic optimisation of the design specifications and ultimately the effect of uncertainties and budget constraints on these optimised specifications. After these steps, the results can be analysed to look into the applicability of risk based economic optimisation of multi layered flood safety, in data scare areas and under budget constraints. The whole process is illustrated below. This chapter presents the literature that is included into this process and the underlying tasks of each main action.

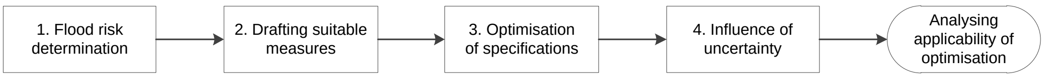


Figure 2.1: *Total work diagram*

2.1. Flood risk analysis

The first sub process in this research is the analysis into the present flood risks. However, before starting risk analyses, it is important to understand what is meant by risk and how it differs from uncertainty. An elaboration on this issue is therefore given first, after which a mathematical representation of risk is presented. With a good understanding of flood risk in mind, the underlying steps to determine the current risk levels are elaborated on in the second half of this section.

2.1.1. Risk versus uncertainty

Classifications of uncertainty

In order to correctly model a flood safety system and its reliability, it is important to understand the differences in what is meant with risk and uncertainty in this research. Both terms are used to describe that a future state is unknown (Squair, 2009), but their definitions are different. Risk is the statistical chance or probability that a potential hazard results in the actual appearance of this hazard, combined with the consequences of the hazard situation. Both the probability as amount of consequences and therefore the risk can be uncertain. The factors of uncertainty can be divided among two classifications: aleatory and epistemic uncertainty. The first is derived from the Latin word *alea*, which actually translates into a game of dice. Aleatory uncertainty therefore originates in the randomness or natural variability of a phenomenon and is also called inherent uncertainty. Examples of aleatory uncertainty are that the exact outcome of throwing a die is not known, nor is tossing a coin or the maximum river discharge in a specific year on a specific location. Inherent uncertainties therefore exist both in time and space and cannot be reduced, since they represent the randomness of nature (Jonkman, 2007). The other type of uncertainty has its meaning derived from the Greek word *episteme*, which means knowledge. Epistemic uncertainty is therefore also called knowledge uncertainty. Epistemic uncertainties are the result of a lack of knowledge by limited data, models or incomplete understanding of the processes in place. Knowledge uncertainties could, in contrast to inherent uncertainties, be reduced by the gathering of more data or the use of more advanced sciences (Kiureghian and Ditlevsen, 2007). Knowledge uncertainties can furthermore be subdivided into model and statistical uncertainties (Jonkman, 2007). Model uncertainty arises when phenomena or processes are not completely understood. Statistical uncertainty represents the fact that it may be unclear if the chosen statistical function, to define for instance the flood probabilities, gives an adequate representation of the phenomenon. The statistical uncertainty can therefore arise from the chosen distribution type and its parameters. The classifications of uncertainties is depicted in Figure 2.2.

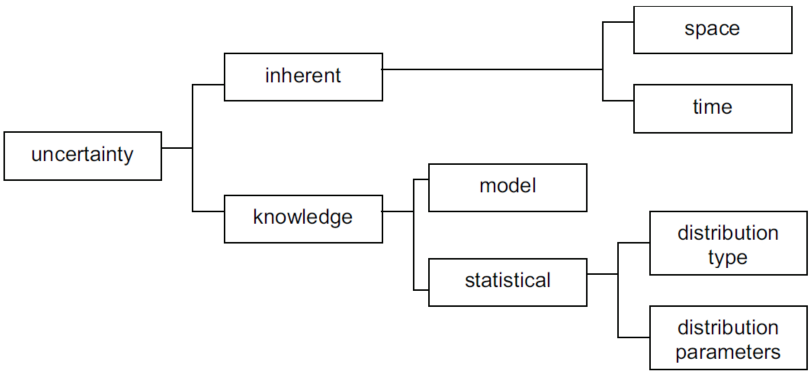


Figure 2.2: *Classification of uncertainties*
Source: Jonkman (2007)

To give an example of the different types of statistical uncertainty, the Rhine is used. The water levels of the Rhine near Lobith, where the river enters the Netherlands, have been gauged since 1900 and translated into corresponding discharges. Several statistical distributions like Pearson III, log-normal and Gumbel can be used to imitate these time series as best as possible and to extrapolate the discharge to return periods larger than the measured series.
Each distribution will however give a different discharge for the same return period, leading to a statistical uncertainty in actual discharge. An averaged function of the above mentioned distributions is presented in Figure 2.3. Furthermore, the extreme high discharges in 1993 and 1995 have led to a shift in the statistical representations (Jonkman and Schweckendiek, 2015). Without the discharges in these years, the Rhine discharge of 15.000 m^3/s corresponds to a situation that on average would happen once in 1250 years. Including the extreme discharges, the return period of this discharge decreased to once in 600 years, as can be seen in Figure 2.3. These two events indicated that there is uncertainty in the statistical determination of discharges due to uncertainty in the used parameters.

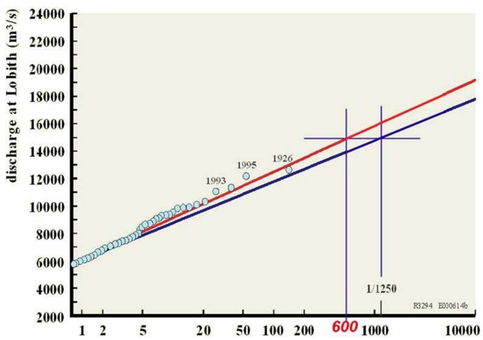
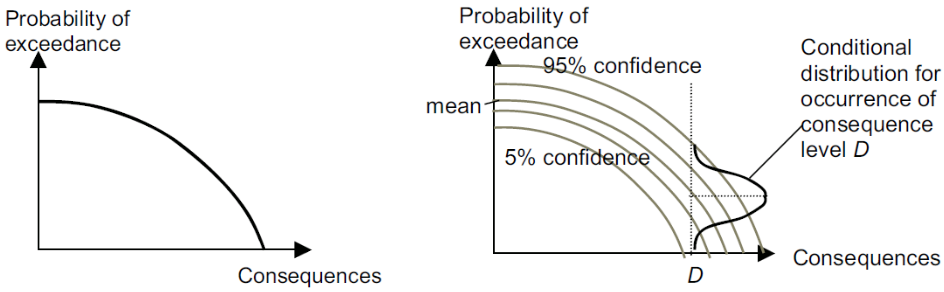


Figure 2.3: *Influence of 1993 and 1995 discharge, leading to decreased return periods. Source: Jonkman and Schweckendiek (2015)*

Dealing with uncertainties
After being aware of the uncertainties is risk analysis, there are three approaches to treat uncertainties. Jonkman (2007) listed all three together with some of their (dis)advantages:

- *Assessment of aleatory uncertainties only.* In this approach it is assumed that the probability of a certain outcome is exactly known and can be described with a single risk curve, as is depicted in the left picture of Figure 2.4. Epistemic uncertainties are not taken into account in this approach. However, being aware of epistemic uncertainties is in reality an important element in the decision making process and neglecting them is therefore less desirable.

- *Separated assessment of aleatory and epistemic uncertainty.* In contrast to the previous approach, epistemic uncertainties in the estimation of probabilities and consequences are taken into account. The inherent and knowledge uncertainties are assessed separately in the sense that the knowledge uncertainty in the estimation of the inherent uncertainty is expressed by a separate distribution, called the conditional distribution. As a result the risk is not displayed by a single risk curve, but by a family of risk curves. Each curve corresponds to a confidence level of the estimation of risk. The 5% risk curve corresponds, for instance, to the estimation with 5% confidence that in reality the combined probabilities and consequences are below this curve. This approach also allows for depicting a conditional distribution of the corresponding probability of exceedance for each consequence level, as is shown in the right picture of Figure 2.4. The advantage of this approach is that the extent of knowledge uncertainty is clearly shown.



(a) *Aleatory uncertainty only (epistemic uncertainty not included)*

(b) *Separated assessment (epistemic uncertainty represented as confidence bounds)*

Figure 2.4: *Two approaches for treatment of uncertainties. Source: Jonkman (2007)*

- *Integrated assessment of aleatory and epistemic uncertainty.* This last approach is based on the Bayesian probability theory, that will not be explained in detail here. The result of this approach is an estimate of the probability of the inherent uncertainty, with the effect of knowledge uncertainties integrated into it. The advantage is that the effects of uncertainty can actually be included into the determination of probabilities and risk levels. If for example the failure probability of a dike segment is determined by means of this integrated method, the inclusion of knowledge uncertainties generally leads to an increase of the failure probability. Reduction of knowledge uncertainties then also results in a reduction of the estimated failure probability. Measures to reduce the knowledge uncertainties might therefore be as effective in lowering the estimated failure probability as physical measures that reduce the inherent failure probability.

Since the main goal of this thesis is to investigate the sensitivity to (knowledge) uncertainties, the first approach is not an option for the risk analyses in this report. The advantage of the separate assessment of inherent and knowledge uncertainty is that the effect of both can be clearly visualised. It furthermore requires less mathematical methods than the integrated Bayesian approach. The second approach is therefore chosen to treat the uncertainties arising in the case study.

2.1.2. Flood risk definition

Risk is defined in many different ways in literature. Normally, flood risk is perceived as the potential impact and can therefore be described as the combination of the probability of flooding times the consequences of the flood, as was described in section 2.1.1. A somewhat different representation is the product of hazard and vulnerability. This expression shows more clearly the different components of risk. It will be shown below that they will produce the same results. At first, it is however necessary to introduce some expressions related to probability theory and how they differ from each other.

Probability expressions

Frequency, probability and return period are often used interchangeably to communicate the chance of a flood. This is however not always correct. The frequency defines the expected number of occurrences of a particular event, for example a particular water level. The return period relates to this in that it represents the estimated recurrence interval of a particular event, derived from a set of data. The probability defines the chance of occurrence of one event compared to the population of all events

(Sayers, 2016). The difference between expected frequency and probability can be explained by the example of throwing a die. The probability of throwing a five with a fair die within one throw is 1/6. The expected frequency of throwing a five with six throws is 1 (=1/6 x 6). The probability of throwing five within six throws is however not 1, since that implies that it is certain that a five will be thrown. The same goes for the occurrence of a storm with a 100-years return period in a time period of 100 years. The expected frequency is 1, the probability of encountering a 100-year storm during this time period is however different. The encounter probability and return period are related through the following equation (Sayers, 2016):

$$P_{exc} = 1 - (1 - \frac{1}{T})^{\tau} \tag{2.1}$$

This equation describes the probability P_e of encountering at least one event with return period T during the specific time period τ. Using this equation the asked probability of a 100-year storm within a time period of 100 years equals approximately 0.63. Using this knowledge, statements such as that a 100-year storm will definitely occur within a period of 100 years or that a 100-year storm will not occur for another 99 years if one took place this year, make no sense any more.

Probabilities have in principle no unit. In practice, the probabilities in risk analysis are generally expressed as the probability per unit time, for example per year (Jonkman and Schweckendiek, 2015). In that case n is 1 and Equation 2.1 reduces to:

$$P_{exc} = 1 - (1 - \frac{1}{T}) = \frac{1}{T} \tag{2.2}$$

From now on the probability per unit time is used to describe the probability of a flood event. The time unit will mostly be per year, since that happens to be convenient for multiple reasons. Amongst others it makes it possible to express the risk in estimated flood damages per year. Furthermore, the probability per unit time now equals the frequency. Also, the return period can now be determined by the reciprocal of the annual probability.

Mathematical representation of risk

Mathematically the risk of a single event can be defined by the following:

$$Risk\ (\$\ year^{-1}) = Probability\ (year^{-1}) \times Consequences\ (\$) \tag{2.3}$$

Or by the following:

$$Risk\ (\$\ year^{-1}) = Hazard\ (m\ year^{-1}) \times Vulnerability\ (\$\ m^{-1}) \tag{2.4}$$

Both ways represent the unit of risk as impact per time period, mostly in the form of money per year. So in other words, the expected economic losses per year. Although in the end the quantity of risk is the same for both equations, Equation 2.4 is more suitable for showing the different causes of risk. It therefore better complements the multi layer safety approach. Both hazard and vulnerability contribute to the quantity of risk and analysing these two factors shows which components are of influence. It not only helps in decomposing the complex reality of risk into a more simple conceptualisation, it also shows which factors can be influenced by measures. Both hazard and vulnerability are elaborated below according to Tariq (2011), in order to achieve conformity in their definition.

Hazard

Kron (2005) defined hazard as the threatening natural event including a defined probability of occurrence. In flood management this natural event is the occurrence of flooding, expressed in for instance inundation depth in meters. Mathematically a hazard can therefore be characterised as follows:

$$Hazard\ (m\ year^{-1}) = Probability\ (year^{-1}) \times Intensity\ (m) \tag{2.5}$$

Probability (P) is here the statistical chance a hazard occurs within a unit of time, as it has been derived in the beginning of this section. Normally this probability is given in chance per year, for example 1/100 per year, or in the corresponding return period of 100 years, in this case. The intensity (I) is the property or combination of properties of the hazard that has consequences. In Equation 2.5, the intensity is measured in inundation depth. Other types can be duration of inundation, velocity of the water and rising rate of the water. The product of velocity and depth is also used as indication of flood intensity. Combining probability and intensity therefore represents a specific flood event with a probability of occurrence per year.

Vulnerability
The occurred hazard can damage the elements that are vulnerable to this hazard. Vulnerability is defined in the following manner:

$$Vulnerability\ (\$\, m^{-1}) = Susceptibility\ (m^{-1}) \times Exposure\ (\$) \tag{2.6}$$

Vulnerability is therefore the lack of resistance to damaging forces (Kron, 2005). Exposure (E) is here defined as the value and life within the potential flooded area that is under threat. Exposure is therefore related to the use of land. If there are no people or economic value in the floodplains of a river, there cannot be any risk of flooding. Similarly, if people are well prepared and assets flood proof, the risk reduces with the reduced susceptibility. To quantify susceptibility (S), this component is usually depicted as damage functions. These functions relate damage to the magnitude of certain flood properties in percentage of total damage.

Back to risk
Coming back to the general representation of risk, the components of hazard and vulnerability can be substituted into Equation 2.4, resulting in:

$$Risk\ (\$\, year^{-1}) = [P \times I]\ (m\, year^{-1}) \times [S \times E]\ (\$\, m^{-1}) \tag{2.7}$$

Thus:

$$Risk\ (\$\, year^{-1}) = P\ (year^{-1}) \times [I \times S \times E]\ (\$) \tag{2.8}$$

Comparing Equation 2.8 with Equation 2.4 shows that the first is a more extensive form of the latter. The product of intensity, susceptibility and exposure therefore represent the consequences of a flood event. The exposure shows the greatest possible damage, the intensity of the flood event and the susceptibility of the flood prone elements determine to which extent this damage occurs. Combining this with the probability of the flood event, the expected risk can be defined.
So far, risk has only be expressed as the probability of one specific event with corresponding consequences. If a certain area is now prone to several flood scenarios each representing a certain probability, the total risk is found by the sum of the risks. With n scenarios, the total risk is the following:

$$Risk_{Total}\ (\$\, year^{-1}) = \sum_{i=1}^{n} P_i\ (year^{-1}) \times [I \times S \times E]_i\ (\$) \tag{2.9}$$

The different scenarios can for example be the result of different possible breach locations or failure mechanisms in a dike ring. In this thesis different scenarios correspond to different river water levels at the case study location, each having their own probability and consequences.

2.1.3. Loss of life

Loss of life framework
Besides the material damages, loss of life is also an important consequence of flooding. The amount of fatalities is however more difficult to estimate than the material losses. How humans are affected by floods is largely influenced by their behaviour. After all, humans can anticipate on the occurrence of flooding and can also react when a flood takes place. Aside from the social aspects, the characteristics of a flood event and the environment are an important factor in the human susceptibility to floods.Jonkman (2007) captured all of the above in a framework for loss of life estimation for flood events, depicted in Figure 2.5. Starting points are the flood event and the initial population in the area at risk. Part of the initial population remains exposed after evacuation or finding a shelter. How much people can evacuate depends on the time that is required to evacuate and the time that is available to evacuate. The required time is for instance dependent on the road capacities. The available time depends on the prediction and warning of the flood event and the flood characteristics itself. The remaining exposed population may loose its life or will survive. The mortality rate among the exposed population depends on the flood characteristics and the dose-response functions, also called mortality functions. These functions are comparable to the depth-damage functions that are used for quantifying the material losses and relate the characteristics such as inundation depth, flow velocities and rise rate of flood waters to mortality. A simplification of the above can be captured in the following formula,

based on Jonkman (2007):

$$N_F(h) = N_{PAR} \cdot (1 - F_E) \cdot (1 - F_S) * F_D(h) \tag{2.10}$$

The number of fatalities N is a function of the flood intensity, in this case the inundation depth h, since that is the only flood characteristic that is used in this research. The population at risk N_{PAR} reduces to the exposed population by means of the evacuation rate F_E and shelter rate F_S. The amount of fatalities among the exposed population is determined by the mortality rate $F_D(h)$, the dose-response function as a function of the flood depth. Jonkman (2007) distinguished three zones for the derivation of the dose-response functions: the breach zone, the zone with rapidly rising waters and the remaining zone. The first two zones are characterised by fast flowing and rapid rising flood waters, the third zone is used for locations where the flood conditions increase more slowly. In the current analysis, dike breaches are not included and therefore the defined remaining zone best describes the flood events in the Nyaungdon area. The mortality functions have been derived based on historic flood events, linking the flood intensities to mortality rates. The mortality function that has been drafted for the remaining zone has been given a lognormal fit and is the following, where Φ_N represents here the cumulative standard normal distribution:

$$F_D(h) = \Phi_N\left(\frac{ln(h) - \mu_N}{\sigma_N}\right) \tag{2.11}$$

$$\mu_N = 7.60 \qquad \sigma_N = 2.75$$

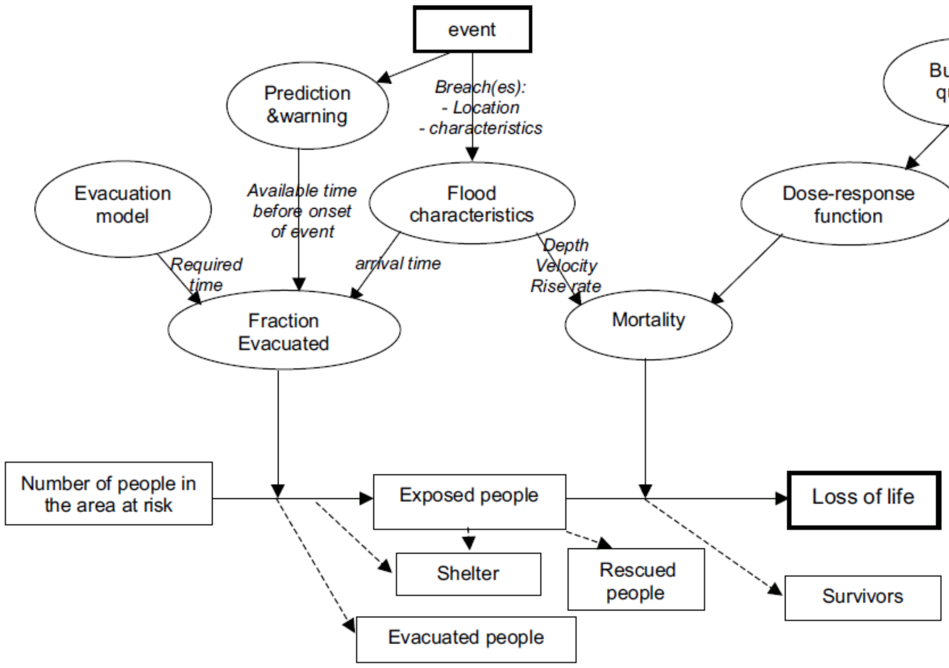


Figure 2.5: *Framework for loss of life estimation, the variables used as input are shown in italic*
Source: Jonkman (2007)

Valuation methods

To be able to relate the costs of measures in the third safety layer to the total costs of loss of life, a monetary value needs to be given to loss of life. Valuing a loss of life might raise ethical questions. However, the investments in flood risk management and reducing the risk of loss of life are always finite, indicating that the value assigned to loss of human life is also finite (Jongejan et al., n.d.). Several methods exist for the valuation of human life, but they can all be brought back to two approaches: the behavioural or non-behavioural approach. Each method leads to different valuation of life.

Behavioural approach
The first approach is based on people's willingness to pay for risk reduction. The two components that are needed for the determination of the value of a statistical life (VoSL) with this method are the following: the amount of money that people are prepared to pay on a yearly basis to reduce the annual probability of premature death by a hazard, and the reduction of annual probability that can be achieved by a form of measure (Kind, 2014a). The willingness to pay has to be determined through questionnaires. This method therefore also implies that the type of risk and the risk perception are of influence for the value of a statistical life (Jongejan et al., n.d.). The Dutch Ministry of Infrastructure and Environment has been using a value of €2.2 million as the social costs of traffic accidents. A study of Bockarjova et al. (2009) has shown that the VoSL for flood events in the Netherlands is around €6.7 million.

Non-behavioural approach
The non-behavioural approach is not based on the willingness to pay, but on people's potential economic production. As a benchmark for human productivity, the net national product per capita is proposed (Jongejan et al., n.d.). Contrary to the domestic product, the national product also includes production outside the country borders. The advantage of using the net product instead of the gross product, is that the depreciation of capital is also included. However, for Myanmar only recent values of the gross domestic product per capita are known and have therefore to be used. How much the national and domestics products differ, depends on to what extent the country is producing outside its borders and to what extent foreign companies are manufacturing within the country. Now, to determine the value of statistical life with this macro-economic evaluation the life expectancy, the countries' age-distribution and discount rate are needed as well. The valuation for people in the Netherlands with this method is around €0.5 million (Jongejan et al., n.d.). It can be noticed that this is considerably lower than how it was determined through the behavioral approach.

2.1.4. Flood risk determination
As given in 2.1.2, flood risk is made up of its probability, flood intensity, susceptibility of the area and the exposure in the area. All four contributors of risk have to be quantified. The input that is needed for this and the process that will be followed is depicted in Figure 2.6.

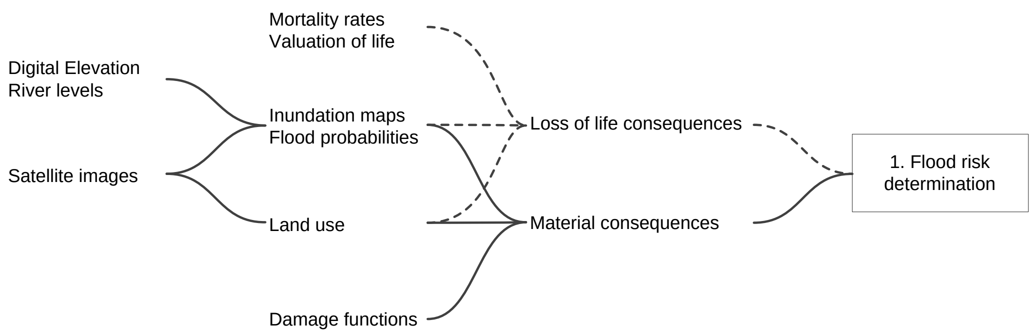


Figure 2.6: *Work diagram Flood risk determination*

The tasks to determine the current risk levels start with data on the elevation of the area, water level measurements and satellite images. Fully modelling the neighbouring rivers to determine the flood extent and intensities in software packages like SOBEK would be a time consuming process. Lack of appropriate data makes this modelling a process which effort does not outweigh the reliability of the outcomes. The method that will therefore be used in this research is combining the river water levels with digital elevation maps of the areas. This method better fits the lack of data. The open source software QGis, a geographic information system, will be used to construct these maps. The time series of river stages are used here to produce a probability distribution of the river water levels. This is done by frequency analysis of the time series and represent the water levels in the statistical Gumbel distribution. This method is faster than drafting a river model, but it is also a crude method that can only takes the flood inundation into account as flood intensity parameter. Some assumptions have to

be made in order to make this method valid. The most important assumption is that the horizontal water surface in the flooded area is perpendicular to the flow, therefore not taking the roughness of the area into account. Another assumption is that flooding only occurs when the optionally present protective measures overflow. Failure mechanisms of protective measures before the water level reaches the crest level, such as piping, are therefore not included. In this method it is also important that the source of flooding will not run out before the inundation depth equals the outside water levels. In river floods of relatively small areas caused by upstream events this is a permissible assumption, since the flood waves in Nyaungdon are often in the order of several days (Van Meel et al., 2014). The drafted inundation maps can be compared with satellite photos and the other little information that is available about recent floods to make a best representation of the floods.
Satellite images are furthermore used to construct land use maps. Combining the land use maps and inundations maps with damage functions from literature, the material consequences of floods can be determined. The inundation maps and land use will also be used to determine the loss of life for different flood scenarios. Mortality rates among the affected population and the valuation of life ultimately lead to the consequences of the amount of loss of life. Combining both the loss of life consequences and the material consequences leads to the determination of the current flood risk.

2.2. Measures

After the determination of the flood risks, measures have to be found to reduce the risks. The design specifications of these measures can subsequently be optimised, which is the next step in the process. In order to come up with suitable measures, an extensive analysis is of great influence on its success. Flood management is not solely a technical design task, but the socio-economic conditions of the environment influence the choice of appropriate measures. The system wherein the flood measures are to be placed therefore has to analysed per situation. The system analysis method that is used for this is presented in this section.

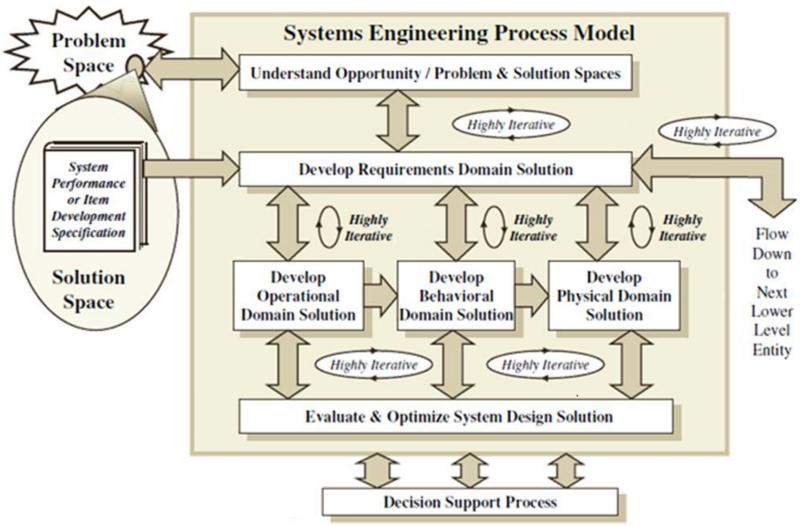


Figure 2.7: *Analysing framework: from problem space towards design.*
Source: Wasson (2006)

2.2.1. System Analysis

Since later in the twentieth century, flood management has been shifting from a solely engineering practice towards more incorporating social aspects (Sayers et al., 2015). A flood management system is operating in a specific environment that has to be taken into account in order to draft appropriate designs. The social and economic conditions define requirements and wishes that the appropriate design has to fulfil. The environment the flood management system is operating in therefore influences the choice of measures in the different safety layers and their design specifications. This implies that the river system and its surrounding area have to be analysed to come up with a suitable flood management design. Wasson (2006) established a framework to analyse a system/entity and to design a plan that suits the needs of the system. The framework can be used to verify whether a design fits the requirements, operations and behavioral needs of the flood prone area. The framework of Wasson is a cyclical process at different levels of detail of the system that is analysed (see Figure 2.7). However, below it is presented as a linear action plan.

1. *Understand the entity's problem and solution spaces.* The problem space describes part of the operating environment that represents a hazard or threat. Translating this to the operating environment defined by the Nyaungdon area, the problem space consists of the possible flooding of the Ayeyarwady River and its effects. The solution space is the combination of resources that can be used to solve this problem. The solution space is bounded by its natural environment, but also by the requirements of the 'user' and the environment it is operating in. The solution space becomes more bounded throughout the process of defining the following four domain solutions: the requirements, operations, behavioral and physical domains.

2. *Develop the entity's Requirements Domain Solution.* The requirements domain defines the requirements that the 'user' has for the entity and the natural constraints it is located in. In this case the requirements that a flood management system has to fulfil and how well, under certain natural boundary conditions.

3. *Develop the entity's Operations Domain Solution.* The operations domain depicts how the system will be deployed, operated and supported. Linking this to the Nyaungdon case means amongst others who will deploy the flood management system and who will operate it.

4. *Develop the entity's Behavioral Domain Solution.* The behavioral domain is often more vague for civil engineering projects. It describes the behavior of the system that is required to fulfil its mission (flood safety) and how it reacts to external influences. This will especially be applicable to the third layer of safety, crisis management.

5. *Develop the entity's Physical Domain Solution.* The solution space is now fully bounded and specified and can be translated in a physical design. This domain defines the suitable measures in the different levels of safety, fitting in the solution space that is bounded by the requirements, operational needs and behavior of the surrounding environment.

2.2.2. Case study background

To put the case study location into perspective, some general information about Myanmar is presented in the following. Myanmar is a country with a tumultuous past and in order to get some insights into the present day society a short outline of its history is furthermore given in Appendix A.1.

Population and administrative divisions

Myanmar homes multiple ethnic groups and religions. A lot of the broader culture of Myanmar originates from the largest group, the Bamar or Burman people, who speak Burmese and adhere to Buddhism. The total population is not exactly known, but according to the most recent census and approximations it lies between 50 and 56 million people. Being the largest country of mainland Southeast Asia in terms of area, Myanmar has one of the lowest population densities of the region (CIA, 2016; UN, 2014). The ethnic groups are distributed over the total population as follows:

- Bamar 68%
- Shan 9%
- Karen 7%
- Rakhine 4%
- Chinese 3%
- Indian 2%
- Mon 2%
- Other 5%

Myanmar is currently a parliamentary republic, divided into 21 subdivisions: seven regions, seven states, one union territory, five self-administered zones and one self-administered division. In Figure 2.8 the states and regions are depicted. The regions are mainly inhabited by the majority Bamar people and often named after its capital city, the states are predominantly home to the ethnic minorities and named after the people that live there. The single union territory is called Naypyidaw Union Territory, named after the new administrative capital of Myanmar it includes. It has to be noted here that not all foreign entities acknowledge the new capital. As for naming the country Burma or Myanmar, some still see the city of Rangoon/Yangon as the capital city. The regions, states and union territory can furthermore be divided into districts. Districts are divided into townships, consisting of multiple towns. Special administrations are the self-administered zones and division, which are areas within the Sagain Region and Shan State that are governed by their own body (Nixon et al., 2013).

Geography and climate

With an area of 676,578 km^2 Myanmar is the largest country in mainland Southeast Asia. In comparison it is slightly larger than Great Britain and France combined or slightly smaller than the state of Texas (CIA, 2016). Myanmar has five bordering countries: Bangladesh in the west, India in the west/north west, China in the north/north east, Laos in the east and Thailand in the east/south. In the south it borders the Andaman Sea and the Bay of Bengal.

This large country contains a variety of terrains. The central lowlands are fertile plains of the major rivers, like the Ayeyarwady River. This is where most of the population lives. The lowlands are surrounded by mountainous highlands up to 5,500m, home for some of the ethnic minorities. Having such a diverse terrain means that there are different climates within Myanmar. In general there is a tropical monsoon climate. The monsoon from north eastern direction lasts from November to April and results in a cool and dry season. Right before the monsoon direction reverses temperatures run high. Especially in the coastal areas the conditions can become unpleasant due to the high humidity. From May to September the monsoon is coming from the Indian Ocean in the south west, bringing in a hot and wet season with almost three-quarters of the annual rainfall. The coastal regions are dealing with an annual rainfall of 2000-2500mm. As the coastal mountains are sheltering the lowlands further inland, the amount of precipitation there is often less than 1000mm a year (NEA, n.d.).

Figure 2.8: *Administrative divisions*
States are depicted in red, regions in black
Source: Wikipedia (2013)

Economy

Myanmar shifted from one of the richest countries in Southeast Asia while under British rule to one of the poorest in the world under de military dictatorship. In the 1990s the government started to liberalise some of the industries that were nationalised in the previous decades, however the lucrative businesses remained in their hands (New World Encyclopedia, 2014). Only since the shift to a civilian government in 2011 the economic policy started to reform. Some of priorities have been the attraction of foreign investments and integration into the global economy. As a result the country's economic growth amounts well over 8% in the years of 2013 and 2014, leading to a gross domestic product of 64.9 billion US$ in 2015 (World Bank, 2016).

Myanmar has an abundance in natural resources and fertile land. One of the most productive sectors is therefore the agriculture sector, with amongst others rice, pulses and beans production. Other major industries are timber, oil and gas, and mining. This also implies that 70% of the population is employed in the agriculture sector. However, Myanmar is still a poor country and approximately 26% of the total population lives in poverty. It is also estimated that the black market, including the production and selling of narcotics, is equal in size with the official economy (CIA, 2016). One of the limiting factors to the economy is the inadequate infrastructures left by the previous regime. Keeping in mind Myanmar's geographic location between two of the world's largest economies, India and China, better infrastructure would offer lots of potential. Another source of economic drawbacks are the frequent heavy floods. The floods of July 2015 affected some of the most vulnerable regions and contributed in lowering the economic growth to 7% (World Bank, 2016).

2.3. Optimisation

With the conceptual design of preventive and adaptive measures, their specifications can be determined. Since this research is into the possibility of risk based economic optimisation, the specifications are defined through optimisation calculations. The optimisation process is based on the cost benefit analysis, which theory is therefore presented first. After that, the principle of economic optimisation is given. An analytical example of optimising a single safety layer is worked out subsequently. This is the baseline that can be extended to multiple layers of safety and the adding of budget constraints, which processes are described thereafter.

2.3.1. Cost benefit analysis

The concept behind the use of a cost benefit analysis (CBA) is that a project should result in an increase of societal welfare. In other words: a project is attractive when the societal benefits that are generated by the project are exceeding its implementation costs (Jonkman et al., 2004). In order to perform a quantitative cost benefit analysis, the time value of money should be taken into account. This notion states that money has more value the sooner it is received, given that money can earn interest and has therefore earning capacity in the future. Costs and benefits that are spent or earned in different time periods can therefore not simply be added or compared (Brealey et al., 2013). The usual way to make this possible is to convert costs and benefits to their present value (PV), by means of a discount rate. In theory the discount rate that is used should be the opportunity cost of the project relative to other possible investments. After subtracting the discounted costs C and benefits B per time period t with discount rate r over the total lifetime τ, they can be summed to find the net present value (NPV) of a project. The net present value represents the net amount of money that is earned by conducting a project and is depicted by the following equation:

$$NPV = \sum_{t=0}^{\tau} \frac{B_t - C_t}{(1+r)^t} \tag{2.12}$$

In the case of flood management, cost benefit analyses are used to examine whether the investments in measures to increase the flood safety (the costs) are lower than the achieved reduction in flood damage (the benefits). Otherwise the project is not worthwhile in economic sense.

2.3.2. Economic optimisation

Principle of economic optimisation

In the case of economic optimisation, the NPV should not only be positive, but the system should be designed in such a way that the NPV is maximised. Van Danzig (1956) introduced a method of optimisation that is closely linked to the cost benefit analysis and used this to derive the 10.000-years safety level of flood protection for the economic heart of the Netherlands. This method states that a flood management project is optimised by minimising the total costs of a project. Here the total costs (C_{tot}) consists of the sum of investments for a safer system (I) and the expected present value of economic damage ($E(D)$):

$$min\,\{C_{tot}\} = min\,\{I + PV(E(D)\} \tag{2.13}$$

The investments here are not only the initial investments, but also the costs of management and maintenance. The costs of expected flood damages are on its turn subdivided in direct and indirect costs. Direct costs are for example the repair of assets and losses due to business interruption within the flooded area. Indirect costs are losses outside the flooded area, mostly caused by business interruption.The link between the approach of minimising total costs and the cost benefit analysis, is that after optimisation it should be verified that the total costs after completion of the project are indeed lower than the costs of the initial situation.

The limiting factor of using absolute values like the net present value or total costs is that it does not facilitate comparison of profitability between projects of different sizes. Therefore the profitability index or benefit/cost ratio is also introduced here. Again, in worthwhile projects the benefits outweigh the costs, resulting in the following criterion:

$$\frac{B}{C} = \frac{PV(B)}{PV(C)} > 1 \tag{2.14}$$

The larger this ratio, the more profitable the project in terms of return on investments. In other words, the project is most cost effective for which the highest protection level can be achieved the lowest cost.

Single layer safety

To give an example of economic optimisation, the procedure of Van Danzig (1956) is reproduced here. He analytically derived the optimal safety level and dike height, corresponding to the economic optimisation of a single layer safety system. In the derivation it is assumed that a flood will occur when the external flood level exceeds the dike crest. Furthermore, the investments are made in year 0 and therefore do not have to be discounted. Despite the assumptions, it presents in particular the thoughts behind the process and gives a baseline that can be extended to more complex situations. Assumptions that were made and relationships that are proposed by Van Danzig can be adapted to the situations encountered in the coming research of this thesis.

As explained earlier, the total costs after implementation of a project are minimised in the optimal economic situation, see Equation 2.13. Therefore representations of the investments and expected damages are needed. Van Danzig proposed a linear relationship for the total investments I of raising a dike, consisting of the initial construction costs I_0 and the marginal cost I_h for dike heightening by h_{dike}.

$$I = I_0 + I_h \cdot h_{dike} \tag{2.15}$$

The expected damage or risk is based on the probability of flooding p_f and its consequences D. For determining the flood probability a exponential distribution P_f of water level was assumed, where A and B are respectively the shift and scale parameter that shape the exponential function. The flood probability is therefore given by:

$$p_f = 1 - P_f = e^{-\frac{h-A}{B}} \tag{2.16}$$

To compare the expected annual consequences to the investments over the dike's total lifetime, the losses have to be discounted. Assuming an infinite lifetime the relation for the present value of expected damage is as follows:

$$E(D) = \frac{p_f \cdot D}{r} \tag{2.17}$$

Equation 2.16 can be rewritten towards the optimal dike height $h_{dike}*$:

$$h_{dike}* = A - B \cdot ln(p_f) \tag{2.18}$$

Equations 2.15, 2.17 and 2.18 can now be substituted in Equation 2.13 to find the total costs after implementation of dike heightening. The total cost is at a minimum where its derivative to the probability of flooding is equal to 0, corresponding to the optimal safety level p_f*:

$$C_{tot} = I_0 + I_h \cdot (A - B \cdot ln(p_f)) + \frac{p_f \cdot D}{r}$$

$$\frac{dC_{tot}}{dp_f} = -\frac{I_h \cdot B}{p_f} + \frac{D}{r} = 0$$

$$p_f* = \frac{I_h \cdot B \cdot r}{D} \tag{2.19}$$

In turns out that in this case the optimal safety level is directly proportional to the the marginal costs, the scale parameter of the exponential distribution of flood levels and the discount rate. The dependence on marginal costs implies that a higher flood probability is desirable when it becomes more expensive to increase the safety level. The optimal flood probability is inversely proportional to the possible damages, so the protected value that can be lost. The higher the value, the lower the optimal flood probability. When all variables are given a value, the optimal flood probability and corresponding dike height and total costs can be calculated.

Multi layer safety

The concept of minimising total costs can also be applied to determine the optimal design of more layers of safety. First it is important to correctly schematise the system. The schematisation affects the formula of expected losses and is therefore important for the whole optimisation process. The multi layer system of prevention, spatial planning and crisis management is neither a series nor a parallel system. A series system would imply a failure of the total system when one of its components fail. In a parallel system all safety layers would be perfect substitutes of each other, meaning that if one layer fails the others can still deal with the hazard. This would also imply that damage will only occur after failure of all layers and that it is economically best to invest only in the layer with the lowest marginal cost (Vrijling, 2013). This is not the case in a multi layer system, where damages take place in a gradual pattern after failure of safety layers. Furthermore a distinction in damages has to be made between material and human losses, each protected by different layers. The multi layered safety therefore needs to be schematised as a quasi-parallel system (Tsimopoulou, 2015). This makes it possible to describe that the layers are not perfect substitutes of each other. Different parts within the flood prone area are only protected by one or two layers and not by all layers at the same time. Different degrees of damage arise after failure of different layers. An example situation where a quasi-parallel schematisation of MLS is needed is presented in Figure 2.9.

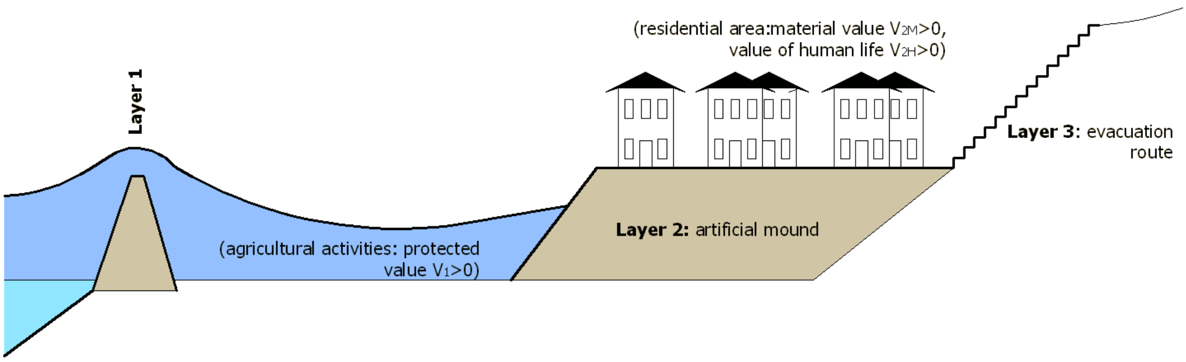


Figure 2.9: *Possible schematisation of MLS consisting of a dike, artificial mound and evacuation. Source: Tsimopoulou (2015)*

Damage occurs in the agricultural area if layer 1 fails. Both layer 1 and 2 have to fail to result in material losses of the residential area. Only when layer 2 and 3 fail, there are losses of human life within the residential area. The total costs for this situation consists of the investment costs in the three layers of safety and the expected damages in the agricultural area, the material losses in the residential area and the human losses in this area. The total cost function therefore looks the following:

$$C_{tot} = I_1 + I_2 + I_3 + E(D)_1 + E(D)_{2M} + E(D)_{2H} \tag{2.20}$$

I_x represents the investment costs in safety layers 1,2 and 3. $E(D)_1$ describes the expected damage in the agricultural area. $E(D)_{2M}$ and $E(D)_{2H}$ respectively the material and human losses in the residential area. As with a single layer of safety, the lowest total cost is found at the optimal value of $p_f* = (p_{f1}*, p_{f2}*, p_{f3}*)$ where the derivative of the cost function is 0, determined by the following condition of partial derivatives (Vrijling, 2013):

$$\frac{\partial C_{tot}}{\partial p_{f1}}(p_{f1}, p_{f2}, p_{f3}) = \frac{\partial C_{tot}}{\partial p_{f2}}(p_{f1}, p_{f2}, p_{f3}) = \frac{\partial C_{tot}}{\partial p_{f3}}(p_{f1}, p_{f2}, p_{f3}) \tag{2.21}$$

It is possible that solving this criterion results in more than one critical point. It must therefore be verified if the derived combination of probability of failures corresponds indeed to a minimum of total costs.
The above explanation of optimisation for multi layer safety systems assumes that using several layers results in lower total costs than using less layers. This is not necessarily true. The economic attractiveness of using three layers over only a single layer or any combination of layers must therefore be verified in the optimisation process. The optimal combination of safety layers is found by the following

condition (Tsimopoulou, 2015):

$$C_{tot}* = min\{C_{tot1}*, C_{tot2}*, C_{tot3}*, C_{tot1-2}*, C_{tot1-3}*, C_{tot2-3*}, C_{tot1-2-3}*\} \quad (2.22)$$

Budget constraints

The previous descriptions of economic optimisation were made without any budget constraints, meaning that the decision makers would be able to invest as much in the system as needed. In real life this is often not the case. Especially in developing countries the budget is limited. Institutions like the World Bank or more developed countries provide a certain amount of money that has to be used to reduce the effects of floods (personal communication J. Udo (2016)). If this available budget is larger than the optimised amount of investments, the limitation in budget has no effects. However, if the budget is smaller than the optimal investment costs, a cheaper project needs to be implemented and the expected damages become larger.

Under the available budget the flood protection system can still be optimised, only taking into account that the sum of the needed investments may not exceed the available budget. The optimisation problem has changed into minimising the total costs under the a certain constraint (Tsimopoulou, 2015). If $p_{fb}* = (p_{fb1}*, p_{fb2}*, p_{fb3}*)$ defines the optimal flood probabilities under budget constraint I_{max}, the constraint function g is given by:

$$g(p_{fb1}*, p_{fb2}*, p_{fb3}*) = I_{max} - I(p_{fb1}*, p_{fb2}*, p_{fb3}*) \geq 0 \quad (2.23)$$

The goal is now to find $p_{fb}*$ on this constraint function where the total cost function is at its minimum. This problem can analytically be solved by means of the method of Lagrange multipliers, where a so called Lagrange function is created that captures both the function that has to be minimised as the constraint function. In this case the Langrange function looks like the following:

$$\mathcal{L}_b(p_{fb1}, p_{fb2}, p_{fb3}, \lambda) = C_{tot}((p_{fb1}, p_{fb2}, p_{fb3}) - \lambda \cdot g(p_{fb1}, p_{fb2}, p_{fb3}) \quad (2.24)$$

The auxiliary variable λ is called the Langrange multiplier, which shows to which extent the optimal flood probability changes under the budget constraints. By determining in which set of flood probabilities the partial derivatives this Lagrange function are 0, the minimum of total costs can be found (Tsimopoulou, 2015). Thus satisfying the condition:

$$\frac{\partial \mathcal{L}_b}{\partial p_{fb1}}(p_{fb1}*, p_{fb2}*, p_{fb3}*) = \frac{\partial \mathcal{L}_b}{\partial p_{fb2}}(p_{fb1}*, p_{fb2}*, p_{fb3}*) = \frac{\partial \mathcal{L}_b}{\partial p_{fb3}}(p_{fb1}*, p_{fb2}*, p_{fb3}*) = 0 \quad (2.25)$$

The solution to this condition shows the optimal flood probabilities of a three layer system under the budget constraint. This solution is given in terms of the Langrange multiplier λ. When these optimal points are substituted in Equation 2.23, the reach of λ can be found for which the constraint function is indeed larger than 0. The lower bound of λ corresponds to the lowest total costs. Using this lower bound the analytical values of optimal flood probabilities are determined.

It might again be possible that single layers or other combinations of safety layer would result in lower total costs. The criterion of Equation 2.22 can again be used to find the solution with the lowest total costs under the budget limitation.

2.4. Uncertainty

Until now the variables in the total cost function were assumed to have a certain value, allowing for a single optimisation result. With deterministically chosen best estimates of for instance the water level distribution, protected economic value and marginal costs of measures, values can be given to the optimal level of safety. In reality, there is uncertainty in the used data and schematisation of the system. If the best estimates differ from the real values and the calculated optimal flood probabilities are implemented, the real situation might not be optimal at all. Furthermore, variables can be subject to changes in the future, caused by human or natural developments of the flood system. An overview of possible uncertainties in riverine flood management is given in Table 2.1, derived from Hall and Solomatine (2008). In this table a distinction is made between variables and functions, where functions do not describe a single input value but its variation.

Table 2.1: *Uncertainties in river flood risk analysis*

Variable or function	Sources of uncertainty	Driver of change in the future
Function: River water level	River model uncertainty	Natural and anthropogenic morphological changes in river
Variable: Dike/embankment level	Scarcity/accuracy of measurements	Settlement
Variable: Digital Elevation Model	Effective elevations at model grid-cell scale	Land use change, especially building size and location
Function: Water level at points in the floodplain	Model grid size Roughness parametrisation Representation of buildings and other obstructions in the floodplain Hydraulic model solution method	
Variable: Location and type of properties and people in the floodplain	Classification and aggregation of properties Census data and numbers of commuting people	Land use, demographic and behavioural changes
Function: Flood damage functions	Aggregation uncertainties for property types Regional and local variations	Changing wealth and household contents
Function: probability of loss of life and other harms to people in the floodplain	Vulnerability of people Velocity, arrival time and other hydraulic properties of flood	Changing public vulnerability with different socio-economic scenarios
Variable: reduction factors for warning, evacuation etc.	Effectiveness of warning, evacuation etc.	Changing public behaviour with different socio-economic scenarios

From the table it becomes clear that there are many sources of uncertainty while designing the optimal flood management system. An uncertainty analysis gives insight in the robustness of the derived system and which activities could be performed to reduce the uncertainty in the optimal design. Hall and Solomatine (2008) designed a uncertainty analysis process to perform a quantitative analysis of the effect of uncertainties. The advantage of a quantitative analysis above a qualitative analysis is that it shows the magnitudes of their effects. The various steps of the process are given in the following and elaborated on if needed.

1. *Establish purpose and scope of the uncertainty analysis.* The scope of the analysis corresponds to its purpose. The amount of variables that will analysed and their scope in the system lifetime need to be established upfront.

2. *Identify and define uncertainties.* Table 2.1 can be used for this.

3. *Assemble evidence about uncertainties.* This step is used to understand and quantify the picked uncertainties. Evidence of their effect can be found in model outputs or measurements of variables at the site.

4. *Construct appropriate functions quantifying uncertainties.* These functions can be in the form of probability distributions or interval bounds.

5. *Propagate uncertainties through to outputs of interest.* Appropriate methods for this are the use of scenarios or the use of Monte Carlo analysis. In the latter case the model (in this case the total cost function) is ran scores of times for different randomly varied input values. The output of this step are for instance scatter plots or histograms around the optimal probability that show the size of the effect of uncertainties.

6. *Store the results in a database.*

7. *Uncertainty-based sensitivity analysis.* In this step it is found out which variables have the greatest contribution to the uncertainty in the required output.

8. *Examine the effects of uncertainties on option choices.* It is now when the effect of uncertainty on the possible options is examined. The options in this case is for instance the choice between single or multi layer safety and the distribution of investments over multiple layers.

3
Flood risk

The case study location is Nyaungdon. This town and the namesake Nyaungdon township is located at the junction of two rivers: the Pan Hlaing River along the north east and the much larger Ayeryawady River along the west. The area has experienced heavy floods in August 2015, when the Ayeyarwady River overflowed after heavy monsoon rains. Drone footage as depicted in Figure 3.1 shows the widespread inundated areas after the river exceeded it banks and water flowed into its low lying surroundings. Houses along the river banks and neighbouring crops are inundated. Numerous of people lost their home and livelihood.

Figure 3.1: *Drone footage of the 2015 flood in Nyaungdon. Source: Naing Win Oo (2015)*

In this first chapter comprising the case study, the current flood risk is determined. To start with, the scope of the case study is defined. After that, the chapter follows the work process as described in the methodology as presented at the start of Chapter 2. This implies that after the current flood risks are established, the next chapter focusses on drafting suitable measures to reduce this flood risk. The specifications of these measures will be based on the economical optimisation process. Ultimately, there is looked into the effects of uncertainty on these specifications to answer the question of the applicability of economic optimisation in this area.

3.1. Scope

Nyaungdon town is located next to the Ayeryawady River. This is the largest river of the country and has its source in the northern mountains of Myanmar. Administration wise, Nyaungdon is located in the Ayeryawady Region, which holds the Ayeryawady delta. Within the Region, Nyaungdon is part of the Maubin District. This district can again be divided in townships, which consists of different towns. Nyaungdon town is the seat of the township that carries the same name. Before starting the analyses, an appropriate case study scope has to be chosen. The two rivers Nyaungdon town is located next to, form part of the boundaries of the scope. Since the surroundings of Nyaungdon town are all lowland, other natural boundaries to flood events such as hills are difficult to establish. The other southern boundary is therefore chosen to coincide with the formal embankments. These embankment partly follows the Pathein Road, until it crosses the Ayeyarwady River. A smaller road is placed on top of the remaining part of the embankment. The height of the embankment is unknown. However, based on satellite images from the 2015 flood, as depicted in the upper right picture of Figure 3.2, the embankment was high enough to retain the flood waters and therefore seems a logical boundary for the area of the scope. It can be seen that for the largest part Nyaungdon Town lies outside the formal embankments. Therefore an 'n'-shaped dike is constructed along the north/north west side of the town, measuring 3445m in length.

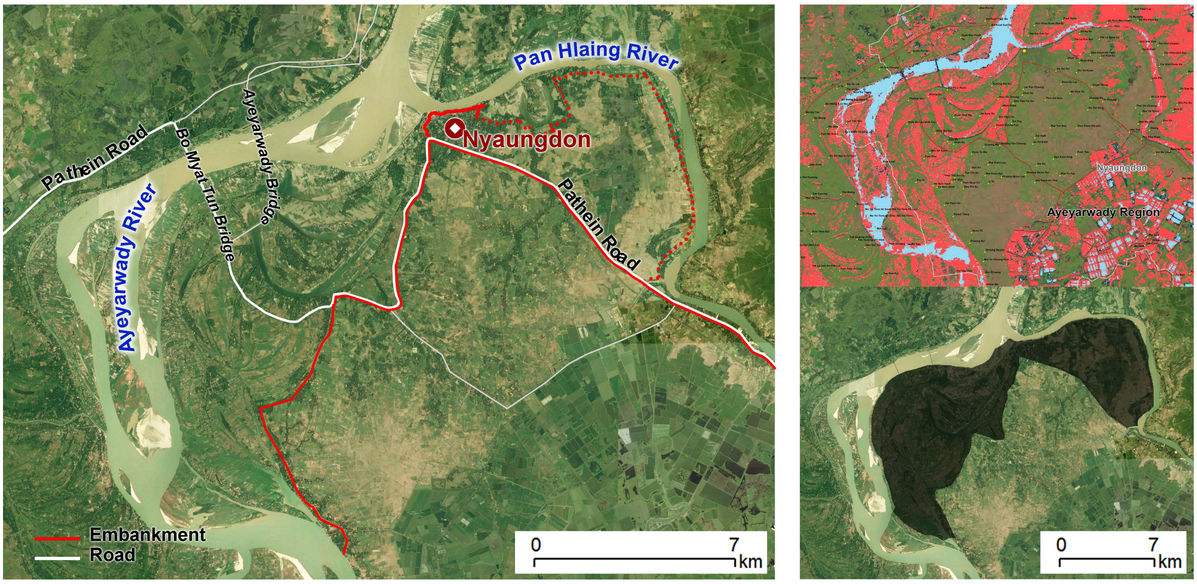


Figure 3.2: *Nyaungdon scope determination: area (left), 2015 satellite image (upper right) and ultimate scope (lower right) Source underlying map: Google Maps (2016). Source satellite image: MIMU (2015)*

The area east of the town looks hardly flooded in 2015 as well, indicating another embankment there. The dashed red line in the left picture of Figure 3.2 follows an elevated road. If this road is seen as another embankment, it matches the flood situation of the satellite image. The scope area is depicted in the lower right picture of Figure 3.2 by the black polygon. Within this scope, Nyaungdon town is situated on the junction of the Pan Hlaing River and the Ayeryawady River. This urban area covers about 3.5 km^2 of the total scope, which amounts 109 km^2. Besides Nyaungdon, eleven small villages are situated within the scope. Compared to the town of Nyaungdon, these villages only consist of small strips of housing. The rest and majority of the area is mostly agriculture.

3.2. Flood events

The first step in the process is the determination of the current flood risk. This risk consists of the probabilities of floods and associated economic damages, but also the loss of life due to flooding. The probability of floods can in this case be based on historic river water level data. How this is done is first described in this section. The second contributor to risk, the economic and human losses, are given thereafter. In the end the probabilities of flood events and consequences are combined to present the current risk of flooding, distributed over the area.

3.2.1. Water level distribution

In Myanmar, the Department of Meteorology and Hydrology (DMH) is responsible for the daily weather forecasts and the prediction of natural disasters, such as floods (DMH, n.d.). Several river stations distributed over the country are in use for this. Unfortunately Nyaungdon is not one of these locations. The water levels to work with in this case are not acquired from an official measuring station, but from a local engineer. This data, that consists of the yearly maxima from 1985-2015 of the Ayeyarwady River near Nyaungdon, is gathered by Blom et al. (2016). The data is presented in Table 3.1 and Figure 3.3 in centimetres above mean sea level (+MSL).

By using an Extreme Value Analysis on this data, something can be said about the probability of water levels to occur. The general idea of this analysis is count how often a specific water level has occurred and how this relates to the total number of measured water levels. In other words, if a water level occurred more frequent than another in the past, it is expected that this water level will appear more frequent in the future as well. The total range between the measured water levels are divided into small interval classes. The measured water levels are subsequently placed in their corresponding class. By counting the frequency of occurrence of an interval and dividing it by the total number of measurements, the probability of a river water level to fall within that interval has been found. This

Table 3.1: *Yearly maxima Ayeyarwady River near Nyaungdon, measured in cm +MSL Source: Blom et al. (2016)*

Year	Value	Year	Value	Year	Value
1985	747	1996	750	2007	647
1986	756	1997	802	2008	701
1987	719	1998	759	2009	674
1988	756	1999	750	2010	692
1989	771	2000	701	2011	725
1990	753	2001	677	2012	698
1991	765	2002	768	2013	732
1992	670	2003	710	2014	701
1993	777	2004	796	2015	786
1994	634	2005	710		
1995	771	2006	698		

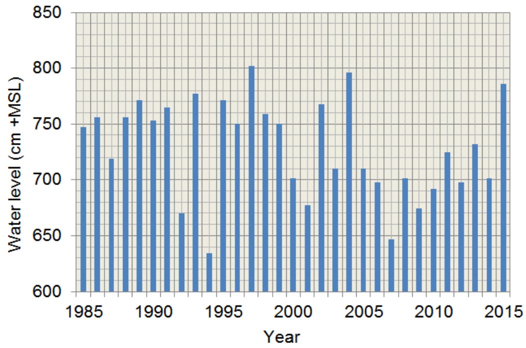


Figure 3.3: *Yearly maxima Ayeyarwady River near Nyaungdon,measured in cm +MSL Source: Blom et al. (2016)*

process is given in Appendix B.1. Fitting a function through these found probabilities and corresponding water levels resulted in a probability density function (pdf, denoted by p), showing the probability of a specific water level. The statistical probability of a precise water level is however not so useful, since this probability will move towards zero in the limit. More valuable is the probability of exceedance (denoted by P_{exc}), giving the probability that some water level will be exceeded. The probability of exceedance is calculated from the cumulative density function (cdf, denoted by P), giving the probability of a water level being smaller than a specific water level. By fitting a function (pdf, cdf or probability of exceedance) through the found probabilities and water levels, the statistical changes of occurrence or (non)exceedance of water levels other than the measured levels are determined. The function that is often used to fit maximum values of river water levels is the Gumbel distribution, also called the Extreme Value Type I distribution (Vrijling and van Gelder, 2002). This distribution is initially used as best estimate of water levels and corresponding probabilities. Its pdf is the following, relating the probability p to water level h:

$$p(h) = \frac{1}{\beta} e^{\frac{h-\mu}{\beta}} e^{-e^{\frac{h-\mu}{\beta}}} \tag{3.1}$$

In this equation μ is the location parameter and β the scale parameter. The Gumbel cdf is defined as follows:

$$P(h) = e^{-e^{\frac{-(h-\mu)}{\beta}}} \tag{3.2}$$

The probability of exceedance is therefore the following:

$$P_{exc}(h) = 1 - e^{-e^{\frac{-(h-\mu)}{\beta}}} \tag{3.3}$$

The location and scale parameter are chosen as such that they best fit the measured water levels and cumulative probabilities of occurrence. Several methods exist for this, such as Method of Moments, Linear Regression and Method of Maximum Likelihood (Vrijling and van Gelder, 2002). Since the Method of Moments is easy and straightforward to use, this method is used to estimate the parameters of the Gumbel distribution. The mean and standard deviation of the Gumbel cdf are defined as the following:

$$Mean = \mu + \gamma \cdot \beta \tag{3.4}$$

$$SD = \frac{\beta\pi}{\sqrt{6}} \tag{3.5}$$

In the Equation 3.4, the parameter γ defines the Euler–Mascheroni constant and is approximately 0.5772 (NIST/SEMATECH, 2012). The Method of Moments (MoM) implies that the mean and standard deviation of the measured water levels are used to estimate the location and scale parameter, therefore assuming that the mean and standard deviation of the data set equal those of the Gumbel distribution (NIST/SEMATECH, 2012). The list of measured water levels as presented in Table 3.1 has a mean value of $728.90cm$ +MSL and a standard deviation of $43.70cm$. Using these values in Equations 3.4 and 3.5 resulted in $\mu = 709.23$ and $\beta = 34.08$, which can be substituted in Equation 3.3. The Gumbel distribution approximating the measured water levels and their probabilities of exceedance is therefore given by the following:

$$P_{exc}(h) = 1 - e^{-e^{-\frac{h-709.23}{34.08}}} \quad (3.6)$$

The above distribution approximating the measured data assumes that every year an extreme event occurs and is captured in the maximum yearly value. It might however be the case that the presented list of water levels both consist of normal values as extreme values. The Peak over Threshold (PoT) method filters out the extreme values by only taking water levels into account above a certain threshold. In this case the level of 700cm +MSL is chosen as threshold, meaning that all measured water levels larger than that threshold value are considered extreme. This level is close to when the water levels are becoming dangerously high, as will be described in the next section about the flood scenarios. The Gumbel distribution that is used in the PoT method is slightly different than the one presented in Equation 3.6. An extra parameter is added, namely the average amount of extreme events per year N:

$$P_{exc}^{PoT}(h) = -N * e^{-e^{-\frac{h-\mu}{\beta}}} + N \quad (3.7)$$

The N-value is determined by dividing the amount of extreme events by the total years measured, which is in this case $N = \frac{23}{31} = 0.74$. Using only the extreme events as sample, the mean value changes into 748.09 and the standard deviation to 30.66, resulting in $\mu_{PoT} = 734.29$ and $\beta_{PoT} = 23.90$. The probability of exceedance of extreme water level events is therefore given by:

$$P_{exc}^{PoT}(h) = -0.74 * e^{-e^{-\frac{h-734.29}{23.90}}} + 0.74 \quad (3.8)$$

There must be looked upon which distribution fits the measured data the best: the normal extreme value analysis or the peak over threshold. By plotting both distributions in the same graph as the measured water levels and their calculated probabilities of exceedance, Figure 3.4 is found:

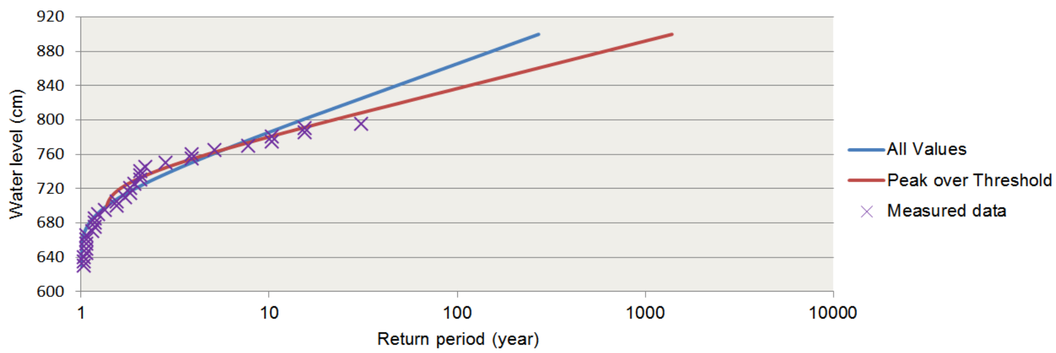


Figure 3.4: *Measured Nyaungdon water levels plotted against their return periods, together with the extreme value analysis distributions of Eq. 3.6 (all values) and Eq. 3.8 (peak over threshold)*

From the graph it seems that the PoT method approximates the measured water levels better than the other method. Equation 3.8 is therefore used for further probability calculations. One extra notion is needed before entering the next paragraph, namely the return period. The return period T is defined as the average recurrence interval of a specific event, in this case denoted in years. The return period is determined by the inverse of the probability of exceedance P_{exc}.

3.2.2. Flood scenarios

Knowing the probability of exceedance of water levels does not yet provide all the information about the probability of flood events in Nyaungdon. The extra information to work with is the so called Danger Level, established by the Department of Meteorology and Hydrology. This level is the level beyond which the river may no longer be able to contain the water, and flooding is likely (DMH, n.d.). For Nyaungdon the danger level is set at 750cm +MSL (Blom et al., 2016). To translate the Ayeyarwady River water levels into flood events a few assumptions are made:

- The Ayeyarwady River is normative for flooding in Nyaungdon, so that the above water level distributions can be used. This means that flooding from its much smaller tributary, the Pan Hlaing River, is disregarded. Comparing their discharges during the wet monsoon period (approximately 2900 m^3/s for the Pan Hlaing River (de Koning and Janssen, 2015) and 32,600 m^3/s for the Ayeyarwady River (Simmance, 2013)), this seems reasonable.
- Flooding will occur when Ayeyarwady River water levels exceed the danger level.
- Flooding will not occur when river water levels are below the danger level. Dike failure mechanisms that could take place before that level, such as piping, are therefore not included.
- The flood wave that propagates through the river is long enough to fill its surrounding up to the river water level, after is has exceeded the danger level, and therefore resulting in an inundation of the area.

The above assumptions make it possible to relate flood events and their probabilities of occurrence to the water levels in the Ayeryawady River. A discrete set of water levels and corresponding flood events will be used to generate the consequences and total risk. The used events range from the danger level up to two meters above the danger level. Using Equation 3.8 to find the probabilities of these events, the following flood scenarios are found and used in the continuation of this case study to determine the economic consequences and possible loss of life:

Table 3.2: *Nyaungdon flood events*

	Water level (cm +MSL)	Probability of exceedance(-)	Return period (years)
Event 1	750	$3.00 \cdot 10^{-1}$	3.33
Event 2	800	$4.59 \cdot 10^{-2}$	22
Event 3	850	$5.84 \cdot 10^{-3}$	171
Event 4	900	$7.23 \cdot 10^{-4}$	1383
Event 5	950	$8.93 \cdot 10^{-5}$	11194

3.3. Economic consequences

As stated before, economic flood damages can be direct and indirect. The indirect consequences, such as business interruption outside the flooded area, are difficult to estimate and not taken into account here. The direct losses are twofold: the material damages that are assumed to be fully repaired to its value prior to the flood event, plus the economic losses caused by damaged crops or other forms of agriculture. As explained in the definition of risk in the previous chapter, the material damages of a flood event are dependent on the intensity of the flood I, the exposure in the area E and the susceptibility of the exposed assets S. Several sources of open data are used to determine the economic consequences within the defined scope. How this is done is described below. The open source software QGis, a geographic information system, is used to run and combine all the steps in the damage calculation.

3.3.1. Flood intensities

Due to the simplified determination of flood events, the flood intensity is only given by the inundation depths. These depths are found by overlaying a digital elevation model (DEM) by the flood events given in Table 3.2. The DEM originates from NASA's Shuttle Radar Topography Mission. During this mission, which took place in 2000, the Earth's surface is digitally mapped. The elevation maps resulting from this mission have been released in several waves. In 2014 the highest resolution of the digital elevation maps, equal to the raw data of 1 arc-second or approximately 30.87m, have been globally released and are now openly available through the Earth Explorer of the U.S. Geological Survey (USGS, 2017). The vertical resolution of the DEM is 1m, which is still quite coarse. The DEM files are therefore given as rasters with 30.87x30.87m grid cells and their elevations in discrete values of 1m. It is however important to notice that the possible vertical errors in the area of Myanmar are up to 10m (Rodríguez et al., 2005). Another drawback is the age of the the data, as it originates from 2000. The Ayeryawady River is a dynamic river and has changed its flow path since then. As a result part of the scope that is now land used to be water, which is also visible in the DEM. This is corrected for by adding several meters to that area of the DEM so that it matches the elevation of the surrounding area. In Figure 3.5 both the original as corrected DEMs are presented.

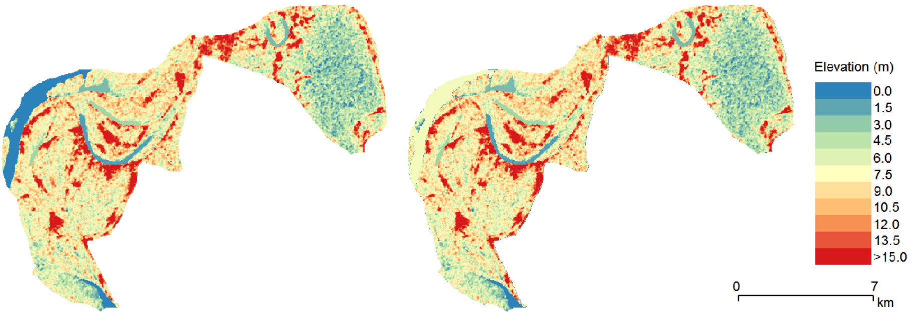


Figure 3.5: *Nyaungdon DEM original (left) and corrected (right) for changing river bend*
Source: USGS (2017)

The inundations depths are calculated by subtracting the corrected DEM raster values from the chosen water levels. By filtering out the negative values, which represents grid cells where the elevation is higher than the water level, the inundation depths are found. The maps that are produced here thus represent the distance between the elevation of each grid and the water level. This follows the assumption that during a flood situation the flood levels fill up the area until the water level of the river. The five flood events are given below. Damage can occur now on those locations that are inundated.

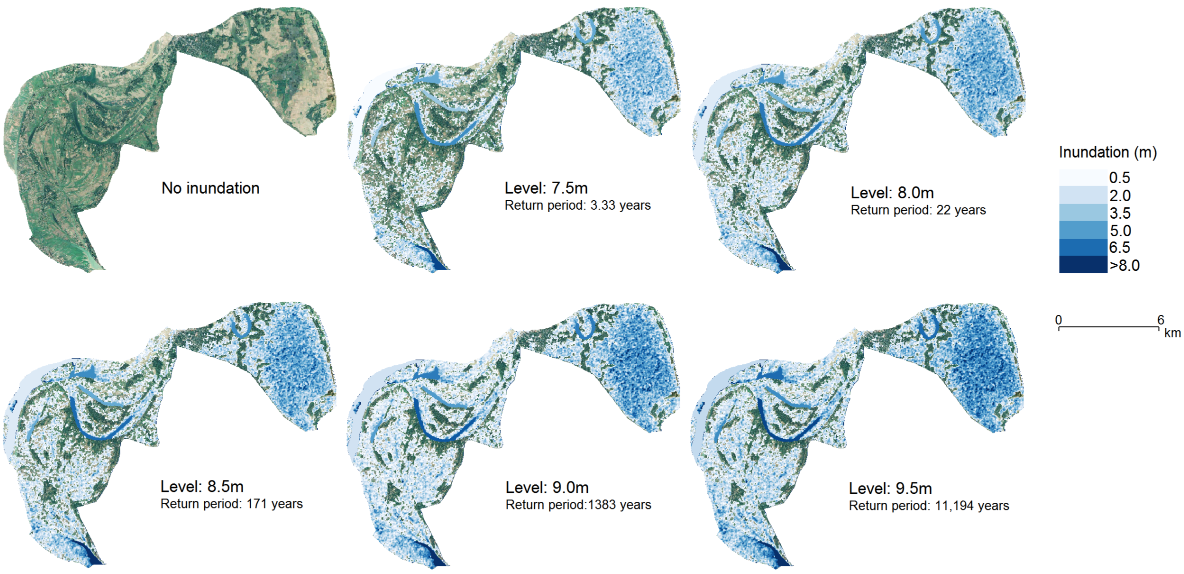


Figure 3.6: *Inundations Nyaungdon for the different flood events*
Source underlying map: Google Maps (2016)

3.3.2. Exposure

Land use

To assign the exposure, the different land use types and their values are needed. Again open source data is used for this, namely the Landsat images produced by NASA and the USGS. The Landsat program has been producing images of the earth's surface with a horizontal resolution of 1 arc-second every 16 days since 1972. The images consists of various bands of different wavelengths. Since every land use has different reflections, the different types can be distinguished. Using the Semi Automatic Classification plug-in developed by Congedo (2017), the different land use types can be mapped. In theory every different reflection can be classified. For the purpose of this research, six land use types are used: crops, fish ponds, bushes/vegetation, built up area, high density built up area and water. The differences between the two types of built up area cannot be seen on the Landsat images, but is made through Google Maps images. This distinction is necessary due to the resolution of the Landsat images. After all, built up cells housing two dwellings have a different value than high density cells housing five dwellings, but would look the same on the land use maps if this distinction was not made. The result of the above described process is the following land use map of Nyaungdon, depicted in Figure 3.7. As can be seen, the area mainly consists of agriculture. In the eastern part of the scope, some fish ponds are present. Nyaungdon town is clearly visible, where an agglomeration of built up area is present.

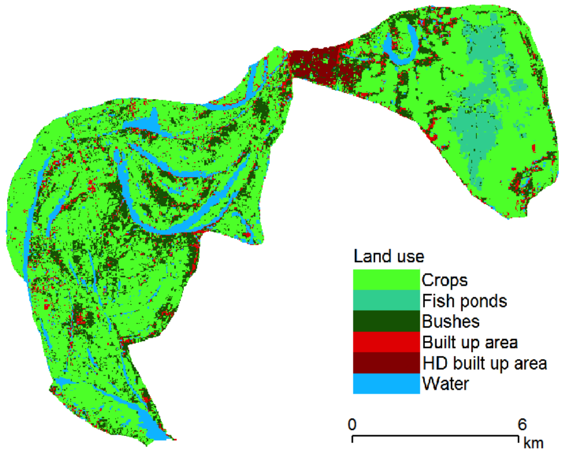


Figure 3.7: *Land use Nyaungdon with six land use classes*

Land values

The land use map is the first step in determining the exposure. The second step is assigning economic values to the different land use types. Bushes and water are seen as valueless and do therefore not contribute to the flood damages, when flooded. The other land use types are elaborated below.

Crops

It is assumed that all crops are rice, this can be seen on the images of Google Maps and is also a reasonable assumptions for this part of Myanmar. The rice ecosystems in Myanmar consist of irrigated, rainfed and deepwater rice fields. Most of the delta region's rice fields are made up of rainfed rice and consists of two production seasons: the main season and the dry season. The main season is planted in June/August and harvested in November/January. The dry season crop is planted in November/December and harvested in April/May (Global Rice Science Partnership, 2013). This means that during the monsoon floods in July/August the rice fields are halfway the main season. According to Tin Htoo Naing (n.d.) the average costs of cultivating wet season rice in the Ayeryawady Region are \$379/ha and the average revenues \$541/ha. Since potential floods take place halfway the season, the maximum economic damage is that half of the costs are lost and the total revenue is lost. This brings the total losses of flooding a rice field to \$730.5/ha or \$0.07305/m^2.

Fish ponds

From satellite images it cannot be seen what type of fish ponds are in place. The southern regions of Myanmar breed amongst others carp, tilapia, catfish and also prawns. On average the fish are sold for 600 Kyat/kg and prawns for 1,400 Kyat/kg (UN Food and Agriculture Organization, 2003). Normally the fish ponds are stocked with juvenile fish and grown to a sellable size within a year. The average production of a fish pond is 12 tonnes/ha per year (UN Food and Agriculture Organization, n.d.). Combining this with the price of fish, the total value of fish ponds is 7.2 million Kyat/ha. With the current exchange rate this is \$5,302/ha or \$0.5302/m^2. The production of prawn ponds are lower, namely 5 tonnes/ha. However, since prawns are sold for a higher price, the value of prawn ponds are still 7 million Kyat/ha or \$5,155/ha or \$0.5155/m^2. Apparently fish and prawn ponds have almost the same value per hectare, which is \$5,200/ha.

Built up area
The final exposed assets are the dwellings inside the area, which can be made from bamboo, wood, concrete or combinations of materials. According to an engineer from the local Irrigation Department the values of the dwellings are $1,150 for a bamboo house, $3,850 for a wooden house and $11,600 for a house made out of concrete (Blom et al., 2016). In the land use maps the type of dwellings can however not be differentiated. These values are therefore combined with data from the latest UN census in Myanmar, when besides the population also the different types of dwellings were counted (Ministry of Population, 2015a). For Nyaungdon slightly more than half of the dwellings are made of bamboo. Slightly less than half are made out of wood, the rest is concrete. The weighted average for a Nyaungdon dwelling based on these data turned out to be $3000 per house. Extra information that is needed is the housing density. This can also be based on the UN census, where the urban populations and average household size are presented. Since the scope of this case location does not follow the areas as described in the latest census, that population data cannot be used straight away. How the population and population densities are determined is presented in Appendix C. It is estimated that there are 2.20 dwellings per grid cell in the normal configuration and 4.82 dwellings per grid cell in the high density region in the land use map.

Summarizing the above, the following numbers can be used as maximum exposed values. Besides the values per hectare or per object, they are also depicted per grid cell of 30.87x30.87m:

Table 3.3: *Nyaungdon land use values*

Type	Value	Value per cell
Crops	$730.5/ha	$70
Fish pond	$5,200/ha	$495
Housing	$3,000 per house	$6,600 (normal)
		$14,460 (high density)

3.3.3. Susceptibility

If a flood occurs, the total value of some asset is not totally lost necessarily, since the damage depends on the inundation depths. The functions that combine the part of damage with the inundation depth are so called depth-damage functions. Each land use type has its own depth-damage function, based on experiments or previous flood events. In literature depth-damage functions can quite different. For now, the functions which seem most suitable are chosen and used to determine the consequences of the flood events.

Crops
For rice the curve developed by FMMP (2010) is used, since this should fit the rice plants in their early stages of growth. During this stage the damage of rice plants is more dependent on the length of submersion than the inundation depth. Total damage occurs after submersion longer than 13 days. Out of 11 recorded floods from the Ayeyarwady River as presented in Van Meel et al. (2014), eight resulted in a flood duration longer than 13 days. It shows that it takes long for water levels to recede in flat areas after severe flood events and it is assumed that this total damage takes place.

Fish ponds
For fish ponds such a depth-damage function does not exist. To construct one an article of Khin Wine Phyu Phyu (2015) in The Myanmar Times is used. In an interview a fish pond owner states that the "water broke through the barriers around the ponds, which are at least 6 feet higher than the normal water level. Still, the flood water was higher." From this information it is derived that fish ponds experience no losses before the flood waters exceed the barriers of 6 feet high, which is around 1.8m. The interviewee furthermore stated that "two-thirds of fish were swept from the ponds" when the water levels had receded again. The depth-damage function that is constructed based on this information is a curve stating a maximum damage of two-thirds of the total value starting from 1.5m.

Built up area
The final land use type that needs a depth-damage curve is the housing. No research into previous flood events in Myanmar and their damages to housing is available. However, Shrestha et al. (2014) derived a depth-damage curve for Cambodian dwellings located in a floodplain, based on a 2006 flood event. Assuming that this type of dwellings is similar to those in Nyaungdon, this function is used. All three depth-damage functions are shown below.

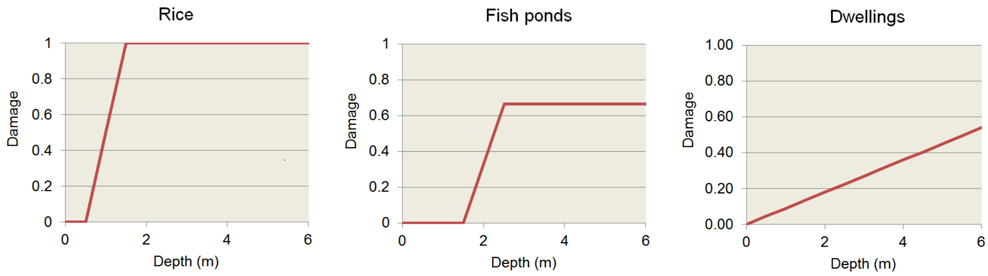


Figure 3.8: *Depth damage curves for rice, fish ponds and rural dwellings*

3.3.4. Material consequences

Combining the inundation maps with the land use map, the maximum land use values and the depth-damage curves results in the consequences per flood scenario. Figure 3.9 shows the damages per water level scenario. Most of the area is in the order of $40-$280/grid cell, corresponding to the total damage of crops. The fish ponds in the upper eastern part of the scope show higher consequences. This part of the area is relatively low and the value of the fish ponds per cell is higher than that of rice. The highest damages occur in the urban areas. Since the town of Nyaungdon is located relatively high, as can be seen on the DEM in Figure 3.5, only a small portion of the town is flooded. Other high values of damage show the scattered spots of dwellings over the area.

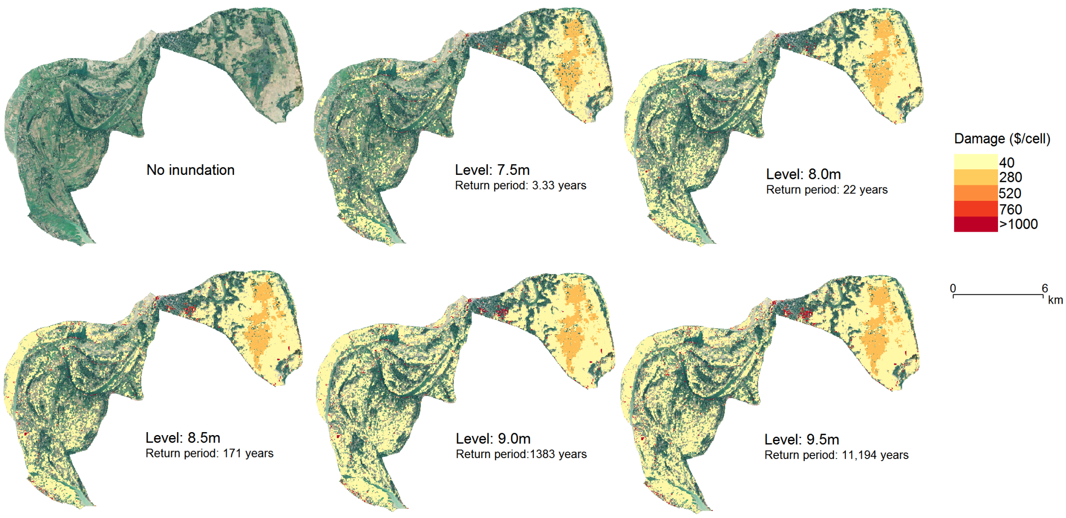


Figure 3.9: *Damages Nyaungdon for the different flood events*
Source underlying map: Google Maps (2016)

3.4. Loss of life

Besides the material consequences, loss of life can be a severe effect of floods as well. Fatalities due to floods have an emotional impact, but also an economical one. How the number of fatalities for the different flood events are estimated is presented below. A monetary valuation of loss of life is furthermore needed for cost benefit analyses. This step is given thereafter.

3.4.1. Fatalities estimation

Estimation method

The loss of life framework of Jonkman (2007) as given in Chapter 2.1.3 could in theory be applied to the case study in Myanmar. The prediction and warning time can be estimated based on upstream water level stations, the flood characteristics have been defined earlier on. Using the census of Ministry of Population (2015a), the number of people at risk can be estimated. Furthermore, Jonkman (2007) has constructed dose-response functions based on historical flood events, also presented in the Literature chapter. It is however the evacuation model that would require an extensive analysis. The required time for evacuation has both social and physical elements. Social elements are amongst others the decision-making process by authorities prior or during flood events, the warning of citizens and the response of the citizens on warnings. The actual evacuation depends also on physical boundaries such as the amount of exits out of the flood prone area and road capacities. Although the construction of such an evacuation model could be possible, it exceeds the scope of this thesis. As with the fully modelling the rivers within the case studies, the effort of modelling the evacuation process does not outweigh the reliability of the outcomes.

However, an estimation of loss of life is still needed. Besides the social consequences of fatalities, the loss of life is needed to investigate the added value of investing in measures in the third safety layer, crisis management. Recall that a simplification of the loss of life framework can be captured in the following formula, based on Jonkman (2007):

$$N_F(h) = N_{PAR} \cdot (1 - F_E) \cdot (1 - F_S) * F_D(h) \tag{3.9}$$

The number of fatalities N_F is a function of the flood intensity, in this case the inundation depth h. The population at risk N_{PAR} reduces to the exposed population by means of the evacuation rate F_E and shelter rate F_S. The amount of fatalities among the exposed population is determined by the mortality rate $F_D(h)$, the dose-response function as a function of the flood depth. All parameters can be determined for each flood event, except for the evacuation and shelter rates. These rates have to be guessed, inducing a large uncertainty.

To have a benchmark value for the expected loss of life, historic flood events in Myanmar can be used. The United Nations Office for the Coordination of Humanitarian Affairs (OCHA) has been providing humanitarian information on global crises and disasters since 1996 on the website `ReliefWeb.int`. All monsoon flood events since 1991 are presented in Appendix B.2. Tropical storms, cyclones and flash floods are not included, since those events do not represent the flood scenarios such as flooding from the Ayeyarwady River. The table shows the month and year of occurrence, the location of the flooding, the affected population and the fatalities. It is debatable what is meant with 'affected population'. It is assumed that this concerns the population whose house is (partly) flooded, whether the inhabitants evacuated or not, therefore being the same as the population at risk. Based on the affected population and the fatalities, the fatality rate is calculated by dividing the number of fatalities by the affected population. The average value of the fatality rates amounts $2.36 \cdot 10^{-2}$% of the affected population, which can now be used as benchmark value to determine the evacuation and shelter rates.

Loss of life estimation

When the inundation maps of Figure 3.6 are combined with the land use map of Figure 3.7, the flooded built up cells can be determined. Recall that the average housing densities are 2.20 dwellings per grid cell for the normal configuration and 4.82 dwelling per cell for the high density set up of houses. Combining this with the flooded cells, the amount of flooded dwellings are found. According to Ministry of Population (2015a), the mean household size amounts 4.2 inhabitants. Multiplying the household size with number of houses per cell, the population densities of 9.23 inhabitants per normal built up cell and 20.25 inhabitants per cell in the high density areas are found. These values are used to estimate the population at risk. The mortality function requires the inundation depth as input, which can again be extracted from the inundation maps. Combining all the above with the evacuation and shelter rates, the expected number of fatalities are found, using QGis. To arrive at the $2.36 \cdot 10^{-2}$% fatality rate for the average number of fatalities for all flood events, around 4.2% of the affected population should remain exposed. That means that 95.8% of the population evacuated or took shelter. When this rate is applied and Equation 3.9 is worked out, the fatalities are estimated as presented in Table 3.4.

3.4.2. Economic damage

To be able to make cost-benefit analyses and perform the economic optimisation process, a monetary value needs to be given to loss of life. A simplified version of the non-behavioral macro-economic valuation of loss of life as presented in Chapter 2.3.1 can be based on the life expectancy and average age of a country. By subtracting them the loss of productive years caused by a premature death is estimated. By calculating the present value of the production value that is now lost, the value of saving a statistical life is determined. In equation form the present value of this annuity looks like the following:

$$VoSL = GDP \cdot \frac{1 - \frac{1}{(1+r)^t}}{r} \tag{3.10}$$

In this equation the GDP represents the gross domestic product per capita and r defines the discount rate. t gives an estimation of loss of productive years, determined as the difference between life expectancy and average age. For Myanmar, the life expectancy and average age are 66.6 and 28.6 years respectively. The GDP per capita amounts $6,000 in 2016 dollars (CIA, 2016). Using a discount rate of 10% in Equation 3.10, the macro-economic valuation of life for Myanmar amounts $58,000. Due to the lower life expectancy, but especially due to the lower considerable GDP per capita, the valuation for Myanmar is around ten times lower than for the Netherlands. It may seem unethical that the valuation of life depends on a country's wealth, but it can be seen as an advantage that risks with respect to loss of human life fits in the context of the national economy (Jongejan et al., n.d.). Using this valuation, the economic damages due to loss of life are the following:

Table 3.4: *Expected fatalities*

	Fatalities	Social costs
Event 1	2.57	$149,219
Event 2	3.42	$198,442
Event 3	4.82	$279,770
Event 4	6.27	$363,828
Event 5	8.23	$477,463

3.5. Current flood risk

So far the material consequences and loss of life per flood scenario have been estimated. However, these maps do not say anything yet about the flood risk of the area. By multiplying the consequences with their probability, the corresponding risk of that specific flood event is found. Summing these risks of these single events, resulted in the total risk for the area. The risks can be depicted through various ways.

Risk map

A risk map for this case study with respect to the material risk only is given in Figure 3.10. Such a map visualises how the risk is distributed over the scope area. It can be seen that most of the area carries a risk of $0-$50 per year, corresponding to the crops. Again the fish ponds are clearly visible, due to their higher value than rice fields. The highest risks are caused by clusters of flooded houses. The flooded dwellings in Nyaungdon Town are less clearly visible than in the consequence maps for the flood events of 9.0m and 9.5m in Figure 3.9. Although the urban damages in those flood events are high, the risk is relatively low due to the low probabilities.

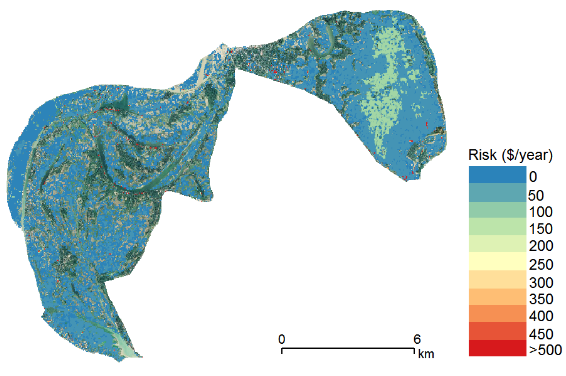


Figure 3.10: *Material risk of the case study area. Source underlying map: Google Maps (2016)*

FN- and FD-curves

The drawback of a risk map is that no inside is given in the contribution to risk of the different flood events. So called frequency-damage curves (FD-curves) can be used for this. FD-curves show the probability of exceedance for different values of risk. Figure 3.11 shows the FD-curves of the different land use types. Similar to FD-curves, an FN-curve has been made to display the frequency of the number of fatalities. By using the non-behavioral macro-economic valuation of life as it has been determined in the previous section, the economic damage of fatalities are also given in an FD-curve. Including this in the total economic risk, the FD-curve for all damages are displayed as well. The individual flood events can be distinguished from the curve by looking at each jump in the curve. When more flood events would be used, the curve becomes more fluent.

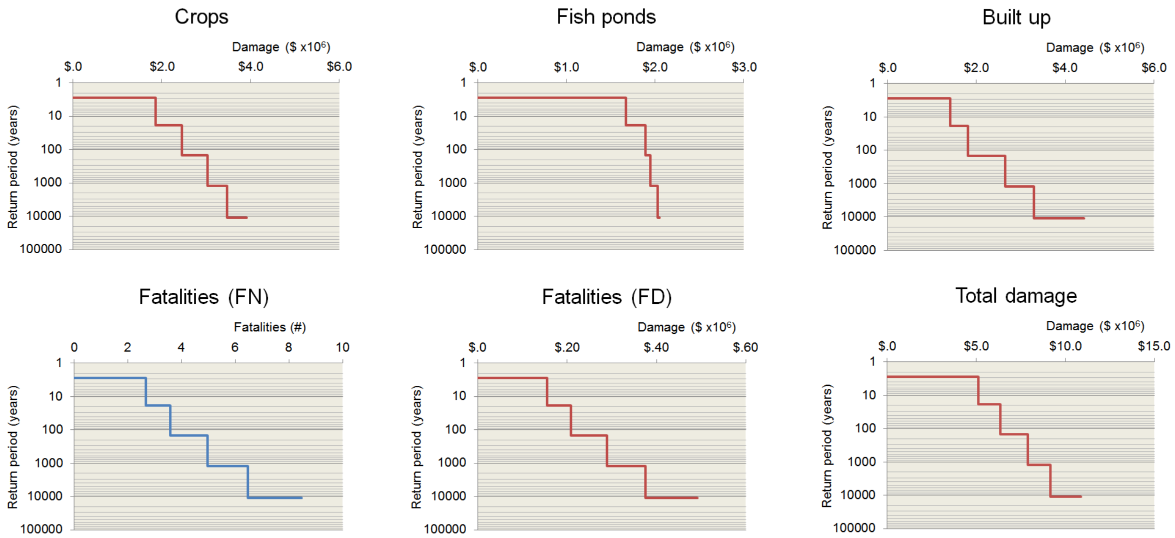


Figure 3.11: *FN-curve and FD-curves for crops, fish ponds, built up, fatalities and total damage*

Total risk values

The FD-curves are used to determine the total risk value by calculating the area under the curve. As can be seen in Table 3.5, the area within the scope has an annual expected damage of about $1,879,247/year. It can also be noticed that the economic costs due to loss of life are relatively small. This is due to the low level of expected fatalities. The risks related to damaged crops, fish ponds and built up area are in the same order of magnitude.

Table 3.5: *Quantified risk values*

Type	Risk value ($/year)
Crops	$693,892
Fish pond	$600,899
Built up	$470,847 (normal)
	$55,408 (high density)
Loss of Life	$55,842
Total	$1,876,889

4

Measures and optimisation

In the previous chapter the current flood risk has been determined. It turned out that the crops, fish ponds and built up areas carry comparable risk. Only the risk of loss of life is considerably lower, due to the low expected number of fatalities. Now that the flood risk for the Nyaungdon area has been determined, measures can be drafted to reduce this risk. For each safety layer several alternatives are presented in this chapter, out of which one per layer will be chosen on the basis of fulfilment of requirements. The specifications of these measures will be determined on the basis of the economic optimisation process, which is the second part of this chapter. The measures, their effect and their costs have to be schematised. In the end it will turn out which measure or combination of measures is most cost efficient. An overview of this is given in the last section.

4.1. Selection of measures

When looking at the situation within the scope area of Nyaungdon, several alternatives are in theory possible to reduce the flood risk. Several alternatives are however more suitable than others. The goal of this section is to generate alternatives and reduce them to one measure per safety layer. The requirements for the area that will be used to select the most suitable measures are given first. After that, the three layers of safety are elaborated separately. This section ends with an overview of the measures that will be optimised in the second part of this chapter.

4.1.1. Requirements

In Appendix A.2, requirements have been derived, using the framework of Wasson (2006). This section gives an overview of the derived requirements, including a small summary of the reasons why.
The to be designed flood management system should...:

1. *result in no or minimal decline in the yield of rice fields.* The current regular floods deposit fertile alluvium on the land and moreover, can serve as irrigation (Steijn et al., 2015). The to be designed flood management system has to take these benefits of flooding in the form of fertility and sufficient water resources into account or the farmers should at least be compensated for it.

2. *protect farmers/rural citizens against severe floods.* With severe flooding, events are meant that have the ability to make fatalities.

3. *enable farmers/rural citizens to remain close to their land.* When farmers are commended by the authorities to evacuate to diked areas prior to flood events, they often choose not to, since they do not wish to leave their properties (Win Min Oo, 2017).

4. *enable fishermen to remain close to the river.* As with the farmers, fishermen are located close to their assets, meaning that they currently often live on the outer side of the current dike. This way they are close to the river and their boat (Blom et al., 2016).

5. *protect fishermen against floods.* Since fishermen often live outside the dike protected area, their dwellings flood regularly. Although they seem to accept this situation, a higher protection level is always desirable.

6. *protect urban citizens against floods.* The town of Nyaungdon is densely populated, which means that the risk related to flood events is high, both economic as in loss of life. The town is already protected with a dike that is recently heightened. However, the current erosion process is reducing its strength (Steijn et al., 2015).

7. *fit the current measures.* Several safety measures are already in place within the scope, an overview is provided in Appendix A.2.2.

8. *result in little disturbances to the inhabitants of the scope area.* Deduced from the National Water Policy of Myanmar the flood management system should be developed in an integral and socially inclusive way (Van Meel et al., 2014). This is needed for the measures themselves, but this can also be applied to the deployment/construction of measures.

9. *be maintainable with the local knowledge and capacity.* Due to its history and the closure of Myanmar from the rest of the world, the water resources knowledge and expertise is lacking behind (Van Meel et al., 2014). Measures should be maintainable with an appropriate level of knowledge.

10. *be able to cope with changes in the natural environment.* Ongoing changes are amongst others the global climate change and the resulting sea level rise, possibly leading to relative land subsidence.

11. *be robust to changes in administration.* Although Myanmar has already undergone its democratic reforms several year ago, further changes in the administration on national, regional or local level are not unlikely. Water resources management and flood protection should however be able to function for a longer period beyond the influence of politics.

4.1.2. Preventive layer

In theory several measures exist for the preventive layer. Examples are dams to be able to spread out the flood wave or dredging of the river to lower the water level near Nyaungdon. These measures would however have large influences on a river stretch much larger than that within the Nyaungdon scope and can therefore not be properly assessed without looking at the total river basin. Although they are potential measures in real life, it does not fit the scope of this research. Dikes are therefore the most logical preventive measure here. For the location and type of embankments some possibilities are still open.

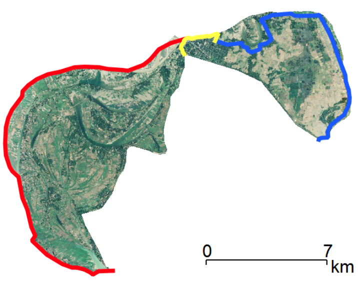


Figure 4.1: *Dike location options Source underlying map: Google Maps (2016)*

Dike location

To start with the location, three options are available. The first option is to design a dike along the total Ayeyarwady River shore of the scope area, including the stretch of dike that is already in place along the town of Nyaungdon and the eastern part of the scope. In Figure 4.1, this section consists of the red, yellow and blue line combined. The second option is to optimise the current embankment along Nyaungdon town and the eastern part of the scope, corresponding to the yellow and blue line together. The final option is to only optimise the dike height of the current dike along Nyaungdon town, depicted by the yellow line in Figure 4.1. All three options are compared below qualitatively and quantitatively.

Qualitative comparison

All three options have their drawbacks and benefits relative to the others. Placing a dike along the total shore would decrease the flood risk of the area much more than staying with the current dike(s) and optimising them. After all, in the latter two options most of the agricultural flood plains are still unprotected. However, full protection has some major disadvantages. First, the yield of the rice fields is likely to decrease. The regular deposit of fertile alluvium due to floodplain flooding will not take place any more or at least less often. Second, diking the rural area would also mean that the way of irrigation and drainage would have to change drastically. Third, the current regular deposit of soil ensures that, to a certain extent, the delta can keep up with the rising sea levels. Also when the sea level rise is not taken into account, absolute land subsidence of the area is likely, resulting in an increase of the flood risk again. An extensive analysis could give answer to the question which of the three options of dike locations is most cost effective in the long term. Thereby weighing the larger initial flood risk reduction of the first option combined with the reduced yield, adapting irrigation and drainage systems and costs of land subsidence in the future, versus the relative smaller flood risk reduction of the second and third option, but without some of these drawbacks.

Comparing the second and third option, there are some differences as well. If only the dike height along the town is optimised, the fish ponds keep carrying the same risk. Looking back at the previous chapter, they are a major contributor to the total risk of the area. Optimising the total dike along the eastern part of the scope might reduce this risk significantly. Furthermore, in the situation that only the dike along the town is heightened, flood waters might still reach the town through backflow of water that has exceeded the embankment along the eastern part. However, the required dike length is of course much larger. A quick quantitative comparison is made in the following to be able to chose an option.

Quantitative comparison
The required dike length for the total shore, the total eastern part of only along Nyaungdon Town are around 28km, 17km and 3,445m respectively. A quick calculation is used to choose between the three options. Suppose that the danger level is increased to 8m +MSL by increasing the dike height by 0.5m. If a dike is placed along the total shore, the whole first flood scenario vanishes. The total risk, discounted to the current year with a 10% discount rate, reduces from $18.0 million with $14.7 million to $3.3 million. If only the dike along the town and eastern part of the scope is heightened, the first flood scenario only vanishes for the area bounded by the embankments. The total risk, again discounted to the current year, then reduces with $9.3 million to $8.7 million. In the option of only heightening the dike along Nyaungdon town, the first scenario only vanishes for the urban area, disregarding any possibilities of backflow. The total risk then only reduces with $600,000 to $17.4 million. However, as written earlier, the dike along the total shore would have to be around 28km, while the embankment around the eastern part is 17km and around the town only 3.445m. In order to be cost efficient, dike heightening should end up with lower total costs than the initial risk. Using the numbers from above, the first option (a dike along the total shore) should be implementable for $525 per running meter of 0.5m dike heightening in order to be cost efficient. For the second option, heightening the dike along the total eastern part including Nyaungdon town, the costs should be lower than $547 per running meter. If only the urban area is protected by a higher dike, the costs should be lower than $174 per running meter. Thus, while not even taking the disadvantages of total floodplain protection into account, the second option is already more likely to be viable. The third option is less likely to be viable. Therefore, the option where the dike around the town of Nyaungdon and the eastern part of the scope is optimised is chosen as location for the preventive layer.

Type of dike heightening
Now that the choice has been made to only optimise the existing dike around the town of Nyaungdon and the eastern part of the scope, the type of dike heightening has to be chosen. Traditional dike heightening by means of extra soil, implies that the base of the dike has to become wider as well. Whether this is easy to implement depends on how close assets are located towards the dike. The policy in Nyaungdon is that the dike should not be affected within 6m of the landside of the dike and 12m on the riverside of the dike (Blom et al., 2016). However, there is not always lived up to these standards, as is shown in Figure 4.2. Based on satellite images it can be seen that most of the disturbances of this free profile are on the landside of the dike along Nyaungdon town, too such an extent that removing all the dwellings within this required free space is not really an option. Therefore two options remain: earth fill dike heightening with soil placed on the riverside of the dike, and dike heightening by means of superstructures, whether or not combined with revetments. Again, both options have their benefits and drawbacks relative to each other.

Figure 4.2: *Disturbances along Nyaungdon dike*
Source: Blom et al. (2016)

Dike heightening method

In general, composite dikes with superstructures are only save if the superstructure has sufficient earth resistance, otherwise the structure might overturn and fail. This means that the dike heightening cannot become too high, or extra soil on the landside of the dike is needed. If it remains below this (still unknown) limit, superstructures require no extra dike base width. This is an advantage for the fishermen that live close to the riverside of the dike.

The extra dike width needed for heightening with soil is the main drawback of this option. For the rest, it is easier to construct a high and stable increase of dike height compared to the superstructure. It also fits better with the current dike sections, which is a collection of earthen dikes and dikes combined with brickwork embankments. Normally it is safest to have a uniform dike stretch. This is already not the case for the dike along the town, but will probably even get worse when extra superstructures are added. Dike heightening with soil provides an opportunity to make the dike more reliable. In short, the dike heightening with soil on the riverside is preferred over heightening with superstructures. Although the superstructures might better fit the wishes from the surrounding citizens, soil heightening is more reliable. As regards the wishes of the fishermen, a new location has to be found for them to settle.

Revetments

The next question is whether revetments are desired or not. A robust grass cover is normally sufficient to protect the dike slope of a riverine dike. The strength of grass will however easily be exceeded in fast flowing rivers and especially in river bends (CIRIA, 2013). Nyaungdon seems to have followed this advice, as the dike section at the junction is fully covered in revetment. It is therefore advisable to keep this section covered in revetments after potential heightening. The other dike sections are less prone to erosion. The dike sections east of the revetment dike are along the smaller Pan Hlaing River, the dike sections south of the revetment dike are protected by a foreshore. Without further calculations, it is assumed that only toe protection would be sufficient on these dike sections and that the rest of the slope can remain covered in grass.

Erosion problem

Now one issue remains: the erosion of the current dike in the junction of the Ayeyarwady and Pan Hlaing River, which is further explored in Appendix A.2. Even when dike heightening is not economically optimal and therefore not chosen as measure in the multi layer flood management system, erosion is a problem that still has to be dealt with to maintain the safety of the hinterland. Since this natural process of erosion is independent on whether the dike is heightened or not, it is not taken into account in the calculations. It is furthermore shown by Vrijling (2013) and Kolen and Kok (2012) that only the marginal costs of dike heightening determine the optimal height instead of the initial costs that would be introduced for erosion prevention measures.

Summary

To summarize, the design of the preventive layer is as follows: only improving the existing dike around the town of Nyaungdon and the eastern part of the scope. In the optimality calculations the dike height will be determined. Dike heightening will take place by means of an earth fill on the riverside of the dike. Compared to heightening with superstructures or heightening with soil with base expansion on both sides of the dike, this is the option that is found to be most safe and achievable. The effect of this measure is that the flood probabilities decreases for the town of Nyaungdon and the total eastern area of the scope, including the fish ponds. This affects the material risk, but also the risk of loss of life. The affected area is displayed in Figure 4.6, the rural area south of Nyaungdon Town is unaffected by the preventive measure.

4.1.3. Spatial planning layer

Concerning spatial planning measures, two approaches are in theory possible: making assets more flood proof or relocating them to less flood prone areas. From a social perspective, it is infeasible to relocate the total town of Nyaungdon, even if this would result in lower total costs compared to other measures. As for the rural area, the wish of the inhabitants is to remain close to their property. Relocating their dwellings is therefore also not an option, since they would have to leave their agricultural land.

Measures within the spatial planning layer therefore have to be in the form of making assets more flood proof. Which dwellings are included in the spatial planning layer and what type of adaptation seems most logical is elaborated in the following.

Included dwellings

A choice that has to be made first is whether all houses can be adapted or only the rural dwellings. As with relocating, it is undesirable to adapt the whole town of Nyaungdon. Even without cost benefit calculations, this would seem an illogical measure. It is therefore decided to only take the rural dwellings into account in the spatial planning layer. The rural area in the eastern part of the scope is different compared to the part south of Nyaungdon Town. The latter is part of the Ayeyarwady River floodplain and is not protected by any embankment. To not make the optimising calculations any more complex than needed, it is decided that only the dwellings in the unprotected rural area can be adapted. This includes not only the area south of Nyaungdon Town, but also the small plot of land in the eastern part of the scope that is located outside the embankment. This is visualised in Figure 4.6.

Figure 4.3: *House on poles*
Source: Myanmar-Trip (n.d.)

Type of adaptation

Adapting can be done by placing dwellings on poles (or lengthen the pile length if they already are) or by constructing a mound to live on. Since the dwellings are scattered over the area, a large number of mounds would be needed, especially since the farmers like to remain where they are and will not cluster on larger mounds. Furthermore, the local community is used to houses on poles and therefore have experience with this measure. The spatial planning measure that is chosen is therefore the adaptation of houses to houses on piles. An example is shown in Figure 4.3. The pile length is to be determined based on the economic optimisation.

Summary

In short, the spatial planning layer consists of houses on poles within the rural area south of Nyaungdon town. All the existing dwellings are adapted with this measure, if this turns out to be economically efficient. The pole length will be determined in the optimality calculations. This measure has effect on both the material losses as the loss of life, as the depth-damage curve and mortality rate will change respectively.

4.1.4. Crisis management layer

Figure 4.4: *Flood shelter*
Source: Raqu (2015)

When looking at how the loss of life is determined, four components can be distinguished: the population at risk, the evacuation rate, the shelter rate and the mortality rate among the remaining population. The preventive measure already reduces the population at risk, as it increases the danger level of the area. (This is only a valid statement with the assumption that flooding only occurs if water levels exceed the danger level and not before that point.) The spatial planning measure has the possibility to reduce the mortality rate. As has been said in the elaboration of the spatial planning measures, relocation is not an option. Measures in the second layer can therefore not decrease the population at risk. The population at risk can also not be reduced by crisis management, since it is defined as the population that lives in the area that might be flooded. Measures within crisis management should therefore increase the shelter rate and the evacuation rate. Which measure is chosen and how it will be modelled is presented below.

Type of measure
Several potential options are available for increasing the shelter or evacuation rate. Improved warning increases the time that is available for evacuation or finding shelter, improved shelter facilities increase the possibility to shelter and improved evacuation processes increase the population that can move outside the flood prone area. However, when there is looked at the flooding process and the wishes from the stakeholders, one measure is likely to be of more added value than the others. For the rural area, the water levels on the floodplain in case of a flood event rise relatively slow. Based on the flood wave that is presented in Blom et al. (2016), the water level in the Ayeyarwady River rises around 2m within two weeks, corresponding to a rise rate of 14cm/day. It is concluded with this rate there is probably enough time for evacuation. That is also why flood fatalities in the floodplains are lower than in mountainous areas, where flash floods in rivers can rise faster (Steijn et al., 2015). The people that lose their life are likely to have chosen to stay near their property and being surprised by the extent of the flood event when it turns out to be more severe than expected, based on the fact that the rural inhabitant often wishes not to evacuate to the diked area (personal communication Win Min Oo (2017)).

A solution for this would be to build various flood shelters distributed over the rural area close to their dwellings that can be reached if the flood event is too severe to stay in their own home. An example of a flood shelter is depicted in Figure 4.4. As regards to the urban areas, shelter is often found in schools and monasteries (personal communication Win Min Oo (2017)). If however a larger area of the town gets flooded, this might not be sufficient. Shelters are therefore also chosen as crisis management measure for the urban area. An advantage of this measure is that it remains unaffected by changes in administration, contrary to measures that require close cooperation between different authorities. As a benchmark for its success, their can be looked at the situation in Bangladesh. Bangladesh has been constructing shelters since 1972 and have been proven helpful to reduce the number of fatalities significantly (Paul, 2009).

Location of shelters
Shelters are most effective at locations where the current risk of loss of life is the highest. Figure 4.5 shows a heatmap of the current risk of loss of life. The darker areas visualise the clusters of high risk of fatalities. Extra shelters on these locations have the highest potential of reducing the loss of life by increasing the shelter rate. Eight potential shelters have been placed at these clusters, which can be seen in the overview map of the measures in Figure 4.6. The circles with a radius of 1.6km represent the scope of the shelter. Studies regarding the situation in Bangladesh have shown that a shelter has to be within 1 mile (1.6 km) in order to reach it during an emergency (Paul, 2009). Although this number concerns coastal shelters, it also seems a reasonable number for river floods in Myanmar. Shelters further away may be reached during floodplain floods, but the farmers also had the wish to remain close to their property.

The shelters in Figure 4.6 are ranked on their effectiveness in the situation where no other measures are taken. Number A is expected to achieve the highest risk reduction, shelter H relatively the lowest. However, shelter B and C are located within the diked area and become less efficient when the dike is heightened. The rest of the shelters are located in the open area and become less efficient when the houses are placed on poles and therefore the fatality rate already reduces. In the optimisation process it will be determined how many shelters should be constructed to be economically most efficient and on which locations.

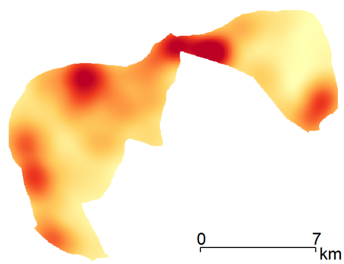


Figure 4.5: *Loss of life heatmap*

Summary
In short, the crisis management measure that seems most suitable is the construction of shelters. Shelters reduce the loss of life by increasing the shelter rate. The potential shelter locations are depicted in Figure 4.6, how much should be constructed depends on the optimisation. This measure only affects the risk of loss of life and contrary to the preventive and spatial planning measure not the risk of material losses.

4.1.5. Measures schematisation

The above presented measures are located at specific locations and have effect on different parts of the scope. Which measure works on what part of the scope is visualized in the map of Figure 4.6. From now on, the yellow area is referred to as the diked area, the red area is referred to as the open or unprotected area. The sizes of the areas are 31 km^2 and 78 km^2 respectively.

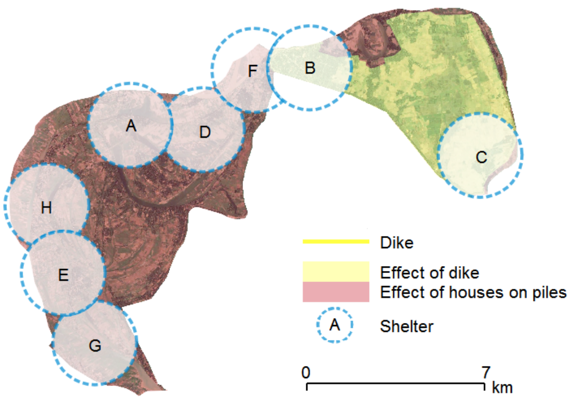


Figure 4.6: *Measures map*
Source underlying map: Google Maps (2016)

It depends on the measure which components of the total risk it affects: the crops, fish ponds, normal and high density (HD) built up, loss of life or combinations of these components; in the open area of the diked area or both. In Table 4.1 the effect of the different measures is listed. If a measure does not affect any component of risk, they remain constant at their initial value after the implementation of the measure.

Table 4.1: *Effect of measures on different areas an risk elements*

Measure	Effect	Open area	Diked area
1. Dike heightening	Effect on	-	Crops Fish ponds Normal built up HD built up Loss of life
	Constant	Crops Normal built up Loss of life	-
2. Houses on poles	Effect on	Normal built up Loss of life	-
	Constant	Crops	Crops Fish ponds Normal built up HD built up Loss of life
3. Extra shelters	Effect on	Loss of life	Loss of life
	Constant	Crops Normal built up	Crops Fish ponds Normal built up HD built up

4.2. Optimisation of single safety layers

The specifications of the measures that have be chosen in the previous section will be determined on the basis of economic optimisation. The general concept is that the total costs will be minimised. The total costs consist of investment costs and the residual risk after the implementation of a measure. The residual risk decreases if the dike height increases and/or the pole length of houses increases and/or more shelters are placed. However, the investment costs increase when the measures' specifications are increasing in size of quantity. Some combination of investment costs and residual risk will bear the lowest total costs and corresponds to the optimal design specification. These specifications are determined in this section for the individual measures. Combination of measures are given in the next section. The model is described in general at first, after that the schematisation and results per safety layer are given.

4.2.1. General optimisation model

The two basic components of the optimisation model, written in Matlab, are the discounted risk curve and the investment curve. When added together they form the total cost curve. Both elements are shortly described below.

Risk curve

By the implementation of measures the discounted risk reduces. What effect the measures have on the risk reduction is given per measure in the following. This paragraph focusses on the general method. An important item is the discount rate. The discounting is needed to determine the present value of having a specific annual risk in the years to come. Since investments are made at the beginning of the system lifespan, the risk can now be compared with the investments. According to theory, the discount rate should be the opportunity cost of the project relative to other investments (Brealey et al., 2013). This means that the discount rate should be comparable to the interest rate that can be earned by other capital investments. Governmental bonds are therefore a good indicator of this opportunity cost. In Myanmar the Government Treasury Bonds are currently around 10% and used in the following as discount rate (Central Bank of Myanmar, 2017). The discounted risk reduction curve can be depicted by a declining curve, in case of the optimisation of a single layer. If two measures are combined, the risk reduction is visualised as a plane, declining for any combination of specifications of the measures. This means that when when all three layers of the multi layered safety principle are combined, one more extra dimension is added.

Table 4.2: *Split Nyaungdon risk values*

	Risk value ($/year)	
Type	Open area	Diked area
Crops	$311,518	$382,374
Fish pond	-	$600,899
Built up	$374,709	$91,138 (normal)
	-	$55,408 (high density)
Loss of Life	$39,973	$15,869
Total	$726,000	$1,150,689

Since the total scope area is divided into two separate areas and the measures have effect on different components of the total risk, some risk values and FD-curves as they were presented in the previous chapter have to be split up as well so that each area has their own risk values. The high density built up area and the fish ponds are only present in the diked area. Therefore nothing has to be done to those values, they represent their risk values for the diked area. The crops and total built up (and therefore also the loss of life) land uses are located in both the diked and the open area. For the purpose of optimisation of specifications, their current risk values and FD-curves have to be determined for both areas separately. The results are depicted in Table 4.2 and the new FN-curves in Figure 4.7. Now all components listed in Table 4.1 are quantified and can be used in the optimisation process. How this is done exactly is described per measure in the coming subsections.

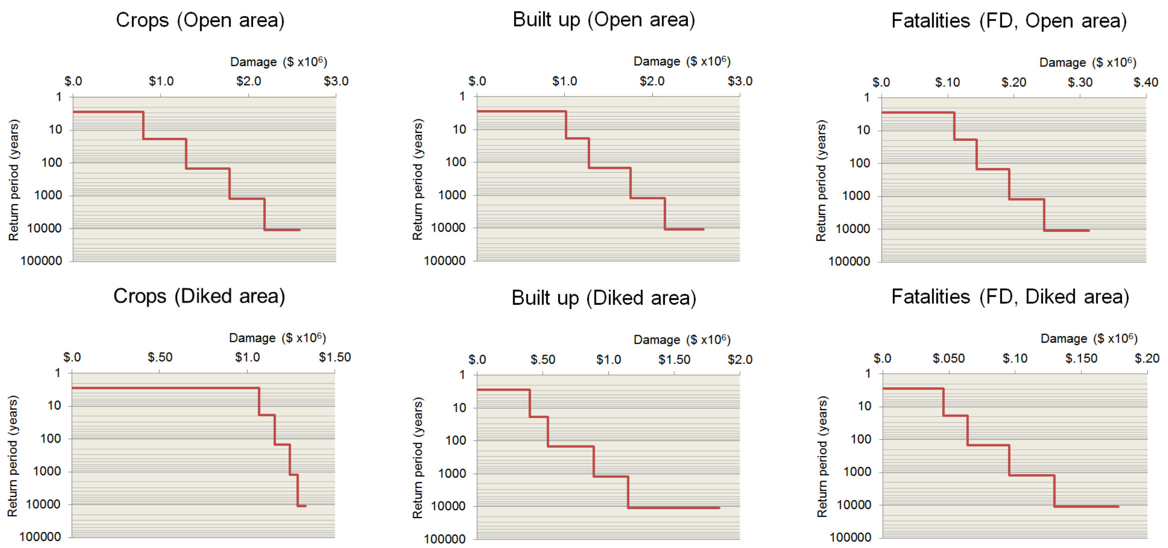


Figure 4.7: *Split FD-curves for crops, built up and fatalities for the open and diked area*

Investment curve
The second component of the total costs are the investment costs. The investment costs are twofold: the initial costs and the marginal costs. The initial costs are constant costs that need to be spend either way, independent on the size of the measure. Initial costs are for instance the mobilisation costs. The marginal costs are the costs that need to be spend to increase the product with one unit, in this case the costs per meter dike or pole heightening or the costs of one shelter. Which costs are covered in the initial costs or marginal costs will differ per measure. Van Danzig (1956) used a linear relationship between the dike heightening and the investment costs, although other relations are also possible:

$$I = I_0 + I_h \cdot h_{dike} \tag{4.1}$$

The initial costs have no effect on the optimal design values, it can only move the total costs curve vertically and not change its shape. It does however affect the benefit/costs ratio, the profitability index.

4.2.2. Optimising dike height

The first specification that will be optimised is the dike heightening. This subsection and the ones following for the other measures, are divided into the method of optimising and its results. The method is furthermore divided into how the risk curve is constructed and how the investment curve is constructed.

Method of optimising dike height
Constructing the risk curve
The effect of dike heightening is that the Danger Level increases. With a higher Danger Level, flooding statistically takes place less often, since the probability of exceedance of this higher water level decreases. For the FD-graphs, this implies that the probability of exceedance decreases, but the damages remain the same for each flood event. In reality this is not the case, since for example a 7.7m flood event results in higher damages than the 7.5m flood event, but this is due to the discrete set of flood events. The effect of dike heightening is visualised in Figure 4.8, where the FD-curve reduces from the top downwards with the grey accented area. The area beneath the curve reduces and therefore the risk. Every time the Danger Level has increased to such an extent that a flood scenario

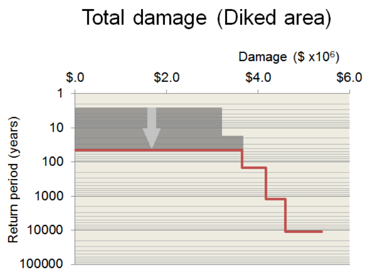


Figure 4.8: *Effect of dike heightening on FD-curve. Prevention lowers probability, consequences remain the same*

vanishes, a jump in the risk curve can be expected. This is due to the schematisation that the damages of flood events remain the same, due to the discrete set of flood events. Therefore the risk corresponding to a new Danger Level slightly lower than a flood scenario (for example 7.9m) is considerably higher than the risk corresponding to a Danger Level slightly higher than a flood scenario that thereby vanishes (for example 8.1m).

The corresponding exceedance probabilities of the higher Danger Levels are determined through the distribution of Equation 3.8, which is the Gumbel distribution through the measured water levels. As regards to the choice of FD-curves, Table 4.1 can be used. Dike heightening affects the total risk of the diked area. For calculating purposes, this means that the risk of crops, fish ponds, normal/HD built up and loss of life can be gathered in one FD-curve. The risk curve can now be constructed through the method as depicted in Figure 4.8. The dike heightening has no effect on the material risk and loss of life of the open unprotected area. This constant value has to be added to the risk curve of the diked area to construct the risk curve of the total area.

Constructing the investment curve
The next step is to determine the investment costs needed for dike heightening. The marginal costs of dike heightening depend on the earthen volume that is added; according to Nay Myo Lin (2017) (personal communication) this amounts 10,000 kyat/sud, where 1 sud equals 100 cubic feet. Converting this number to dollars and cubic meters, the marginal costs of dike heightening C_{dike} are \$2.61/m^3 (with the April 2017 exchange rate). The costs of heightening therefore depends on how much volume is added to the dike. Figure 4.9 is used for this. This figure depicts the earthen dike that is currently in place along Nyaungdon Town (Blom et al., 2016). The dimensions of the other dike sections along the town and along the rest of the eastern part of the scope are not exactly known and assumed to be comparable.
The existing earthen dike is 3m high and has a base of 15.9m, resulting in a cross section area of 29.1 m^2. If the new dike keeps the same slopes and dike width at the top, the dimensions can be expressed in terms of the extra dike height h. By dividing the cross section into two triangles with a base of a m and height $(3+h)$ m, and a block in the middle with width and height of 3.5m and $(3+h)$ m respectively, the area of the new dike is determined. By subtracting the cross section area of the current dike from the new dike and rewriting the equation, the extra amount of soil is given by:

$$V_{extra} = \frac{(3+h)^2}{tan(\frac{3}{6.2})} + 3.5 \cdot h - 18.6 \tag{4.2}$$

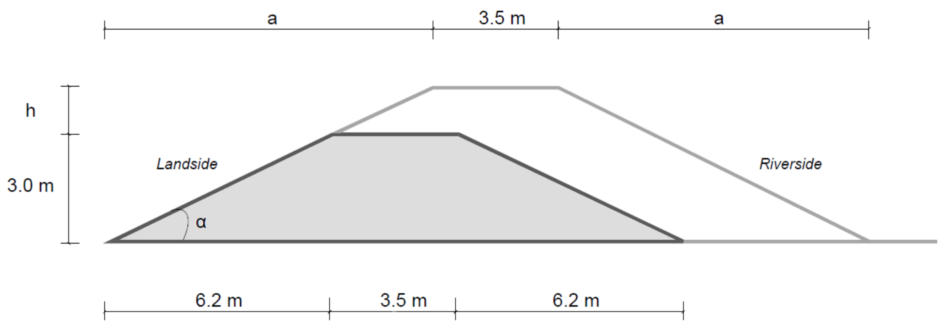


Figure 4.9: *Effect of dike heightening on cross section*

It can be noticed that the relation between dike heightening h and the extra volume is not linear in this schematisation, but quadratic. Therefore so will be the relation between the dike heightening and its costs. The dike length around Nyaungdon town is 3,445m and the embankment length along the rest of the eastern part 17,340m, resulting in a total dike length L_{dike} of 20,785m. The total amount of extra volume is found by multiplying Equation 4.2 with this length. The investment curve is now found by multiplying this extra amount of volume times the costs per cubic meter of extra volume, therefore linking the dike heightening in h meter to the increase in costs:

$$I_{dike}(h)\ [\$] = I_0\ [\$]\ +\ V_{extra}(h)\ [m^2] \times L_{dike}\ [m] \times C_{dike}\ [\$/m^3] \tag{4.3}$$

I_0 in this equation refers to the initial investments costs, that need to be spend independently on the size of the dike heightening. In the optimality calculations of Van Danzig (1956) for dike ring 14 in the Netherlands, the initial costs amounts 110 million Dutch guilders and the marginal costs 40 million Dutch guilders per meter heightening along the total dike ring. These values return in several other papers, for example Kolen and Kok (2012) and Slijkhuis et al. (n.d.). The ratio between these initial and marginal costs is 2.75, which will be used here to estimate the initial costs. A meter dike heightening costs slightly below a million dollars, resulting in initial costs I_0 of around $2.67 million.

Results of optimising dike height

The results of the cost optimisation of dike heightening is presented in Figure 4.10. The (red) risk costs curve starts at the initial risk of $18.7 million and decreases when the dike height is increased. The risk costs curve decreases steeply within the first 0.5m of dike heightening. This is due to the fact that the first flood event carries the highest risk, due to its relative high probability of exceedance. When more flood events become obsolete the risk curve flattens. The curve stabilises, but will never reach zero. After all, the dike can only protect part of the area and the risk carried by the open area ($7,26 million), remains present. The predicted jumps due to the discrete set of flood events are clearly visible as well. However, the size of the jumps decreases when more flood events become obsolete. This is also the result of the lower risks of higher flood events, implying that the differences in risks between two flood events also become smaller.

Table 4.3: *Optimal dike heightening results*

Parameter	Value
Optimal dike heightening	1.0 m
Optimal Danger Level	8.5 m
Optimal probability of exceedance	$5.8 \cdot 10^{-3}$
Optimal return period	171 years
Minimal total costs	$11,193,000
Investments	$3,649,700
Risk reduction	$11,226,000
Profitability index	3.08

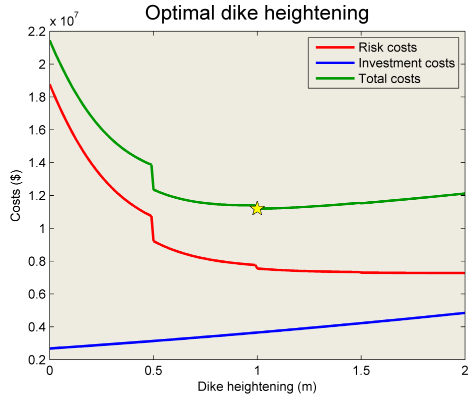


Figure 4.10: *Optimal dike heightening determination. Optimal dike height located at yellow star*

The upper curve shows the total costs, produced by adding the risk costs and the investment costs. Its minimum value is located at the yellow star. This location corresponds to a dike heightening of 1.0m, increasing the Danger Level to 8.5m +MSL and the return period of flooding of the diked area to 171 years. With this measure the present value of the risk has decreased by around $11 million, while the investment costs are substantially lower. The profitability index, defined as the ratio between benefits and costs, is therefore well above 1. It can be noticed that the total costs is relatively flat around the optimal location. A slightly lower dike heightening than 1.0 m would result in approximately the same total costs, but even lower investments.

4.2.3. Optimising pole length

Method of optimising pole length

Contrary to preventive measures, the effect of adaptation measures such as houses on poles is that the damages of flood events reduce, but the probabilities of the events remain the same. Houses on poles only affect the damage of the built up land use type and the loss of life. Both have to be dealt with separately.

Constructing the risk curve: built up

Reducing damages due to houses on poles means that in the built up FD-curve the surface is decreasing from the right and thereby the risk reduces, as visualised in Figure 4.11. The question is how much. For dike heightening the reducing probabilities of exceedance are covered in a function, for reduced damages by increasing pole length this is not possible. The damages per flood event depend on exposure, intensity and susceptibility. Although the susceptibility is covered in a function, the exposure and intensity of a specific area are defined by the land elevations and land use. How much dwellings are flooded per scenario and to which extent can therefore not be translated into a function. However, if the interval between the increase in pole heights coincides with the interval of the current flood events, so 0.5m, information from the current built up FD-curve can be used. When the pole length beneath a house increases by 0.5m from the current status, the water level at the dwelling is equal to the situation of a flood event with water levels that are 0.5m lower than the current one. This is however only valid under the assumption that no damage occurs to the houses before the flood levels have reached the ground floor. The schematisation implies that if the length is increased by 0.5m, the damages to the houses is equal to that of the previous flood scenario. In other words, the damage to a house on 0.5m high poles during the 8.5m flood event is equal to the same house without poles during the 8.0m flood event.

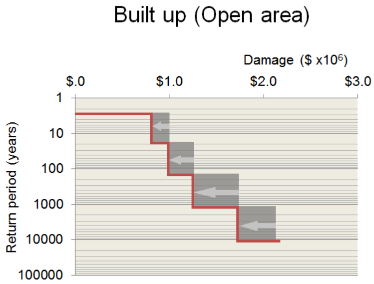


Figure 4.11: *Effect of pole heightening on FD-curve. Adaptation decreases consequences, probabilities remain the same*

Since the damages of the first scenario also decrease, QGis is needed to determine the damage of virtual flood scenarios with water levels lower than 7.5m. Flood scenarios can become obsolete in theory, but in practice this would mean that the poles have to be very high. Therefore there will be no jumps in the risk curve. Sharp corners will however be present, since the reduced damages are a discrete set of values and the risk curve is made with interpolation between discrete set of risk values.

Construction the risk curve: loss of life

Besides the reduced material risk of the dwellings in the open area, houses on poles also affects the loss of life. This is under the assumption that the dose-response function as derived by Jonkman (2007), comparable to the depth-damage function of houses, is to be applied for the affected population on ground level. If this 'ground level' elevates due to houses on poles, the mortality rate decreases, comparable to how the damage to the houses decreases. After all, the water level people experience gets lower when they are situated in houses on poles relative to houses on ground level. The risk reduction due to houses on poles for loss of life can therefore be determined in the same way as the risk reduction for houses, as depicted in 4.11. Since the loss of life is monetised, the FD-curves of the loss of life and that of the built up area can be added together for the optimisation calculations.

The risk value of the crops in the open area is not affected by houses on piles and therefore remains constant, as do the risk values for everything that is situated in the diked area. These constant values have to be added to the risk curve of the open area to construct the risk curve for the total area.

Constructing the investment curve

The investment curve for pole heightening is dependent on several variables. First of all, the number of houses at risk within the open unprotected area. These houses at risk get flooded in one or more of the flood scenarios. In QGis the flooded built up cells can be determined. Combining this with the housing density per cell, the number of houses at risk in the open area is found. This amounts 4,615 dwellings. The next variable is the number of poles per house. Cho Oo et al. (2003) did a study on the traditional houses in Myanmar. Different ethnic groups have different building styles. The most common group in the Ayeyarwady Region is the majority Bamar population. A traditional Bamar house is depicted in Figure 4.12, mainly made out of bamboo and wood. According to the Ministry of Population (2015a), the biggest part of the population in Nyaungdon lives in bamboo and wooden houses, expected to be comparable to the house depicted in Figure 4.12. In the right image of the figure, the floor plan, it can be seen that the dwelling is built with 21 vertical poles.

Figure 4.12: *Traditional Bamar house, floor map (right) shows amount of poles*
Source: Cho Oo et al. (2003)

The article of Cho Oo et al. (2003) furthermore shows that these poles are made with indigenous types of timber, such as Pyinkado. This type of wood costs around $475/m^3 (Fordaq, 2010). Assuming poles of 20x20cm or 0.04/m^2, the needed volumes of wood can be computed. The material cost per meter pole heightening can now be determined by multiplying the total number of poles in the area times the volume (dependent on the pole height), times the price of the wood. Other part of the investment curve are the initial costs. With lack of a better alternative, the same ratio between initial and marginal costs as for dike heightening will be used, namely 2.75. The above results in marginal costs of around $1.84 mln/m and initial costs of around $5 mln. Contrary to the dike heightening, the relation between pole heightening and its costs is a simple linear function.

Results of optimising pole length

Where dike heightening seems an efficient solution, pole heightening does not. The results of the optimisation process are given in Figure 4.13 and Table 4.4. The minimum of the total costs is found at 0.5m pole height. However, doing nothing would result in lower total costs, namely $18.77 million while doing nothing against $23.53 million with pole heightening. This is clearly visible in the fact that the curve of the total costs is nowhere beneath the initial value of the risk curve. It are mainly the initial costs that make it a cost inefficient solution. However, even when these costs are disregarded and the material costs of the wood are the only investment that needs to be spend, the risk reduction is only slightly larger than the investments. The risk reduces too little with pole heightening to be cost efficient. This is due to the relatively low value of the dwellings and the low value of risk of loss of life which can be reduced. After all, houses on poles do not affect the other components of the total risk, such as the crops in the open area and the risk of the diked area.

Table 4.4: *Optimal pole heightening results*

Parameter	Value
Optimal pole heightening	0.5 m
Minimal total costs	$23,530,000
Investments	$5,985,000
Risk reduction	$1,223,300
Profitability index	0.20

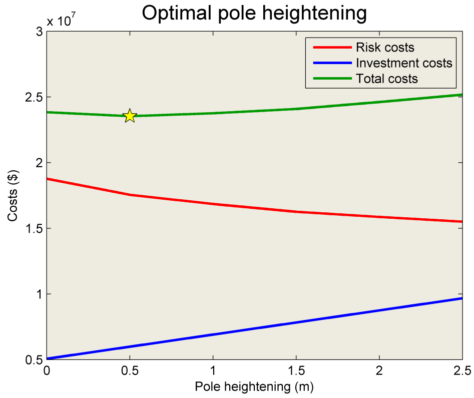


Figure 4.13: *Optimal pole heightening determination.*
Optimal pole height located at yellow star

4.2.4. Optimising number of shelters

Method of optimisation number of shelters

Constructing the risk curve

As with the spatial planning measure, the crisis management measure is a mitigative measure. This again implies that the damages, in this case the monetized value of the number of fatalities, reduce by an increase in measure specifications while the probabilities of the flood events remain the same. The more shelters are built, the more the damage reduces. As regards to the FD-curve, this means that the curve is reducing from the right and thereby the risk reduces. A shelter only has effect on the fatalities within its 1.6km radius. The assumption for now is that for people outside this circle the shelter is too far to be able or willing to reach. Starting point for constructing the risk curve is the current risk of loss of life. As has been done for the material risk, this risk is distributed over the area. Figure 4.5 has shown where the hotspots concerning risk of loss of life are located. Recall that the current risk is determined through the implementing the following formula in QGis:

$$N(h) = N_{PAR} \cdot (1 - F_E) \cdot (1 - F_S) * F_D(h) \tag{4.4}$$

The first three terms are used to translate the total population at risk into the exposed population. The exposed population is therefore the population that has chosen not the evacuate or take shelter. The latter term of the equation is used to determine the mortality rate among this exposed population. For the current shelter and evacuation rate combined a number was chosen so that the number of fatalities for the total area matched with historical data of flood events. The effect of shelters is now schematised as follows. When a shelter is constructed, the exposed population within its scope moves into the shelter during a flood event and is therefore not prone to dying any more. For the total number of fatalities this means that it reduces with the expected number fatalities within the scope of a shelter. When more shelters are constructed, the exposed population reduces even more and therefore the total number of fatalities. Since the risk of fatalities differs per scope, their is no logical relation between the initial risk and the risk reduction. The reduction in number of fatalities has therefore been determined through QGis per shelter. The reduction in economic damage is subsequently determined by multiplication of the number of fatalities and the macro economic valuation of life. The shelters only reduce the risk of loss of life. Therefore all material risks of both the open as diked area remain the same. To find the total risk for the whole area this constant value has to be added to the risk curves of loss of life reduction.

Constructing the investment curve
To construct the investment curve, the construction costs of shelters need to be known. The World Bank (2014) provides a project appraisal for the construction of multi purpose shelters in Bangladesh. Such shelters provide a safe accommodation during flood events, but can also be used during non-disaster periods. The use during non-disaster periods depends on the needs of the local community. For example, the shelters from the project appraisal in Bangladesh provide extra primary schools or community centres. The shelters from the appraisal have water supply systems, water storage, sanitation systems, food storage and relief supplies (World Bank, 2014). It is also a possibility to include room for livestock. The project appraisal includes the construction of 552 new shelters for $222 million, resulting in around $400,000 per shelter. However, the appraised structures provide shelter to 1,300 to 1,750 people. The estimated exposed population within the 1.6km scope of the proposed shelters are in the order of 150-200 people. As a best estimate the costs per shelter for the Nyaungdon case is $400,000/(1,300/200), so around $62,000.

The initial costs are different compared to the dike and pole heightening, due to a different building process. The previous two measures have costs that are almost constant independent on whether the dike or pole heightening is 0.5m or 2.0m. Examples are mobilisation costs and labour costs. However, the mobilisation and labour costs for shelters change drastically between having to build one shelter or eight shelters. These costs are covered in the marginal costs of shelters. Remaining initial costs are spend on project management. Comparing the project size of the Bangladesh appraisal (552 shelters) to the Nyaungdon case (maximum of 8 shelters), these initial costs are around $20,000.

Results of optimising number of shelters
Again the results are depicted in a figure and a table. In Figure 4.14, only the risk and total costs curves for the loss of life are presented. If the total risk and costs would be visualised, the risk curve would be almost horizontal, due to the relatively small contribution to the total risk. After all, shelters only affect the risk of loss of life, while the number of expected fatalities is already low. It turns out that the optimal number of shelters is 3. Looking back at the measure map in 4.6, this would be shelters A, B and C. It can be seen in Table 4.5 that the profitability index is still close to one, implying that the risk reduction is not much larger than the investments. However, in the figure it can be noticed that the total costs for two shelters is only slightly higher than for the optimal number of three shelters. In fact, the total costs only differ $950. The benefit/costs ratio would increase to 1.68 when two shelters are build. Three

shelters are the optimal solution in terms of costs, but two shelters would have a higher efficiency in terms of return on investments.

Table 4.5: *Optimal number of shelters results*

Parameter	Value
Optimal number of shelters	3
Minimum total costs	$18,733,000
Investments	$206,000
Risk reduction	$242,160
Profitability index	1.18

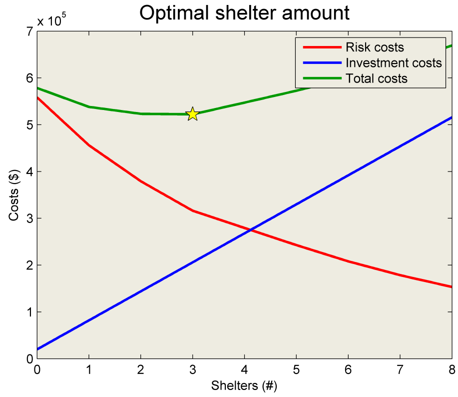


Figure 4.14: *Optimal number of shelters determination. Optimal number located at yellow star*

4.3. Optimisation of multi safety layers

So far the three layers of safety have been treated individually. In this section any possible combination of multiple layers is elaborated. When dike heightening corresponds to layer 1, pole heightening to layer 2 and shelters to layer 3, the possible combinations are 1-2, 1-3, 2-3 and 1-2-3. As with the individual layers, the subsections are divided into the method of optimisation and the results. Since much of the input of the optimisation model has already been derived, the explanations can be shorter than for the individual measures.

4.3.1. Optimising dike height & pole length

Method of optimising dike height & pole length

The first combination is that of optimising the dike height of the diked area and the pole length of the dwellings in the open area. Due to the separate areas, the preventive and adaptive measure do not intervene with each others risk components. The dike heightening affects the crops, fish ponds, (HD) built up and loss of life in the diked area. The houses on poles affect the built up and loss of life in the open area. The crops in the open area remain constant. Both declining risk values can simply be added for any combination of dike and pole height. In the end the constant risk of the crops in the open area has to be added as well to find the total risk.

Where the individual measures resulted in risk and costs curves, this combination results in risk and costs planes in a 3D domain. One axis corresponds to no dike heightening, being the same as houses on poles as only measure. The other horizontal axis is the other way around. Therefore the shapes of the individual measures will still be clearly visible. The vertical axis still represents the costs.

Results of optimising dike height & pole length

It turned out that the optimal combination is 0.5m pole length and 1.0m dike height, pointed out by the white star in Figure 4.15. This happens to be the same design values as when these measures were treated individually. Adding houses on poles as measure is a viable option now, although the total costs are higher than when only dike heightening is considered.

In Figure 4.15 the same colours are used as in the 2D graphs: red for the risk costs, blue for the investment costs and green for the total costs. Within the risk and total costs planes, the individual measures are clearly visible. The jumps and the sharp corners due to the discrete set of flood scenarios can still be distinguished. It can furthermore be noticed that dike heightening can reduce the significantly more than pole heightening. Together they achieve a risk reduction that is higher than for dike heightening alone.

Table 4.6: *Optimal dike & pole heightening results*

Parameter	Value
Optimal dike heightening	1.0 m
Optimal pole heightening	0.5 m
Minimal total costs	$15,954,000
Investments	$9,634,200
Risk reduction	$12,449,000
Profitability index	1.29

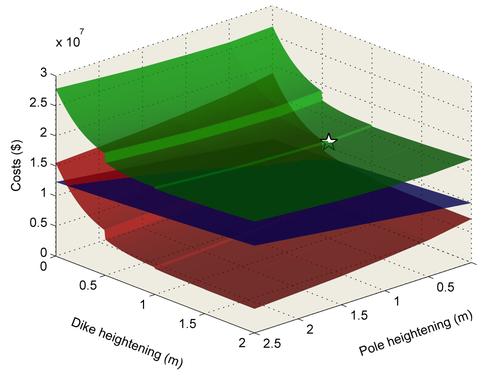


Figure 4.15: *Optimal dike & pole heightening determination. Optimal combination located at white star*

4.3.2. Optimising dike height & shelters amount

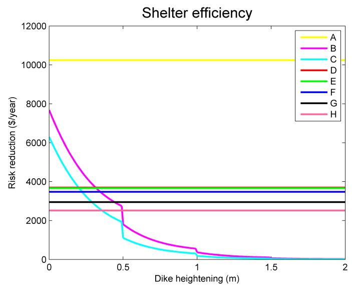


Figure 4.16: *Effect of dike heightening on shelter efficiency, Shelter B and C reduce in effiency after dike heightening*

Method of optimising dike height & shelters amount
Where the effect of the dike and pole heightening could be determined separately, for the effect of dike heightening and shelters this is not possible. Shelters B and C are located within the diked area. The loss of life in the diked area is therefore dependent on both the dike heightening as the shelters (if more than one shelter is constructed, so that shelter B and C are built). This also means that shelters B and C become less efficient when the dike is heightened, since the chance to be of help reduces as the probability of exceedance of the dike increases. Figure 4.16 shows how the efficiency of the shelters declines when the dike is heightened. The efficiency is depicted as the risk of loss of life that it reduces. Shelters A and D-H are constant, since they are located within the open area and therefore unaffected by any dike heightening. However, after 0.5m of dike heightening, shelters B and C move from being the second and third most efficient to becoming the least efficient shelters. This has to be taken into account in the optimality calculations. Furthermore, if the results of the calculation shows that the dike heightening should be higher than 0.5m and the number of shelters more than one, the order of efficiency of the shelters is not ranked from shelter A to H, but A-D-E-F-G-H-B-C. The risks components that remain constant are the crops and normal built up in the open area.

Table 4.7: *Optimal dike heightening & shelters results*

Parameter	Value
Optimal dike heightening	1.0 m
Optimal number of shelters	1
Minimal total costs	$11,173,000
Investments	$3,731,700
Risk reduction	$11,328,000
Profitability index	3.04

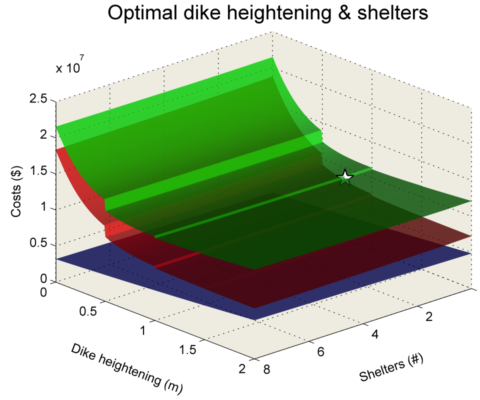


Figure 4.17: *Optimal dike heightening & shelters determination. Optimal combination located at white star*

Results of optimising dike height & shelters amount
Keeping the above described dependency of the shelters on the dike heightening in mind, the results as depicted in Table 4.7 and Figure 4.17 can be found. Although the dike heightening is higher than 0.5m, the optimal number of shelters is only one, corresponding to shelter A in the measure map of Figure 4.6. It can be noticed that the effect of shelters on the risk reduction is low, as the risk plane hardly shift its shape when more shelters are added. As has been said before, this is due to the already low number of fatalities. The profitability index for this combination of measures is still high. This is logical, since despite the low effect of the shelter, the extra investment besides dike heightening is also low. The numbers in Table 4.7 are therefore comparable to dike heightening alone.

4.3.3. Optimising pole length & shelters amount

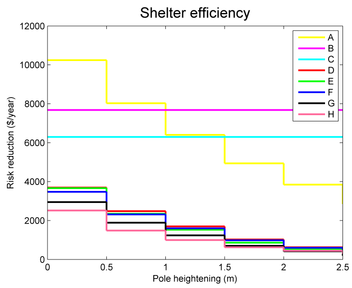


Figure 4.18: *Effect of pole heightening on shelter efficiency, Shelters A and D-H reduce in efficiency after poles*

Method of optimising pole length and shelters
Pole heightening and shelters also share a risk component: the loss of life in the open area. Pole heightening only takes place in the open area, affecting the efficiency of all shelters except B and C within the diked area. The efficiency of the shelters reduces when the pole height increases, since the saved number of fatalities reduces when people remain save in their dwellings. Figure 4.18 shows the effect of pole heightening on the efficiency of shelters. Shelter B and C in the diked area remain constant, while the others decrease in efficiency. After 1.0m pole heightening, shelter B becomes most efficient. After 1.5m of pole heightening, shelter C takes second place. This has to be taken into account in the optimality calculations, when every combination of pole height and shelters is combined. The components that remain constant are the crops in the open area and all components except the loss of life of the diked area. They have to be added in the end to find the risk of the total area.

Results of optimising pole length and shelters
Adapting the houses to houses on poles was already a cost inefficient measure, so is the combination of poles and shelters. The 'optimal' combination turned out to be 0.5m pole length and 3 shelters. Since the pole length is not larger than 0.5m, the to built shelters remain in their original order of efficiency: shelters A, B and C. The benefit/cost ratio increases slightly compared to poles alone, but it remains well below one. The minimum of total costs is around $5 million higher compared to doing nothing.

Table 4.8: *Optimal pole heightening & shelters results*

Parameter	Value
Optimal pole heightening	0.5 m
Optimal number of shelters	3
Minimal total costs	$23,516,000
Investments	$6,190,500
Risk reduction	$1,443,300
Profitability index	0.23

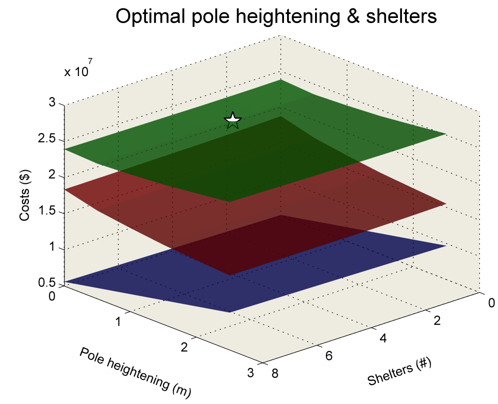


Figure 4.19: *Optimal pole heightening & shelters determination. Optimal combination located at white star*

4.3.4. Optimising dike height & pole length & shelters amount

Method of optimising dike height & pole length & shelters amount

At last, the full multi layer safety system can be explored. This combination also requires the most extensive calculations. The interdependencies between the different measures are still present. The loss of life in the open area is affected by both the houses on poles as shelters, the loss of life in the diked area is affected by the dike heightening and the shelters that are located in that area. This implies that shelters B and C become less efficient when the dike is heightened and the rest of the shelters becomes less efficient when houses are placed on poles. This also means that the order of most efficient shelters changes continuously for different combinations of measure specifications. An overview of this is given in Appendix D. Furthermore, almost all components of the total risk are affected by a combination of the three measures. Only the risk of the crops in the open area remains constant.

Results of optimising dike height & pole length & shelters amount

The determination of the optimal specifications of individual measures could be visualised by a curve. When the combinations of two measures where elaborated, the results where visualised as planes. With three different measures and their costs, it means that the results have to be visualised in four dimensions. In Figure 4.20, the fourth dimension is colour, showing the total costs over the different specifications of the three measures. Red visualises high total costs, blue shows low total costs. Only a discrete set of values is displayed to ensure a clear view. Its minimum value is located at the yellow star.

Table 4.9: *Optimal dike & pole heightening & shelters results*

Parameter	Value
Optimal dike heightening	1.0 m
Optimal pole heightening	0.5 m
Optimal number of shelters	1
Minimal total costs	$16,069,000
Investments	$9,716,200
Risk reduction	$12,416,000
Profitability index	1.28

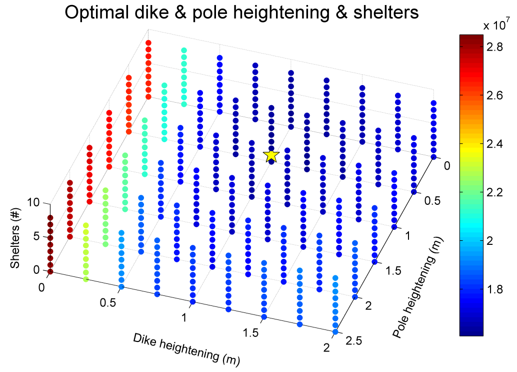


Figure 4.20: *Optimal dike & pole heightening & shelters determination. Optimal combination located at yellow star*

The location that corresponds to the location of the yellow star is 1.0m dike heightening, 0.5m pole length and 1 shelter (shelter A). This requires the highest investments of all possible individual or combinations of measures. However, the total costs are not at an overall minimum.

4.4. Optimal design

All individual measures and combinations of measures are explored. This last section of the chapter provides an overview of the derived values of minimum total costs, investments, risk reduction and profitability index.

Minimum Total Costs

Of all the possible measures or combinations, one carries the lowest total costs and is therefore the optimal design. Figure 4.21 ranks all the options from lowest to highest total costs. It includes the option of doing nothing. The (combination of) measures with higher total costs than doing nothing are not viable options. These are the options of putting poles under the dwellings and poles in combination with shelters. It can furthermore be noticed that the options which include poles strongly increase the total costs. The best options include dike heightening. The combination of dike heightening and shelters results in the lowest total costs and is therefore economically the best design with the current calculation parameters. However, the difference with the option of dike heightening alone is minor.

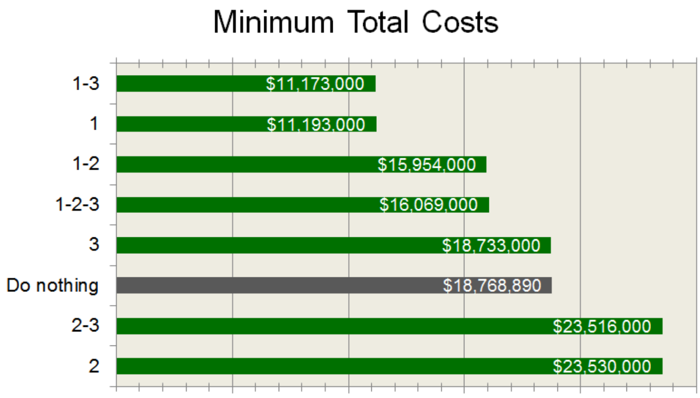


Figure 4.21: *Overview of options and their minimum total costs*

Investments

Although the total costs indicate the best option in terms of optimal solution, the needed investments might also be important. If two options are comparable in minimum total costs, but one is cheaper to implement, this option becomes the most suitable option. In this case, the options with the lowest total costs (dike heightening and dike heightening combined with shelters) are also among the cheapest options. Only the option of building shelters alone is cheaper, but this option is hardly any better than doing nothing. This makes options 1 and 1-3 even more attractive. Options 1-2 and 1-2-3 score relatively well in terms of low total costs, but they are the most expensive solutions.

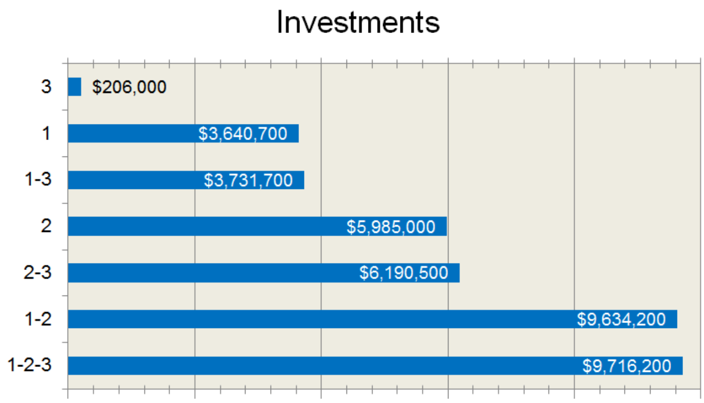


Figure 4.22: *Overview of options and their needed investments*

Risk reduction

Looking at the total risk reduction in the optimal designs, the most expensive options score the highest. However, the difference with the options of dike heightening, whether or not combined with shelters, score high as well. Again the options with dwellings on poles without dike heightening score bad, their risk reduction is minor. The lowest risk reduction is achieved by building shelters alone, since this only affect the risk of loss of life.

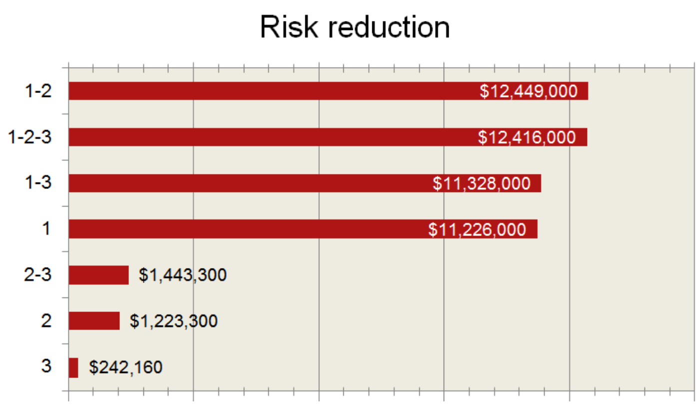


Figure 4.23: *Overview of options and their risk reduction*

Profitability index

Together with the minimum total costs, the profitability index is the most important indicator of efficient options. This index shows the ratio between benefits and costs. The higher this value, the more value for money is achieved. If this index is lower than one, the option is not viable. It can therefore be concluded that the options of pole heightening, whether or not combined with shelters, are not economically attractive. Only the options of dike heightening alone and combined with shelters score an index well above one. Linking this to the fact that these options also achieve the lowest total costs, makes these the best measures from economic perspective.

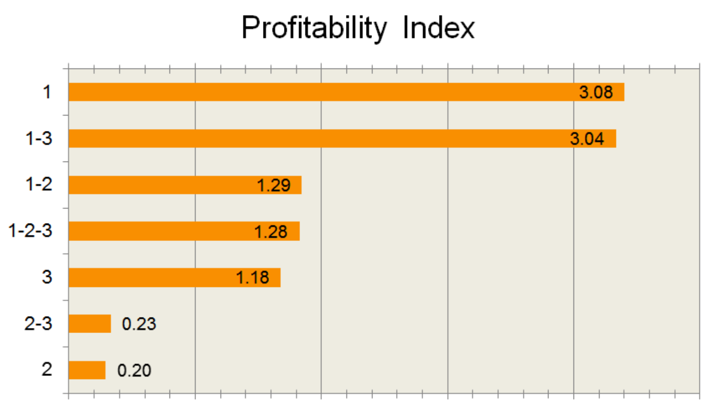


Figure 4.24: *Overview of options and their profitability index*

5

Uncertainties

Until now, the flood risk and optimisation calculations were based on single variables. With single variables the optimal design turned out to be dike heightening by 1.0m together with the construction of one shelter. In reality, the variables can be uncertain, especially when little data is available. This chapter investigates the effects of uncertainty on the optimal design specifications. The question is how robust the derived optimal design of dike heightening and shelter is. The chapter starts with an elaboration on the sources of uncertainty and how they propagate through the optimality calculations, after which the uncertainties are quantified. The effect will ultimately depend on the sensitivity to specific uncertainties and their combined effect.

5.1. Sources of uncertainty

The first step in analysing the uncertainty is to investigate where uncertainties can originate from and how they work through the calculations. The uncertainties for this case arise mainly from uncertainties in data and the used models. Unsure future or unsure size of budget for flood risk reduction can however also have their effect on the outcomes of the optimal design specifications. All four are shortly introduced in this section. The uncertainty in data is the focus point of the uncertainty analysis, but the information that flows from this is used in analysing the other sources of uncertainty at the end of this chapter.

5.1.1. Data uncertainty

The main issue in the uncertainty analysis is the effect of uncertain data. In principle are all used variables and functions uncertain. These variables and functions and how they propagate through the calculations are presented in the flow diagrams given below. A distinction is hereby made between the material damages and loss of life, which have both been determined in QGis, and the specifications of design parameters, which have been computed in Matlab.

Uncertainty in material damages

Figure 5.1 displays the propagation of uncertainties within the estimation of the material damages. All yellow accented parameters are starting values of the calculations and bear a specific uncertainty. These uncertainties affect the process they are used for, thereby making the intermediate parameters such as damage rates also uncertain. Starting values are derived the land use map, corresponding land values, the depth-damage functions and the Digital Elevation Model. The first three terms can be subdivided into corresponding uncertainties for crops, fish ponds and dwellings.

Uncertainty in economic loss of life

The propagations of uncertainties in the estimation of economic loss of life is similar to that of the material damages, since it is based on the same estimation process.The flooded land is however substituted with the exposed population and the flow diagram is extent with the determination of this factor, as is depicted in Figure 5.2 The determination of the exposed population is based on shelter/evacuation rate and population densities, which are both uncertain.

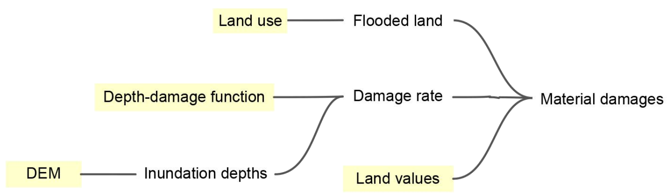


Figure 5.1: *Propagation of uncertainty in the estimation of material damages*

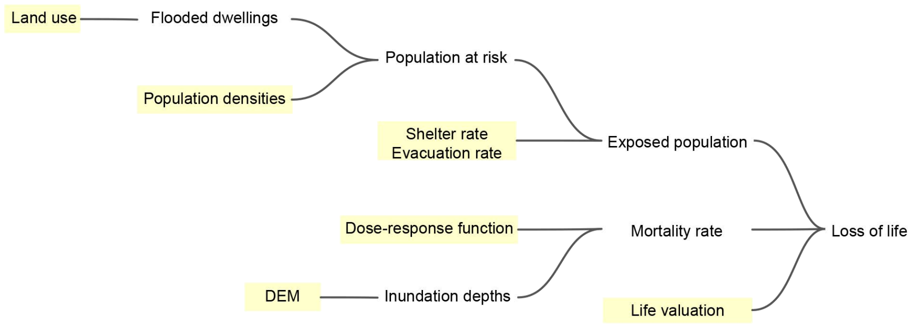


Figure 5.2: *Propagation of uncertainty in the estimation of economic loss of life*

Processing the uncertainties

Both the material damages and the loss of life have been determined in QGis with fixed values of the used variables and functions, as given in Chapter 3. The subsequent economic optimisation with these fixed parameters is presented in Chapter 4. The goal of the uncertainty analysis is to change the used variables and functions into distributions that depict the uncertainty around a specific parameter. This cannot be processed in QGis. Fortunately, another method is possible that approximates the values for material damage and loss of life derived from QGis very well.

The other method works as follows. What is done in QGis is simply the multiplication of maximum land use values and a specific damage rate per raster cell. This damage rate is based on the inundation depths and susceptibility (the depth-damage or dose-response functions). The other method is to extract the number of flooded cells and average inundation depths per land use type and per scenario from QGis. An approximation of the damages can now be made by the multiplication of the flooded cells with the maximum land use values and the damage rate that corresponds to the average depth, as derived from the corresponding depth-damage functions. The calculated values will deviate from the values derived in QGis, since it reduces the 2D schematisation of the environment to working with average values. However, the error is small. If the derived values for the different land use type damages and loss of life are used as input for the optimisation model in Matlab, the same optimal design specifications will return as determined in Chapters 4.2 and 4.3. A comparison is made for the full multi layer flood design (dike, poles and shelters) and the differences turned out to be minor: the changes between the QGis model and the calculations from the new method which works with average values are -1.3% for the minimum total costs, 0% for the investments (since the design specifications are the same), +3.8% for the risk reduction and +3.8% for the profitability index.

Since the differences are small, this new method can be used to determine the material damages and the loss of life. Contrary to QGis, this enables it to work with uncertainty in the used variables instead of single parameters. By use of a Monte Carlo analysis the uncertainty in damages can be found that will be used in the last part of the uncertainty propagation.

Uncertainty in design specifications

Now that the uncertainty in material damages and loss of life can be derived, the process continues with the propagation of uncertainty towards the design specifications, as presented in Figure 5.3. The material damages, loss of life and their uncertainties are input parameters for the optimisation model. In this model some other uncertain parameters have been used: the probability distribution, the effect of measures, the measure investment costs and the discount rate. The Monte Carlo analysis will determine how robust the design specifications are to uncertainty in the used variables and functions.

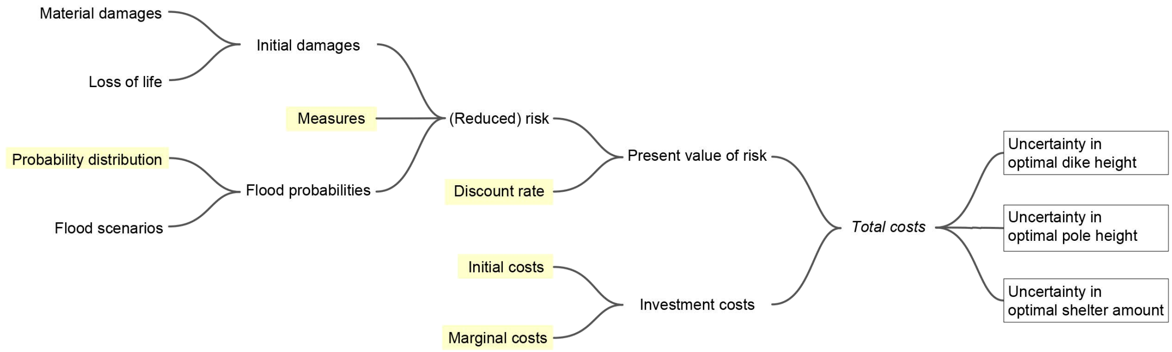


Figure 5.3: *Propagation of uncertainty in the estimation of design specifications*

5.1.2. Other sources of uncertainty

Uncertain size of budget

In the optimisation calculations an unlimited budget was assumed. If the available budget is lower than the investment costs needed for the optimal design, the budget might affect these optimal specifications. It needs to be investigated whether this only influences the specifications or also the optimal combination of measures.

Uncertain future

Whether knowledge uncertainty is included in the calculations, it still only represents the uncertainty in a stationary situation. There are however two main drivers of change in the future: climate change and land use change. Climate change might lead to increased flood probabilities, due to increased precipitation. Furthermore, the land use might change. This can happen independent on the flood management system, but a safer feeling due to risk reduction measures might also increase the population that lives in the area in the future.

Model uncertainty

More difficult to quantify is the uncertainty in the used models. The models are simplifications of the reality and might therefore lead to differences between the real situation and the model. These models include amongst others the inundation mapping, the (linear) cost functions and the effect of shelters. If possible, model uncertainties are included in the quantified uncertainty analysis. Others, such as the mapping of inundations and the discrete set of flood events, can only be assessed qualitatively.

5.2. Quantification of epistemic uncertainty

The epistemic uncertainty in the used variables needs to be quantified in order to quantify the effect on the ultimate design specifications. In the flow diagrams of Figure 5.1, 5.2 and 5.3 all input variables have been accented yellow. Most of the reasoning behind the quantification of their uncertainty can be found in Appendix E. An overview of the results is given in the second part of this section. The quantification of epistemic uncertainty around the Gumbel probability of exceedance distribution is not based on reasoning alone. The uncertainty bounds around the flood probabilities are derived with statistical calculations. Due to its prominent position in the flood risk analysis, this process is given here in the main report.

5.2.1. Uncertainty in the Gumbel distribution

At the start of the flood risk analysis, the following Gumbel distribution has been derived to estimate the probabilities of exceedance for specific water levels:

$$P_{exc}^{PoT}(h) = -0.74 * e^{-e^{-\frac{h-734.29}{23.90}}} + 0.74 \tag{5.1}$$

This distribution includes two sources of knowledge uncertainty: the choice of distribution type and the parameters for this distribution. Both determine how well the probabilities of exceedance match the measured sample data and the real life situation. An indicator for the goodness of fit if presented first, after that the uncertainty around the distribution is presented.

R-squared

A measure of goodness of fit with the measured sample data is the R^2 value, also called the coefficient of determination. It shows how well the distribution estimates the real data points. The R^2 will lie between 0 and 1, exceptions excluded, where a value of 1 corresponds to a perfect fit. The coefficient can be determined through a series of sum of squares, as given in the Equations 5.2 to 5.4 below (Eberly College of Science, n.d.). Within these equations the measurements are depicted as y_i and the average value of the measurements as $\bar{y}$. The estimators, or the values that follow from the Gumbel distribution of Equation 5.1, are given as f_i.

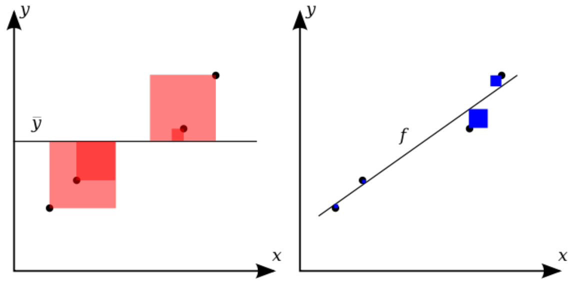


Figure 5.4: *R-squared graphically explained. Left: total sum of squares, right: residual sum of squares*
Source: Orzetto (2010)

$$SS_{total} = \sum_i (y_i - \bar{y})^2 \quad (5.2)$$

$$SS_{residual} = \sum_i (y_i - f_i)^2 \quad (5.3)$$

$$R^2 = 1 - \frac{SS_{residual}}{SS_{total}} \quad (5.4)$$

What is actually done while computing the R^2 is depicted in Figure 5.4. The total sum of squares is proportional to the variance of the data, so the deviation of the measured variables to its mean value. The higher the deviation around its mean value, the higher the total sum of squares. The residual sum of squares computes the squares between the measured and estimated data points. If the fit between the estimators and the measured data increases, the R^2 gets closer to 1. For the Peak over Threshold distribution of Equation 5.1, the R^2 amounts 0.915, meaning that 91.5% of the variance of the data can be explained by the Gumbel distribution (Eberly College of Science, n.d.). The R^2 is most valuable for the comparison between different models, such as distributions with different functions or parameters. Although value of 0.915 cannot be benchmarked to other options in this case, it is close to 1. Furthermore, the p-value, corresponding to the probability of the hypothesis that the Gumbel distribution is not correct in predicting the water levels, is close to zero and therefore significant. Combining the high R^2 and low p-value, the Gumbel distribution is seen as a good fit.

In this research, the determination of the Gumbel parameters was conducted by the Method of Moments. The ultimate choice of distribution and its parameters for the probabilities of exceedance could also have been based on the residual sum of squares. Multiple combinations can be explored to minimize the residual sum of squares, or maximize the value of R^2. In this research, such optimisation was not used. The choice for distribution type was made on the knowledge that river maxima are often best described by a Gumbel distribution, the determination of the parameters was done by the Method of Moments.

Confidence intervals

Although the R^2 of the used distribution is high, it is not a perfect fit and therefore uncertainty is present. This is a result of the fact that the derived Gumbel distribution is based on observed data. From a statistical point of view, the size of this sample is not very large: only 31 annual maxima. To include the knowledge uncertainty, so called confidence intervals with a corresponding probability can be constructed. This allows for confidence statements about uncertain parameters. To be able to construct such intervals, a measurement of uncertainty in the estimator is needed: the standard error SE. The standard error is related to the standard deviation, but not the same. As known, the standard deviation depicts the dispersion of individual observations around the mean value of the population (in this case the population refers to river water levels) and thereby indicates the variability in the individual observations. The standard error depicts the dispersion of sample means around the population means, thereby showing the variability of the estimator. When different sets of samples (in this case samples refer to water level measurements) are drawn from the same population, these set would have different values of sample means. This implies that there is a distribution of sampled means. This distribution again has its own mean and deviation (Weisstein, n.d.). Now, the relation between standard deviation and standard error is in general the following:

$$SE = \frac{\sigma}{\sqrt{n}} \tag{5.5}$$

From this equation, it can be derived that with increasing sample size n the standard error decreases. This also follows from the definition of the standard error: if the sample size increases, the estimate of the population mean will improve. Put simply and related to the topic of this research: when more river measurements are performed, the estimation of river water levels will improve.

Back to theory. The relation between the estimated mean and its standard error is often assumed to be standard normally distributed when the sample size is large. The classic bell shape of the standard normal distribution is depicted in Figure 5.5. If now an ϵ% confidence statement for the estimated value is asked, the critical values z_{1-p} and z_p need to be found so that the highlighted area in Figure 5.5 covers ϵ% of the total area. In general the value of $\alpha = 1 - \epsilon$ is equally distributed over the left and right tail of the distribution, where α represent the remaining area within the tails. Due to the symmetry of the standard normal distribution z_{1-p} is the same as $-z_p$ (Dekking et al., 2005). This reduces the graphical explanation of the above to solving the following for the critical value z_p:

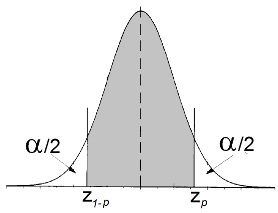


Figure 5.5: *Critical values on the standard normal distribution*

$$P(Z \geq z_p) = \alpha/2 \tag{5.6}$$

The corresponding critical value of the standard normal distribution can be found in tables or from built in functions of mathematical software such as Microsoft Excel and Matlab. Now, multiplying these critical values with the standard error and adding this to the mean estimate results in the lower and upper limit for the estimated value with a confidence level of ϵ%. In equation form this looks like the following:

$$x_{l.l.} = \overline{x} - z_{\alpha/2} \cdot SE \tag{5.7}$$

$$x_{u.l.} = \overline{x} + z_{\alpha/2} \cdot SE \tag{5.8}$$

The current situation is however slightly more complicated. First of all, the standard deviation of the population is not exactly known. At best an estimation of the standard deviation of the river water levels can be given based on the samples. The standard deviation of the measurements is not called σ, but s. The relation between (estimated) standard deviation and standard error is also not as simple as in 5.5. For a Gumbel distribution whose parameters are estimated by the Method of Moments, the standard error for the water levels for a given probability is defined as (TUH-Harburg, n.d.):

$$SE_{Gumbel} = \frac{s_x}{\sqrt{n}}\sqrt{1 + 1.14K_p + 1.1K_p^2} \tag{5.9}$$

$$K_p = \frac{\sqrt{6}}{\pi} \cdot (-ln(-ln\,P)) - 0.45 \tag{5.10}$$

The standard error is now dependent on the derived probability of exceedance. The standard error is smallest around the mean value of the measured water levels (748cm +MSL) and diverges as it moves away from this mean value. Furthermore, due to its small sample size, the assumption that the uncertainty in the estimated values is normally distributed is not valid any more. As an alternative the Student-t distribution is used, a distribution that plays a role in statistics when the standard deviation is unknown and the sample size is small. The Student-t distribution its only parameter is the sample size.

Its shape is comparable to the standard normal distribution, but with heavier tails. This means that the values far from the mean still have significant probabilities of occurrence. The more the sample size increases, the more the distribution matches the normal distribution (Dekking et al., 2005). As with the standard normal distribution, its values can be found in tables or is covered in mathematical software. Input values are the confidence interval that is asked for and the degrees of freedom, which is defined as the sample size minus 1. The corresponding equation for the confidence interval now becomes:

$$x_{l.l.} = \overline{x} - t_{\alpha/2} \cdot SE_{Gumbel} \tag{5.11}$$

$$x_{u.l.} = \overline{x} + t_{\alpha/2} \cdot SE_{Gumbel} \tag{5.12}$$

Figure 5.6 displays the estimated Gumbel distribution as it has been derived earlier together with the measured data and several confidence intervals. If a statement has to be done with a higher confidence, the interval between the boundaries becomes larger. In this figure only three confidence intervals are drawn: 70%, 90% and 99%. For the Monte Carlo analysis, a full distribution is needed for each estimated value of the probability of exceedance. Around the water level of 850cm +MSL such a distribution is sketched. This distribution can be determined by calculating Equations 5.11 and 5.12 for all possible values of α.

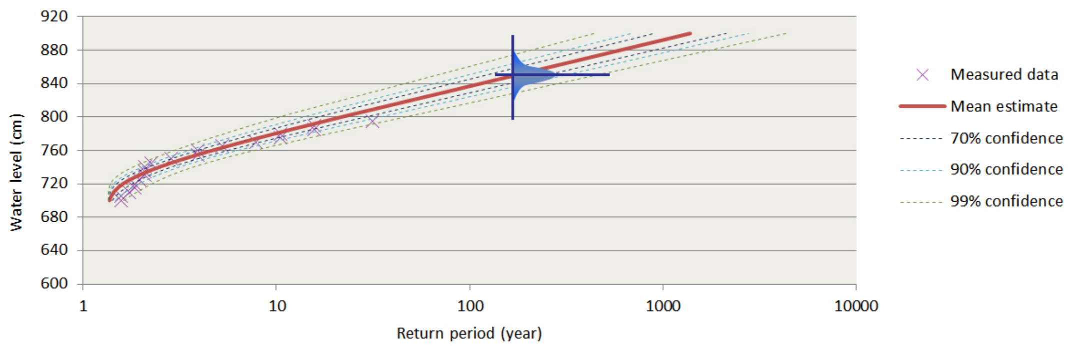
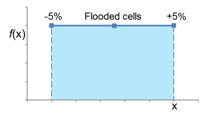
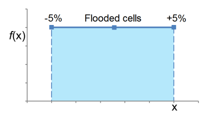


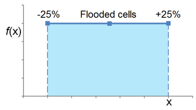
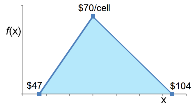
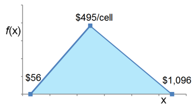
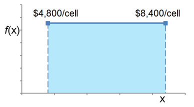
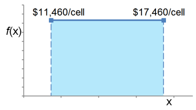
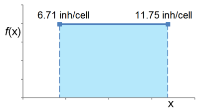
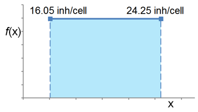
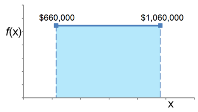
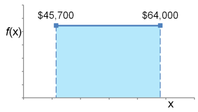
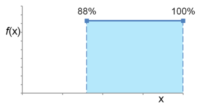
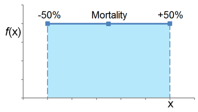
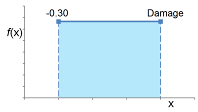
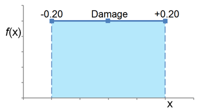
Figure 5.6: *Measured Nyaungdon water levels plotted against their return periods, together with the extreme value analysis distribution of Eq. 5.1 and its confidence intervals*

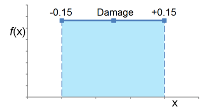
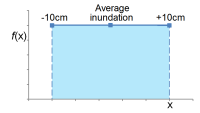
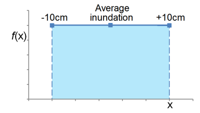
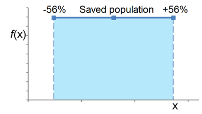
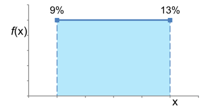
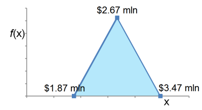
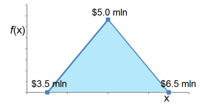
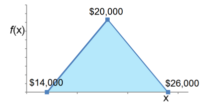
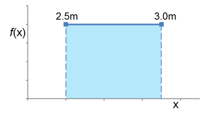
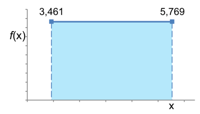
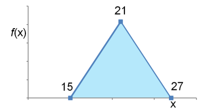
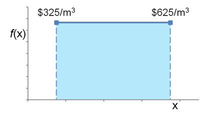
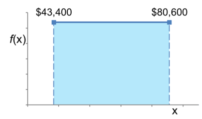
5.2.2. Overview of uncertainty quantifications

The distributions to work with in the Monte Carlo analysis are given in Table 5.1. The different uncertainties are divided into different items and sub items. Their sources of uncertainty are shortly depicted in italic per sub item. An extensive reasoning behind the quantification of the uncertainties can be found in Appendix E. Most of the parameters have a uniform distribution, meaning that all values between the lower and upper boundary are equally likely to happen. The triangular distribution is used for parameters that have a mean value that is more likely than the other values. The advantage of using a triangular distribution over a normal distribution for such cases, is that the triangular distribution has clear boundaries and will therefore not reach negative values. If possible, the value that is used so far is depicted in the table as well. If the parameter is constructed from a set of values or a function, the entry is left blank.

Table 5.1: *Overview of uncertainties*

Item	Sub item	Single parameter	Distribution
Land use	Flooded 'Crops' cells *Difference between satellite image and land use map*	-	
	Flooded 'Fish ponds' cells *Difference between satellite image and land use map*	-	

	Flooded 'Built up' cells *Difference between satellite image and land use map*	-	
Land values	Cell 'Crops' value *Production costs, yield, rice price*	$70/cell	
	Cell 'Fish ponds' value *Yield, fish price*	$495/cell	
	Cell 'Built up' value *Houses per raster cell*	$6,600/cell	
	Cell 'HD Built up' value *Houses per raster cell*	$14,460/cell	
Population density	Normal density *Houses per raster cell*	9.23 inh/cell	
	HD density *Houses per raster cell*	20.25/cell	
Life valuation	Behavioural valuation *Willingness to pay*	$860,000	
	Non-behavioural valuation *Discount rate*	$58,000	
Shelter/evacuation rate	- *Deviation within historic events*	95.8%	
Dose-response function	- *Deviation within historic events*	-	
Depth-damage function	Damage function 'Crops' *Range within existing functions*	-	
	Damage function 'Fish ponds' *Not substantiated*	-	

	Damage function ’Dwellings’ *Range within existing functions*	-	
DEM	Average inundation depth *1m vertical resolution*	-	
	Adapted average inundation *1m vertical resolution, built up elevation*	-	
Influence of measures	Saved population by shelters *Population at risk, shelter/evacuation rate, mortality rate*	-	
Discount rate	- *Range in World Bank projects*	10%	
Initial costs	Initial ’Dike heightening’ costs *Not substantiated*	$2.67 million	
	Initial ’Pole heightening’ costs *Not substantiated*	$5.0 million	
	Initial ’Shelter construction’ costs *Not substantiated*	$20,000	
Marginal costs	Current dike height *Unknown dike cross sections*	3.0m	
	Houses at risk *See ’land use’*	4615	
	Poles per house *Type of houses present, not further substantiated*	21	
	Wooden pole costs *Range in wood costs*	$475/m^3	
	Costs per shelter *Not substantiated*	$62,000	

It can be noticed that the life valuation and inundation depth are mentioned twice. Both parameters are treated in another way than the rest of the variables or functions, namely as different set ups. In the flood risk analysis and also the optimisation process the decision has been made to work with the non-behavioural macro-economic valuation of statistical life instead of the behavioural approach that is based on willingness to pay. It is however a matter of choice which value is used in flood risk and optimisation analyses. The uncertainty analysis will therefore both be run with the non-behavioural valuation as the behavioural. The behavioural valuation is quantified based on comparison to the Dutch value, as is described in Appendix E. This led to a mean value of $660,000. However, since this value should be determined based on the risk perception of the citizens, the uncertainty is significant around this value.
The other set up is needed due to the Digital Elevation Model. The presumption is that it embeds an error around elevated objects, since the DEM is constructed based on the reflection of signals send from the SRTM satellite. If this signals reflect on objects such as trees or the roofs of houses, it overestimates the ground elevation by measuring the elevation of this objects. Another set up is used in the uncertainty analyses where the built up cells have an increased inundation of 3m, since this is a reasonable roof height. A fourth set up is based on the combination of both the behavioural valuation of life as the adapted built up inundation depths. The four set ups for the uncertainty analyses are therefore:

1. *Set up 1: Original*. This set up works with the original parameters and their uncertainty. This means it is based on the non-behavioural macro-economic valuation of life and the original DEM.

2. *Set up 2: Behavioural VoSL*. In this set up of the uncertainty analysis the behavioural valuation of life is used, which is much higher than the non-behavioural valuation.

3. *Set up 3: Adapted DEM*. To counteract the error in the Digital Elevation Model around elevated objects, this set up works with an increased average flood depth of built up cells by 3m.

4. *Set up 4: Behavioural VoSL and Adapted DEM*. Since it is possible that both the behavioural valuation of life will be used in the flood risk analysis and the digital elevation model turns out to be incorrect, the combination of the two set ups is also used.

5.3. Sensitivity Analysis

Before turning to the full Monte Carlo analysis, a sensitivity analysis is performed. Such an analysis has multiple purposes. Since a Monte Carlo analysis will be conducted hereafter, the main goal is to find out to which uncertainties the system is most sensitive. Or in other words, which uncertainties have more effect on the optimal design specifications than others. This leads to more understanding of the system. Another important result of knowing the sensitivity to the different parameters is that it shows which variables or functions can best be investigated more to reduce the uncertainty in the ultimate outcomes. After all, reducing the knowledge uncertainty by extra research or measurements of parameters that hardly have any influence is not efficient.
Moreover, it shows how robust the system is to the presence of uncertainties in the first place. The current sensitivity analysis is conducted by the 'one-at-a-time' approach. This means that single variables are changed while the others remain at their (mean) baseline value. This change can affect the choice of (combination of) measures and also the values of minimum total costs, corresponding optimal investments, risk reduction and profitability index. The analysis is twofold: first the original set up will be used to investigate how the change in parameters change the minimum total costs, investments, risk reduction and profitability index. Second, their effect on the minimum total costs for all four set ups will be compared.

5.3.1. Sensitivity within the original set up

In this subsection, the effect of uncertainty in the different parameters are elaborated. The optimisation calculation of the full multi layer safety system is hereby used: the combination dike heightening, pole heightening and construction of shelters. Although it turned out not to be likely that this is the most efficient combination of measures, it is the most complete model that includes all the used variables. Corresponding reference values are the total minimum costs of $15,859,000, optimal investments of $9,716,200, risk reduction of $12,898,000 and profitability index of 1.327. These values belong to the calculated approximations based on flooded cells combined with average inundation depths and not to the values from the model in QGis, which differ slightly. Otherwise a change with the reference values would always be present, even as the parameter has no effect on the design values.

Figure 5.7 shows four circle diagrams. They present the changes in percentages compared to the reference values. They depict the changes if the left boundary values of the uncertainty distributions are run through the system one at the time. All parameters are therefore smaller than the mean values used before. If the right boundary conditions are used it would show more or less the same but mirrored results, as the deviation from the mean values is often equal on both sides. An extra note has to be given to the probability of exceedance distribution. Its boundary corresponds to a tail probability of the Student-t distribution of 2%, meaning that for a specific water level the corresponding probability of exceedance has a 98% chance of being smaller than this value. The returned probabilities of exceedance are therefore larger than the best estimated values used before.

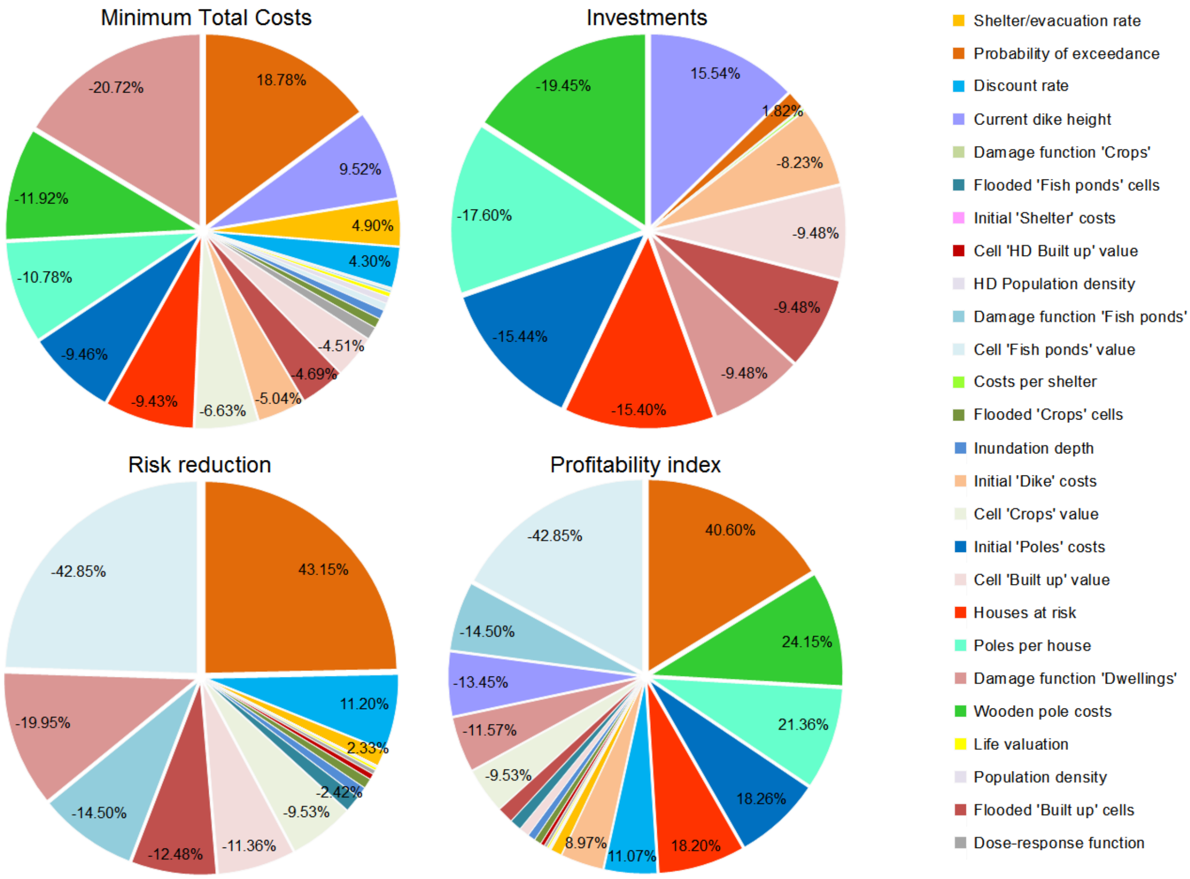


Figure 5.7: *Sensitivity to uncertainties within the original set up on minimum total costs, investments, risk reduction and profitability index*

Minimum Total Costs

Looking at the Total Costs circle diagram, it can instantly be noticed that not all values have the same size of effect. Furthermore, some parameters lead to an increase in minimum total costs while most lead to a decrease in total costs. Positive effects are only there for the probability of exceedance, current dike height, shelter/evacuation rate and discount rate. It is logical that these have a positive relation: increased probability leads to higher risks and therefore also higher total costs, if the optimal design values stay more or less the same (see the next paragraph about the Investments). Moreover, if the current dike height is lower than expected, more investments need to be made to return to the same optimal dike height. There are however large differences in sensitivity. Most sensitive is the system to changes in the probability of exceedance: changing the probability resulted in an increase of total

costs of almost 19%.
The largest negative effect corresponds to the damage function of dwellings. Apparently a decrease in 0.15 damage results in a change of minimum total costs comparable in size to the effect of the uncertainty in the probability of exceedance. This is probably due to the high maximum value of houses. Other significant influences are the costs of wooden poles, the number of poles per house, the initial costs of placing houses on poles and the number of houses at risk. Apparently all the investment components of pole heightening have a large effect. On the contrary, elements that hardly affect the minimum total costs with their uncertainty are the population densities, life valuation and dose-response function. It looks like, although the uncertainties are significant, the valuation of life is too low to have effect.

Investments
With regards to the investments, all effects are negative, except for the current dike height, probability of exceedance and discount rate. The latter two do only have a small effect on the optimal investments. The reason for this is that their individual uncertainty hardly changes the optimal design specifications of 1.0m dike heightening, 0.5m poles and 1 shelter. A lot of other parameters do not change these specifications on their own at all. Significant negative values are again the components related to the costs of houses on poles. However, their individual uncertainties have not changed the optimal design specifications. The change in the order of 15-20% can therefore only be dedicated to a large uncertainty in pole investment costs.

Risk reduction
Looking at the circle diagram of the risk reduction in the optimal situation, it can be noted that the sensitivity effects are dominated by the uncertainty in fish ponds value and again the probability of exceedance. With a higher fish pond value, a larger value of risk can be reduced by the same dike heightening. Although this is true for all the land use types in the diked part of the scope area, the sensitivity to the others is much less. This has two reasons. First, the uncertainty in fish ponds value is much larger compared to the others, which can be estimated with smaller uncertainty. Second, almost all of the fish ponds get inundated in this model of the area, compared to only parts of the crops and dwellings. Strangely enough did this increased fish pond value not affect the optimal design specifications of 1.0m dike heightening, 0.5m poles and 1 shelter. Another large negative effect is again due to the damage function of dwellings.
With a higher probability of exceedance the optimal dike heightening increased to 1.16m. If the probabilities increase, also the risk increases, as risk is the product of probability and consequences. With an almost equal dike heightening, the risk reduction is also much more compared to the reference situation. Important absentees are the cost components of pole heightening. The uncertainty in costs was not sufficient to change the design specifications and therefore their effect on risk reduction was zero.

Profitability index
As the profitability index is the division of risk reduction and investments, the pattern of its circle diagram has elements of both components. Again the fish ponds value and probability of exceedance have large effects, corresponding to a high sensitivity for the uncertainty in these values. Also the elements of pole heightening costs return. Although their individual effect on risk reduction was zero, a decrease in these elements led to a significant decrease in investments and therefore an increase in profitability index.

5.3.2. Sensitivity over different set ups

Where in the previous subsection the sensitivity to minimum total costs, optimal investments, risk reduction and profitability index was explored for the original set up, this subsection compares the effects on uncertainty between the different set ups. As reference values for the circle diagrams are the baseline situations where only the valuation of life and/or the inundation depth has increased and the rest of the variables of functions are still kept at their original mean values. Only the minimum total costs are visualized in this subsection. Deviation in minimum total costs will probably lead to most deviations in optimal measure combinations and optimal design specifications as well. In the upper left circle diagram of Figure 5.8, the original set up is presented again. In the following paragraphs this will be compared to the other set ups.

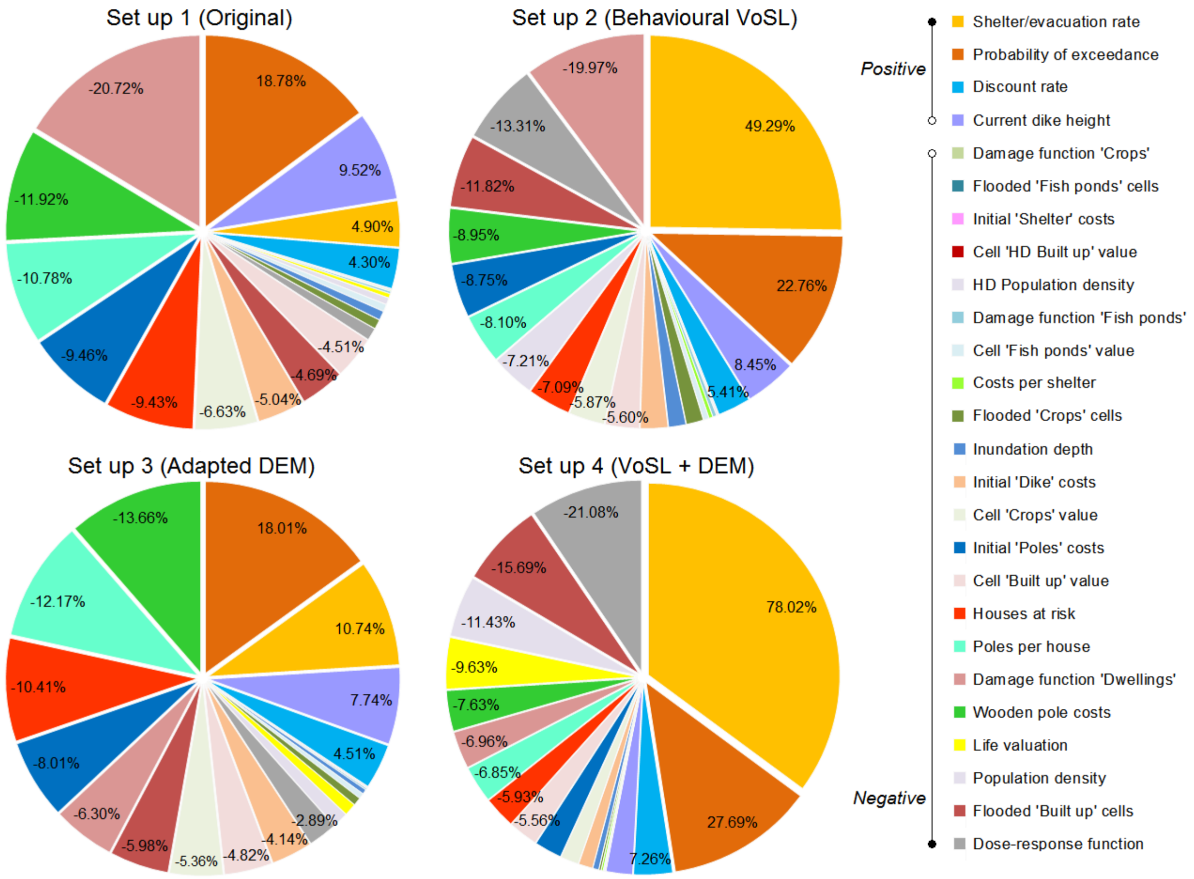


Figure 5.8: *Sensitivity comparison between the different set ups on minimal total costs*

Set up 2: Behavioural VoSL

Recall from the previous subsection that the components related to loss of life had small effects on the total minimum costs. After all, the macro-economic valuation of life is not high and combined with a small number of fatalities do the changes in these values also have little effect. In the second set up is the valuation of life significantly increased. This changes the circle diagram completely. The minimum total costs increase by almost 50% if the shelter/evacuation rate reduces from 95.6% to 88% while all other parameters remain the same. Also the uncertainty in dose-response function becomes more present. The total minimum costs are sensitive to the (large) uncertainties related loss of life now that the valuation of life has increased. This phenomenon will also be visible in the Monte Carlo analysis later on.

The parameters that the model was most sensitive for in the original set up are still present next to the uncertainties related to loss of life: the damage function of the dwellings, current dike height, the probability of exceedance and components of pole investment costs. Although not depicted here, these elements would also dominate the investments circle diagram. Higher sensitivity to loss of life increases the optimal number of shelters, most times the optimal number of shelters was 6. However, due to their low investment costs the effect on investments is still small. The pattern within the risk reduction is also comparable to the original set up, only the evacuation/rate has become an extra dominant element in the circle. This is not surprising, as a significant amount of risk can now be reduced by reducing the number of fatalities by means of shelters.

Set up 3: Adapted DEM

A significant effect of the larger inundation depth at built up areas is that the optimal pole height has increased in most situations to 1.5m. Also the base value of minimum total costs for this set up increased to $19,514,000. Most important difference is the reduction in sensitivity to the damage function of dwellings compared to the original set up. However, this can be clarified: a decline of 0.15 in

damage is of more influence when the damage ratio is still low compared to the situation where the damage is already high due to the higher inundation depth. Another change is the increased effect of the shelter/evacuation rate. This can be explained by the increased mortality rate due to the increased inundation depths. Although the valuation of life is still relatively low, it becomes significant when the estimated number of fatalities rises.
Interestingly, the effect of the damage function of dwellings becomes more important in the investments and risk reduction diagrams, contrary to its minor effect in minimum total costs. Compared to the original set up, the baseline value of optimal investments are already $2 million higher. Changes in the damage function mostly result in extra pole heightening, which have a significant contribution to the investments made. The calculations remain sensitive to changes in the components of the pole investments costs for this same reason.

Set up 4: Behavioural VoSL and Adapted DEM
In this fourth set up the increased valuation of life and the larger inundations at built up areas are combined. This has led to an optimal value of total costs of over $30 million, which is almost double the size of the original set up. It can also be seen in the last circle diagram that the loss of life related parameters become even more important, in the sense that the calculations become highly sensitive to changes in these values. The uncertainty in the behavioural valuation of life can lead to an increase in minimum total costs of almost 80%. The dose-response function claims a third position in the power to affect the minimum total costs, only slightly under the probability of exceedance. Also the uncertainty in flooded built up cells becomes significant. All in all, if there would be worked with the larger value of valuation of life and an adapted version of the DEM is used, the calculations become more dependent on the economic loss of life. This also implies that the large uncertainties that are present in the estimation of loss of life become more important. This is something that will be seen in the Monte Carlo analysis as well.

5.4. Monte Carlo Analysis

Now that the sensitivity to the different uncertainties in the optimisation calculations have been explored, the full Monte Carlo analysis can be conducted. The variables within the Matlab scripts have been replaced with the uncertainty distributions from Table 5.1 and the probability of exceedance distribution is extended to include its uncertainties. The idea behind the Monte Carlo analysis is that a random number is picked from the individual uncertainty distributions and the optimisation calculations are performed. By doing this numerous of times, a spread will arise in the results of minimum total costs, optimal investments, risk reduction, profitability index and measure specifications. A choice has therefore to be made on the number of iterations. The more iterations, the more reliable the outcomes, but the longer the computations will take. When in this case the number of iterations is set at 10,000, the spread in computed values follows a smooth shape without any undefined peaks.

A lot of information could be gathered from the Monte Carlo analysis. For each combination of measures the spread/uncertainty in optimal design specifications can be derived, including the corresponding uncertainty in total costs, investments, risk reduction and profitability. This means that at least 40 graphs could be depicted, showing the results of including uncertainties. When the other three set ups besides the original set up are ran in the Monte Carlo analysis as well, this increases to 120 graphs. Such an overview would however not lead to any conclusions. The results are therefore analysed in two steps. First the robustness of the choice of combination of measures is explored for the four different set ups. After that the robustness of the design specifications of the optimal combination of measures is analysed.

5.4.1. Robustness of optimal combination of measures

The first step is two analyse how robust the choice for the optimal combination of measures is. Without taken the uncertainties in account, the option of dike heightening whether or not combined with shelters led to the lowest total costs. In the next paragraphs, the total costs of all possible combination of measures are explored for the four set ups. Recall that dike heightening corresponds to layer 1, pole heightening to layer 2 and shelters to layer 3. Possible combinations are therefore 1-2, 1-3, 2-3 and 1-2-3. This makes the elaborations in the following more concise.

Set up 1: Original situation
Looking back at the sensitivity of the calculations to its input parameters, the probability of exceedance and damage function of the dwellings both can have effects up to around 20% of the minimum total costs. A significant uncertainty is therefore expected in all the combinations of measures. Other dominant parameters were the components related to the costs of houses on poles. These are only of influence on the (combination of) measure(s) that includes poles. Extra uncertainty is therefore expected in their minimum total costs. The influence of loss of life related components remained low. The total costs of combinations of measures that include shelters will therefore remain almost similar to those without. This means that measure combination 1-3 remains comparable to layer 1 alone, 2-3 is almost equal to layer 2 alone, 1-2-3 is similar to 1-2 and layer 3 alone remains comparable to doing nothing. In Figure 5.9 the above can be verified. The picture shows the different combinations of measures and their deviation from its mean value in optimal total costs, depicted as total costs versus its probability.

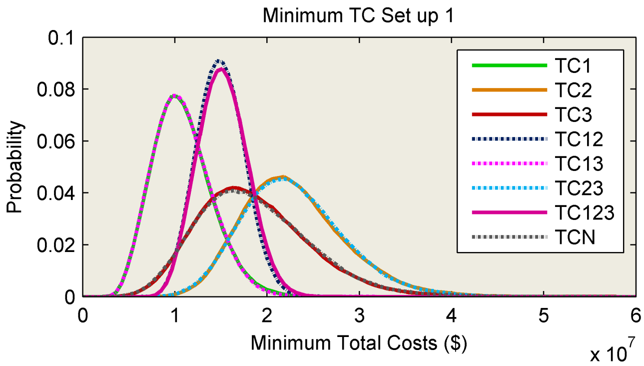


Figure 5.9: *Monte Carlo results of minimum TC for set up 1*

It can be noted that the spread in lowest total costs in the case of doing nothing already lies between $5 and $40 million, implying that the estimation of the present value of the risk is also heavily prone to the uncertainties in the used parameters. This spread is therefore also present in the option of placing shelters alone. The large expected uncertainty in the optimal total costs of layer 2 and the combination 2-3 are clearly visible. Moreover, these options result in higher total costs than doing nothing most of the times. The spread for the measures of dike heightening alone and its combinations with poles and shelters are more compact. Apparently a lot of uncertainty is taken away if some of the risk is prevented by dike heightening.
The question is whether the choice for dike heightening alone (and therefore dike heightening with shelters too) is as robust as it looked like when there was worked with single values. The lowest minimum total costs are still achieved by this measure, as can be seen from its location on the most left side of the costs axis in Figure 5.9. However, looking at the probabilities of option 1-2 and 1-2-3, combing dike heightening with poles are not very unlikely to achieve the lowest total costs.

Set up 2: Behavioural VoSL
The figure gets more chaotic when there will be worked with a higher valuation of life, as can be seen in Figure 5.10, which depicts the minimum total costs for set up 2. The uncertainty in minimum total costs for all (combinations) of measures increase, especially for those that exclude layer 1. Their peaks become less distinctive, meaning that the possible results are more scattered.
Contrary to the original set up, combining options with layer 3 clearly leads to deviation from the curves without this layer. The difference in option 1-3 is to such an extent that there are sufficient possibilities that combining shelters with dike heightening becomes more efficient than dike heightening alone. Placing shelters alone also has a peak with lower total costs compared to doing nothing, but the uncertainty is large. Layer 2 is still likely to result in higher total costs than doing nothing, as was also the case in the original set up. However, combining layer 2 and 3 has a good possibility of resulting in comparable total costs as doing nothing. Looking at the probabilities and the shape of the spreads it is most likely in this set up that dike heightening combined with shelters has the highest chance of being the optimal solution, although layer 1, option 1-2 and option 1-2-3 are close.

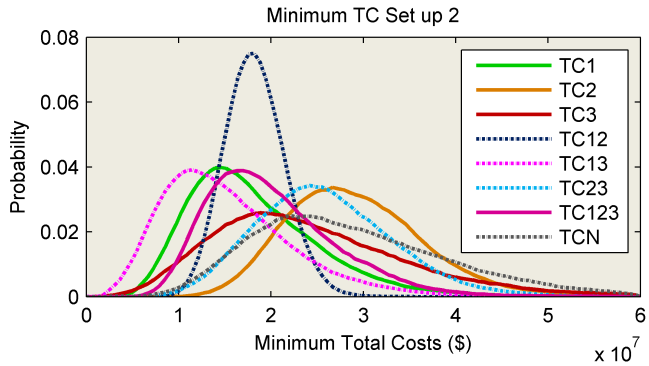


Figure 5.10: *Monte Carlo results of minimum TC for set up 2*

Set up 3: Adapted DEM

When the built up areas are given an extra average inundation of 3m, dike and pole heightening together (whether or not with shelters) get almost as likely to be most efficient as dike heightening alone. Looking at the higher peak in Figure 5.11, the uncertainty is also smaller for these options. After all, dike heightening can only reduce the risk (and its uncertainty) for the diked area. Combining it with poles enables for risk reduction over the total area, thereby making the corresponding uncertainties also become obsolete. The individual measure of poles alone or combining it with shelters is apparently too expensive to have a chance to be the most efficient option, as was also the case for the previous two set ups.

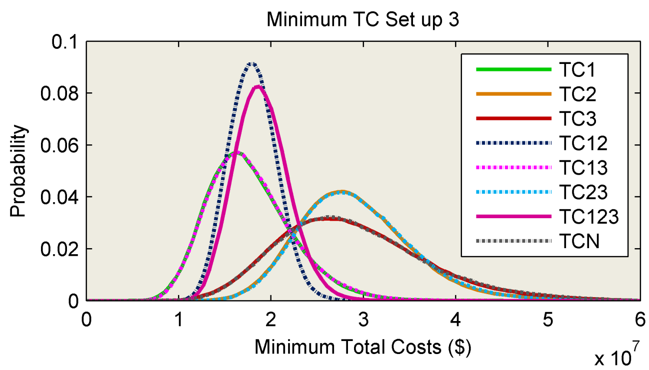


Figure 5.11: *Monte Carlo results of minimum TC for set up 3*

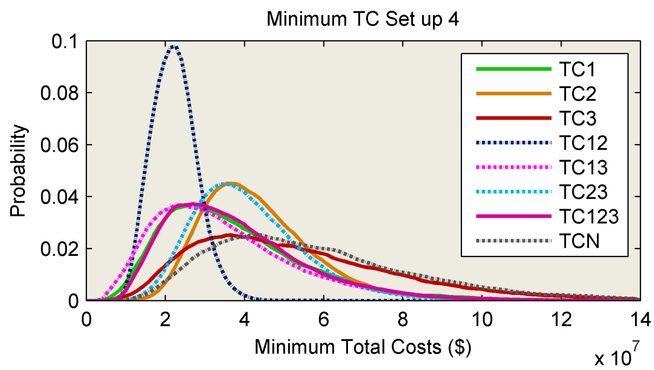


Figure 5.12: *Monte Carlo results of minimum TC for set up 4*

Set up 4: Behavioural VoSL and Adapted DEM

When there is both worked with a higher valuation of life and the built up areas are inundated more than the original DEM predicts, the uncertainties get large, as can be seen in Figure 5.12. Notice that the range of the x-axis has increased from $60 million to $140 million. The total costs of doing nothing (so the present value of the risk) extent from around $10 million to $100 million. In this set up all possible options have a peak value with lower total costs than doing nothing. Lowest total costs are found at option 1-2, layer 1, option 1-3 and options 1-3. Option 1-2 has however the highest peak value, meaning it is least uncertain. Based on the total costs alone all can be a good solution.

Comparing investment costs and profitability

In the above, the optimal total costs of the different options over the four different set ups are compared. In almost all set ups, the peak value of dike heightening had the lowest costs compared to other option. However, combining dike heightening with houses on poles and/or shelters was becoming more attractive over the different set ups. Based on the minimum total costs the choice for layer 1 is therefore not robust when uncertainty is added to the calculations, since other combinations lead to comparable values of minimum total costs. However, minimum total costs are not the only criterion. In this paragraph, the investments costs and profitability index are compared for the options 1, 1-2, 1-3 and 1-2-3 as well. The other options are not attractive based on the minimum total costs and not included in this comparison.

The pictures in Figure 5.13 compare the corresponding optimal investments for the above mentioned options for all four set ups. It can be noticed straight away that option 1-2 and option 1-2-3 require much higher investments to reach the optimal total costs compared to implementation of solely layer 1 or option 1-3. Also the uncertainty in 1-2 and 1-2-3 is large, again due to the high sensitivity to the uncertainties in the components related to the costs of placing houses on poles. The combined effect is that 1-2 and 1-2-3 are not attractive, since higher investments are needed for similar total costs. The difference between layer 1 and options 1-3 is less obvious. However, implementing only layer 1 is likely to be cheaper for all set ups. This implies that implementing layer 1 with the corresponding optimal dike height is likely to require lower investments than the optimal design specifications of layer 1-3.

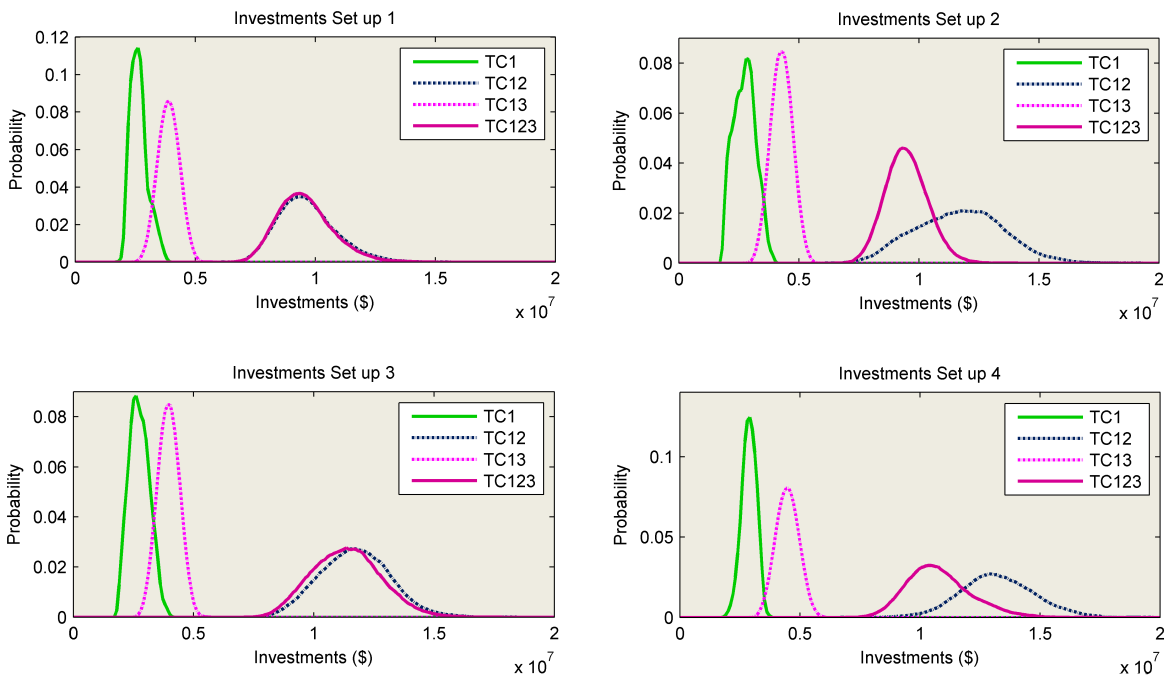


Figure 5.13: *Monte Carlo results of optimal investments for all set ups*

For the sake of completeness are the profitability indices for the mentioned options and for all set ups depicted in Figure 5.14. The same conclusions can however be drawn as was done for the investments. Options 1-2 and 1-2-3 have in general lower profitability indices than layer 1 or option 1-3, indicating that the latter two offer more value for money. The options with pole heightening also have fair probabilities of having a profitability smaller than 1, meaning that it is not a cost efficient investment. Also for the profitability index is the difference between layer 1 and option 1-3 not that large, but layer 1 alone leads in general to a higher cost-benefits ratio.

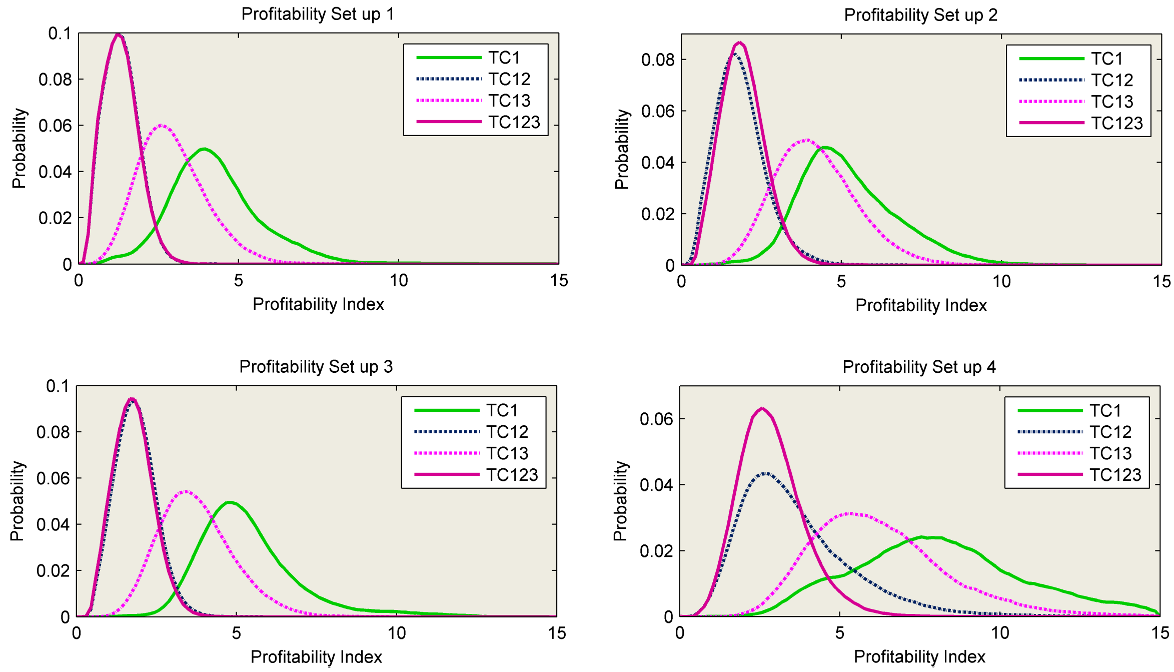


Figure 5.14: *Monte Carlo results of profitability for all set ups*

To conclude: the choice for the optimal (combinations of) measure(s) is a robust choice. This cannot be based on optimal total costs alone, but when the investments and profitability indices are compared as well, the choice for implementation of dike heightening alone becomes obvious. At second place is the combination of dike heightening combined with shelters, which has comparable total costs, required investments and profitability indices in all four set ups. The options of 1-2 and 1-2-3 can reach comparable total costs, but would require much higher investments. Although they might also be viable options, it is not logical to spend more to achieve the same results.

5.4.2. Robustness of measure specifications

Dike heightening within the four set ups

It has been shown that the measure of dike heightening alone is the most efficient option, even under uncertainties in variables and set up. Next part is to explore how robust the optimal dike heightening is. Without uncertainties, the optimal dike heightening was 1.0m. This would increase the Danger Level to 8.5m +MSL and the return period of flooding to around 171 years. Figure 5.15 shows the optimal dike heightening for all four set ups as a result of the Monte Carlo analysis.

Within the first set up 1.0m dike heightening clearly was the optimal design most of the times. Only during a small amount of times out of the 10,000 iterations was another height a better choice. Within the second set up, the choice becomes less clear. Slightly less than a third of the times was 1.1m dike heightening calculated as optimal solution. This increases a little in the third set up. Within the fourth set up is 1.5m dike heightening the most preferable option, although 1.0-1.2m still score high as well. It looks like the 1.0m dike heightening is not an obvious and robust choice when a higher valuation of life is used and the built up areas are more inundated than the DEM indicates. The question is whether this is due to the large uncertainties. The next paragraph will show that the optimal dike height is more robust than it seems to be now.

Effect of uncertainty reduction

The possibility to reduce the uncertainties around the used variables can be classified in several groups. An enumeration is presented in the following. A more extensive explanation per variable is given in Appendix E.

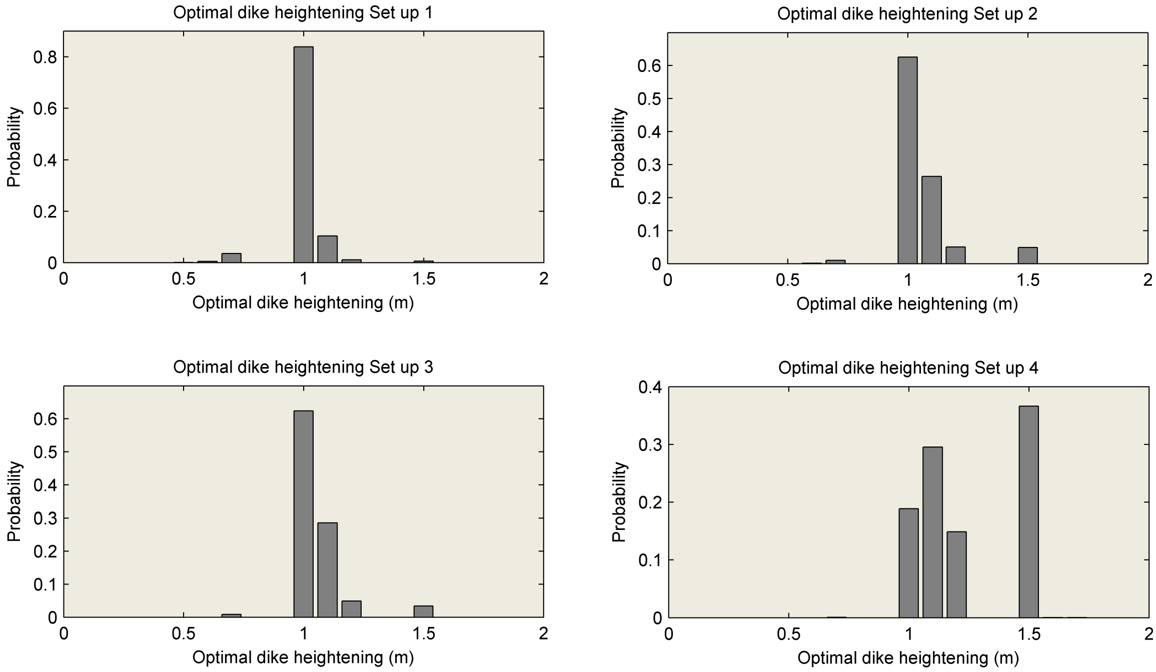


Figure 5.15: *Monte Carlo results of optimal dike heightening for all set ups*

1. *Uncertainty reduction by more extensive analysing.* Some uncertainties can simply be reduced by spending more time in analysing the variables. Gathered under this class are the land use and the population densities, which are dependent on the land use. The land use is based on satellite images, from which a land use map is constructed semi-automatic. A more extensive comparison between the satellite image and the land use map that needs to be constructed would make it more accurate.

2. *Uncertainty reduction by field work/questionnaires on site*. The uncertainties in this class can only be reduced by field work. This field work includes investigation of the natural environment, but also questionnaires or interviews among the local inhabitants. The errors in the DEM can be reduced by field work and would verify if set up 1 or set up 3 is more likely as regards to the elevation of the built up areas. Field work can also contribute to make a more profound choice for the depth-damage function of rice and dwellings, depending on the type of paddies and dwellings that are present. Interviewing the local inhabitants can be used to make a better estimation of land values, especially of the rice paddies and the fish ponds. Among them are also the local contractors that can give more insight in the investment costs. More extensive questionnaires are needed to reduce the uncertainty around the shelter/evacuation rates during a flood event. Also the effect of shelters might be better estimated this way by questioning the attractiveness of shelters. At last can the behavioural valuation of life be explored, since this is partly based on the willingness to pay.

3. *Uncertainty reduction by experiments.* Some uncertainty is present in the depth-damage functions, especially in that of the fish ponds. Experiments could be performed to evaluate the relation between inundation and damage of the fish ponds. For the rice and built up functions a lot of research is already been done and it is mostly the choice of the right function that embeds uncertainty, as is described above.

4. *Uncertainty reduction by choice*. In the end, the choice of discount rate and life valuation is mainly made by a profound decision. It is a matter of preference which rate and valuation is used, more than it is a matter of uncertainty.

5. *Difficult to reduce.* Two functions remain whose uncertainty is difficult to reduce and will therefore still be present after more research. The first is the dose-response function. More research

could in theory be done in the dose-response relation for countries such as Myanmar, based on historic flood events. However, also the used dose-response function for more developed countries embeds a lot of uncertainty due to the the high amount of outliers in the data. This uncertainty is likely to be present in more location specified dose-response functions as well. The second component is the probability of exceedance distribution. Only the yearly maxima were available to work with. Daily maxima should be available to use, which reduces the uncertainty a bit. However, more years of measurements are needed to make certain statements about the water levels corresponding to high return periods.

In theory a lot of the variables could be improved in terms of certainty. Only the dose-response function and the probability of exceedance distribution are more difficult. Also for the other variables some uncertainty will always remain. This is due to origin of the variable (for instance the depth-damage functions that are based on trendlines through data) or the inclusion of human behaviour (in for example the evacuation/shelter rate and the efficiency of shelters). The optimal dike heights for the four set ups are determined once more, but now with variables that carry an uncertainty up to ±10% or ±0.10 for the depth-damage functions. The probability of exceedance distribution and the dose-response function keep their initial uncertainty bounds. The results are comparable to the dike heights depicted in Figure 5.15. Unexpected is however that the 1.5m dike heightening has reached higher probabilities in the fourth set up than when the full uncertainties where used. The 1.5m dike heightening has reached a probability of being the optimal design of over 0.4, while the 1.0-1.2m dike heightening have decreased in size. There is a reason to clarify this, which is that the difference in minimum total costs between 1.0m and 1.5m dike heightening is small. This is visualised in Figure 5.16, where a random five out of the 10,000 curves are depicted. Between 1.0m and 1.5m the Total Costs curve is almost horizontal. Until 1.0m the risk us reducing faster than the investment costs are increasing, after 1.5m the investments costs slowly push the total costs upward. Due to the small uncertainties the calculations might one time result in 1m (or 1.1m or 1.2m) being the optimal solution and 1.5m the other time. Due to the discrete set of flood scenarios, resulting in the jumps in the total costs curve, 1.3m and 1.4m would never result in lower total costs than 1.0m or 1.5m.

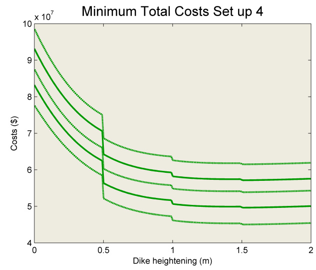


Figure 5.16: *Comparison of different Total Costs curves in set up 4*

Using the above, the choice for 1.0m dike heightening is also a robust choice. The chance that dike heightening by less than 1.0m results in lower total costs is very small. Dike heightening by more then 1.0m leads to comparable total costs. Since it hardly makes any difference between 1.0 and 1.5m, it is logical to choose the 1.0m as this needs the lowest investments. Efforts in reducing the uncertainties would in this case and this modelling of the system not give better results.

5.5. Other uncertainties

In the previous sections the knowledge uncertainty in the used parameters has been included to see its effect on the optimal design. It turned out that the already derived option of 1.0m dike heightening was robust enough to remain the best option, even when uncertainties are taken into account. This last section of the current chapter elaborates on the other uncertainties: the size of budget, the uncertain future and the model uncertainty.

5.5.1. Uncertain size of budget

The optimality calculations were performed under the assumption that there is sufficient budget to implement the measures needed to reach the minimum total costs. It might however be the case that the available budget is lower. The investment costs that are needed for reaching a Danger Level of 8.5m +MSL by means of dike heightening lie between \$3 and \$4.8 million with a most likely value of \$3.8 million (taking the current uncertainties in investment costs into account). Since the optimal design only uses one type of measure, it is logical what to do when the budget is smaller than the needed investments: heighten the dike as much as possible. Up to 1.0m dike heightening the probability of exceedance declines fast, meaning that every 10cm extra heightening results in significant risk reduction.

In the theoretical case that a combination of measures turned out to be the optimal design, the answer on how to handle budget constraints would be more difficult. Figure 5.17 depicts the risk reduction of the three possible measures (R1, R2, R3) together with their investment costs (I1, I2, I3). This is without uncertainties taken into account. The left picture shows the curves for the original set up, the right picture shows the curves for set up 2 with a higher valuation of life. First a comparison is made for the situation that the option 1-2 would be preferred and there would not be sufficient budget to implement the full design specifications of dike and pole heightening. It can be seen that the investment costs for dike heightening are lower, while it leads to more risk reduction, at least up to 1.0m of dike heightening. It would therefore be advised to start with dike heightening and continue with houses on poles, as long as the budget enables to. This is the case for both a low as a high valuation of life.

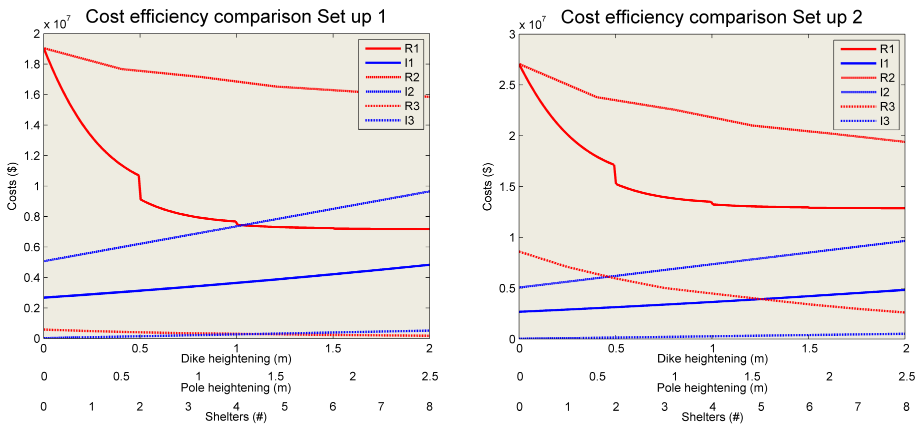


Figure 5.17: *Costs efficiency comparison for set up 1 (left) and set up 2 (right)*

The next theoretical situation is that option 1-3 is preferred, but the budget is insufficient to implement the optimal design. In set up 1 with a low valuation of life, the investment costs of shelters are significantly lower compared to dike heightening, but their effect is low as well. With a higher valuation of life a significant risk reduction can be achieved with low investments. In that case it would be wise to first investment in building shelters and only after that in dike heightening with the remaining budget. Combining the results from option 1-2 and 1-3 results in the advise that option 1-2-3 can best be implemented in the order 3-1-2, if the budget is insufficient. A final possibility is that the budget is too low for the initial investment costs of dike heightening as well. In that case the construction of shelters would be a smart investment for risk reduction, especially with a higher valuation of life.

5.5.2. Uncertain future

Although knowledge uncertainties have been included, they represented uncertainties in a static situation. Several factors might however change in the future. First, the land use might change. This can happen either way, but might also be caused by the safer situation that would be created by the dike heightening. This can lead to more built up in the diked area and the value of the dwellings might also increase. This also results in a higher population within the diked area. A safer feeling can also result in a reduction of flood preparedness, thereby increasing the number of fatalities during flood situations. Another important driver of an unsure future is climate change. Weather events are expected to become more extreme. More extreme rainfall events upstream the Ayeyarwady River can increase the flood probabilities near Nyaungdon. Both the influence of the human part as this natural part of uncertain future are elaborated below.

Human changes

Looking back at the sensitivity analysis, changes in housing related parameters such as the damage function of dwellings, the value of dwellings and the houses at risk for the loss of life estimation can have significant effects on the total minimum costs. Their future changes could have effect on the optimal combination of measures and the measure specifications in the future situation. However, the first is not very likely. The mentioned human changes would probably result in more built up area in the diked area. This does not effect the choice for houses on poles, as this is only seen as measure in the rural area. Focussing on houses on poles instead of the dike would only become less attractive than it already is.

With respect to loss of life, extra shelters may become an option, as this has always been a close call with the options of dike heightening alone. Looking at the results of the Monte Carlo analysis, which already include a lot of uncertainty, the choice for dike heightening alone is probably robust enough. This can be validated by the numerical optimisation model in Matlab. When the material damages related to dwellings and the estimation of loss of life are multiplied by two, it would still produce the same optimal design specifications. Apparently is the shape of the risk reduction curve as such, that its minimum values will remain at the same location. The main change is that the curve moves upward by the increased risk values. Only in the fourth set up, the dike heightening increases to 1.2m. However, this is comparable to the situation in Figure 5.16, where the total costs between 1.0m and 1.5m heightening are almost similar.

Increased flood probabilities

To assess the effect of higher flood probabilities, there must be looked at how the total risk curve for dike heightening is built up. The first flood scenario has a high probability corresponding to a return period of around 3.3 years. This contributes most to the risk. After this scenario and the second scenario become obsolete due to 1.0m dike heightening, the risk curve has flattened out a lot. This means that preventing the higher flood scenarios have a much lower influence. Even when all flood scenarios get a higher probability due to climate change, this distinctive shape of the risk curve remains. When all flood scenarios get two times as likely, the optimal dike height only increases to 1.15m. But again, a 1.0m dike height would result in comparable total costs. Climate change is therefore not of much importance on the optimal design.

This conclusion can however only be made due to the current high probability of the first flood scenario. This results in the fact that dike heightening up to 1.0m is much more effective than heightening over 1.0m. If exceeding the Danger Level would correspond with smaller probabilities, the curve would look different and this conclusion could not be drawn as easily. The 1.0m is also optimal due to the discrete set of flood events and the resulting jumps in the curve. This has as consequence that dike heightening lower than 1.0m will almost never lead to lower total costs.

6

Derived methodology

Over the course of the report, a methodology has been developed and used within the current case study. This chapter provides an overview of this methodology to serve as guideline for the risk based economic optimisation of similar studies.

6.1. Methodology

The methodology will be presented step by step in the following. For each individual step there is referred to the corresponding chapter in this report.

1. Data collection
   (a) Collect River time series
   (b) Collect Digital Elevation Model, from U.S. Geological Survey
   (c) Collect Landsat images, from U.S. Geological Survey
2. Data processing
   (a) Determine flood probability distribution (Chapter 3.2.1)
   (b) Set up flood scenarios (Chapter 3.2.2)
   (c) Produce inundation maps (Chapter 3.3.1)
   (d) Produce land use map and values (Chapter 3.3.2) and find corresponding depth-damage functions (Chapter 3.3.3)
3. Flood consequences determination
   (a) Material consequences: combine land use, land values, inundation maps and depth-damage functions (Chapter 3.3.4)
   (b) Loss of life: combine land use, statistical valuation of life, evacuation/shelter rate, inundation maps and dose-response function (Chapter 3.4)
4. Flood risk determination
   (a) Multiply flood probabilities and consequences (Chapter 3.5)
   (b) Depict results in a risk maps and/or FD-curves (Chapter 3.5)
5. Drafting measures
   (a) Select requirements (Chapter 4.1.1 and Appendix A.2)
   (b) Set up measures (Chapter 4.1.2-4.1.4)
   (c) Determine effect of measures (Chapter 4.1.5 and 4.2.1)

   (d) Determine investment costs of measures (Chapter 4.2.2-4.2.4)

6. Optimisation of measures
   (a) Optimise prevention layer (Chapter 4.2.2)
   (b) Optimise spatial planning layer (Chapter 4.2.3)
   (c) Optimise crisis management layer (Chapter 4.2.4)
   (d) Optimise combinations of measures (Chapter 4.3)
   (e) Compare all options on optimised total costs, investments, risk reduction and profitability index (Chapter 4.4)
7. Uncertainty analysis
   (a) Determine sources of uncertainty (Chapter 5.1.1)
   (b) Quantify uncertainties if possible (Chapter 5.2.1 and Appendix E)
   (c) Perform sensitivity analysis (Chapter 5.3)
   (d) Determine effect of uncertainties by Monte Carlo analysis (Chapter 5.4.1 and 5.4.2)
   (e) Analyse effect of budget constraints (Chapter 5.5.1)
   (f) Analyse effect of an unsure future (Chapter 5.5.2)
8. Conclude
   (a) Critically assess the reliability of the optimisation results and influence of uncertainty
   (b) Choose the best (combination of) measures

6.2. Integral approach

The approach of optimisation of safety measures is mostly based on the economic motive. It has already been said at the very beginning of this research, that this is not the only motive in designing appropriate flood management plans. The flood risks, the environment and the use of measures are connected and must be assessed as a whole. This integral approach is visualised in Figure 6.1. Several findings are summarised in this framework.

Environmental constraints versus MLS

Besides the economic motive, a suitable choice of safety measures should be made on the basis of environmental constraints, as depicted on the left side of the framework. These constraints can be derived with the method of Wasson, as it has been used in Appendix A.2. Technical constraints mostly effect the choice of hard measures, social constraints mostly the choice of soft measures. This dependency is visualised by the difference in line thickness between the environmental constraints and the separate safety layers. Suitable crisis management measures should be designed with knowledge on what would work for the population. The choice for hard, structural, preventive measures, are largely defined by the technical possibilities. For spatial planning measures, social and technical constraints are both important. These measures can have a large effect on how people live and therefore the wishes of the population have to be taken into account. Note that this does not mean that preventive measures are not influenced by social constraints and crisis management is not affected by technical constraints at all. In this case study the choice has been made not to dike the rural area, which was partly based on social requirements. Also soft measures such as improved evacuation still need to fit within the technical constraints of the environment, for example the road capacities.

Flood risks versus MLS

On the right side of the framework the (direct) flood risk is depicted, divided into loss of life, structural and agricultural risks. The risk of loss of life can be reduced by all safety layers. Crisis management has no or hardly effect on the structural risk, which can therefore only be reduced by spatial planning or prevention. Disregarding relocation, agricultural risk can best be reduced by prevention of flood events. Which component of risk is most present in the area can therefore partly partly determine which safety layer is most attractive.

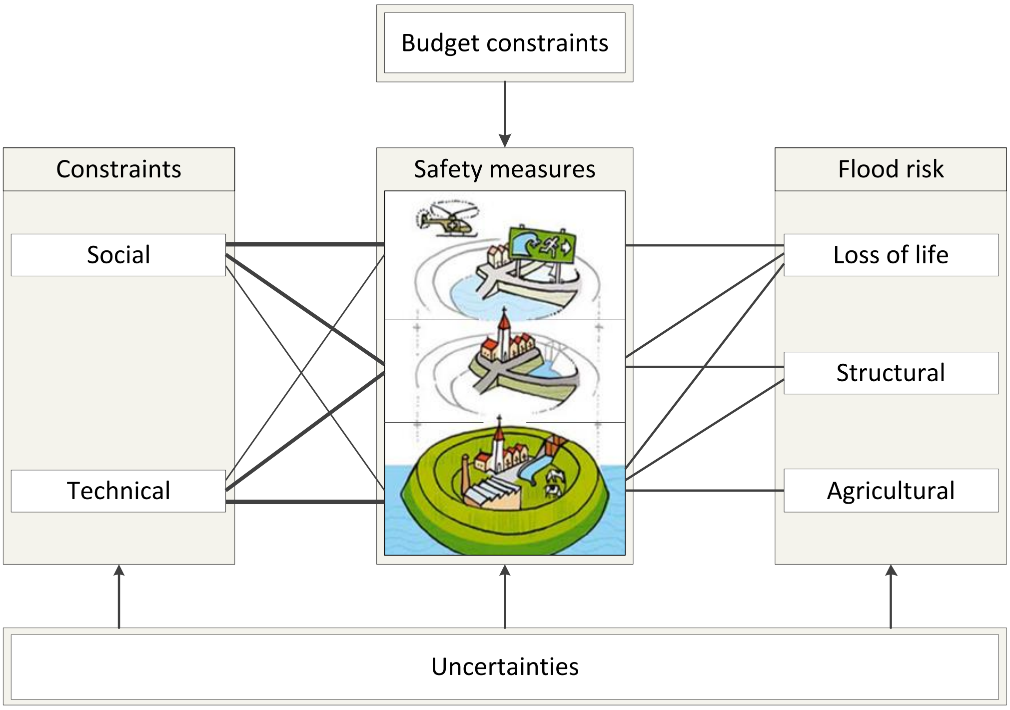


Figure 6.1: *Integral approach of multi layer flood safety. Source MLS figure: Rijkoverheid (2009)*

Under sensitivity to uncertainties and budget constraints
Both the environmental constraints as the flood risk estimation and the effect of safety measures are uncertain. Recall the difference in dependency between constraints and measures. As a result does uncertainty in the components of social constraints, such as human behaviour, most effect on specifying the crisis management layer. Uncertainty in technical constraints, such as soil strength and river dynamics, mostly effect the preventive layer. Last but not least must the safety measures be constructed under limited budget, which not only affects the choice of measures, but potentially also their specifications.

7 Discussion

Before entering the conclusions, this chapter discusses the findings of this thesis so far and what lessons can be taken from it under the used assumptions. The goal of this research is to explore the applicability of risk based economic optimisation of multi layer flood safety under sensitivity to uncertainties and budget constraints. This goal can be split into two components. Although these two components are connected, they are examined separately here: the applicability of the risk based assessment and the applicability of the subsequent economic optimisation of multi layered flood safety, both under the constraints of limited budget and data scarcity. The methods that have been derived for them are discussed first, after which the main assumptions within these methods are presented. The effect of inherent uncertainties and of the made assumptions on the reliability of the two components is elaborated on subsequently. At the end of this chapter, the research is discussed as a whole.

7.1. Derived method

The design process of flood management systems is increasingly based on risk assessments. This allows for better understanding of how flooding can occur, how likely this is and what its consequences are. Among the obtained insights is how the flood risk is distributed over the area of interest and what the current risk levels are. Example projects with this approach are however mostly located in more developed areas of the world. These locations have sufficient resources and also an extensive amount of data to work with. Part of the question of this research is how the flood risks can be acquired for data scarce areas and how reliable the outcomes are. When the risk approach is taken a step further, the specification of risk reducing measures are economically optimised. How these approaches are used in this research are shortly presented in the following.

7.1.1. Risk based approach

During the course of the research a method has been developed to estimate the flood risks for the Nyaungdon area. Important for the applicability of risk based assessments in data scarce areas is that there is at least some baseline information available. The flood risk is determined by the product of flood probabilities and consequences. A prerequisite for a fluvial flood risk assessment is therefore that there is some sort of data series available of the river water levels over time. Without this, estimating the flood probabilities becomes very difficult. (Although, currently global hydrological models are being developed which might overcome this prerequisite, an example is the ‘eWaterCycle’.) In this case a time series of 31 annual maxima of the Ayeyarwady River was available, from which the probability of exceedance of particular water levels could be determined. This information was gathered by a Delft University of Technology student group that went to Nyaungdon in 2016, referenced to as ‘Blom et al. (2016)’ in the report. Further copied data from their trip are the Danger Level for Nyaungdon, costs of houses and some information about the current dike system. Some data was furthermore obtained from engineers from Myanmar, who are currently employed at the TU Delft: the costs of dike heightening and the evacuation process.
All other information can be found on the internet. The flood events are modelled on the basis of NASA’s Digital Elevation model, resulting in inundation depths distributed over the scope area. Landsat

images are available which are used to verify the extent of the flood events. The Landsat images are furthermore converted into land use maps, which are validated with Google Maps. The remaining information regarding the land values and the depth-damage functions can be find in literature. A separate element of the flood risk is the loss of life. Due to the influence of human behaviour, this is most difficult to estimate. The used method for the estimation of fatalities is crude, but data to make it more comprehensive is not available.

7.1.2. Economic optimisation

The type of measures suitable for this case study have been derived in an integral way. This resulted in dike heightening of the current embankment, pole heightening of the dwellings outside the diked area and the construction of shelters over the total scope. Together they form a multi layered safety system. The economically optimal choice for any combination of measures and subsequently the design specifications have been derived in this research for the case study situation.

The method for economic optimisation consists of three sub elements, one for each safety layer. Except for the investment costs has all the necessary information already been derived in the flood risk estimation. The dike heightening is based on increasing the Danger Level. By increasing crest height, the probability of exceedance decreases, thereby decreasing the risk of the diked area. Other failure mechanisms of the embankments are not included. The effect of houses on poles is based on 'virtual flood scenarios', implying that the damage to a dwelling in 0.5m inundation and no poles is the same as 1.0m inundation and 0.5m poles. The effect on loss of life is comparable to this. Important to notice is also that all houses in the unprotected area undergo the same amount of pole heightening, despite having different risks of flooding. The effect of shelters is, similar to all the components of loss of life, estimated in a crude way. A particular scope is defined wherein all the inhabitants that would normally lose their life in the flood situation are saved by the shelter. Other possible crisis management measures are improved warning systems or improved evacuation planning, but this would only require more information that is not present. Even with sufficient information, the influence of these measures would be difficult to quantify and especially monetize.

7.2. Assumptions and simplifications

Within the above described methods, some assumptions and simplifications had to be made. This was needed to increase the workability or when more extensive analyses were simply not possible due to lack of information. Some effects have already been included in the uncertainty analysis, such as the large uncertainty in loss of life due to the used approach. Others are more difficult to quantify and elaborated below. The presented shortcomings will affect the reliability assessment of the derived methods in the next section.

7.2.1. Simplifications of reality

To estimate the risk and to perform the optimality calculations, the reality had to be schematised. This led to several simplified models that is worked with. The uncertainty around the input variables can be included, but the uncertainty or maybe even errors due to the used models has hardly been taken into account so far. This subsection provides an analysis of the used models and if possible their effect.

Inundation modelling

Most important schematisation is the determination of the flood events and corresponding inundations. The water levels in the Ayeyarwady River for the given flood scenarios were combined with the elevation of the area. The difference between the used water level and elevations resulted in the inundation per raster cell in QGis. This is a crude method of flood modelling that is only valid under some assumptions: surface roughness has little effect on the flood propagation over the land; the river will not recede before the area is filled; flooding will not occur before the danger level is reached. When satellite images of the 2015 flood situation are compared with the derived inundations maps, it shows a good representation for the rural area. It therefore looks like as this method of inundation modelling is an appropriate approach. The diked area is however flooded more than expected. This can either show that the Danger Level for the rural area is lower or that the model does not represent reality very well. This would affect the estimation of the risks and therefore the determination of optimal measures.

Some uncertainty is taken away by including the probability of flooding in the Monte Carlo analysis. If the area will inundate less or more than expected for a specific return period, the uncertainty is comparable to the case that the area has a higher or lower return period for a specific inundation depth. The effect of this inundation model will however affect the inundation within the diked area the most. The diked area is located along the smaller Pan Hlaing River instead of the Ayeyarwady River for its largest part. The inundation model only works if the water levels of the Pan Hlaing River follow those of the Ayeyarwady River. Especially since the area is a relatively low lying piece of the scope, the effects can be significant. Some uncertainty is again covered by spread in the inundation depths for the diked area in the Monte Carlo analysis. Again the effect on the optimal design was little. To be completely sure, the regularity of flooding of the diked area, especially the land along the Pan Hlaing River, should be validated.

Discrete flood events
Related to the inundation modelling is the use of a discrete set of flood events. The effects have often been discussed before. Main error are the jumps in the risk curve or plane for the designs that include dike heightening. These jumps had as result that dike heightening lower than 1.0m would not be returned as attractive from the optimality calculations. If the risk curve would have been a fluent and continuous curve, there would be more uncertainty in optimal dike heightening. It is however expected that this spread would not be large. The risk curve has a steep declining slope up to the first meter of dike heightening. For the total costs curve to be at its minimum for values much smaller than 1.0m, the slope of the investment curve would have to be very steep as well. With the used cost components this is not very likely. It is guessed that dike heightening lower than 0.8m would not easily result in the optimal design. The other measures, houses on poles and construction of shelters, did not lead to any jumps in the risk curve.

Estimation of damages
Only a limited number of land use types have been used in the analysis. Although being the most important land use types and also the most frequent of occurrence, some are not taken into account. For example, there might be buildings present in the area that have a higher value than the average built up. It is however expected that the spread in built up values used in the Monte Carlo analysis has covered this.
Another type is the infrastructure. Relative to the other land use types infrastructure is small in scale and not likely to have contributed a lot in direct damages. However, the indirect damages are not taken into account at all. Flooding of infrastructure can have significant effects on indirect damages when repairing takes time and therefore the inhabitants of the scope remain (partly) isolated from its surroundings, blocking production and trade. However, with the used information the inhabitants of the scope do not seem heavily reliable on its surroundings. Furthermore, the damages of the crops and fish ponds already included the lost revenues.

Investment curves
The investment curves that were used are based on a linear relationship between the unit of the measure (dike heightening, pole heightening and number of shelters) and the marginal costs. (The relationship for dike heightening is based on extra volume instead of dike height, but the ultimate relation is almost linear). Initial costs are added to these values. A linear relationship seems logical, but in reality a more complex relation might be a better estimation of the costs. If there would be economies of scale, implying costs advantages when larger quantities are produced, the relation would not be linear. Also the initial investments would vary. However, since the differences between investment values for dike heightening, houses on poles and shelters are large, it is expected that a change in the shape of the investment curve would still lead to the same optimal measure: dike heightening.
A full economic optimisation of measures would not only include the investment costs, but also the maintenance costs and the time of maintenance. This might have a significant effect on the outcomes. Some measures require large initial investments, but low maintenance costs. There are also differences in the interval between maintenance works. Due to the discounting of future values, maintenance works in the nearby future are more expensive than those later on. These influences are not taken into account at all in this research. The computations would have to be extended for this.

Risk discounting
As regards to the present value of the risk, the used simplification is as follows. The present value of a future cash flow is calculated by dividing this cash flow by the factor $(1+r)^t$, where r is the discount rate and t the year it is received or spent. The present value of different cash flows in different years can then simply be added. This computation is expanded when the cash flow turns into a constant annual stream of money over a particular period of time. If this period extends to infinity the present value of annual future cash flows reduces to the simple form of the yearly cash flow divided by the discount rate. Throughout the report this computation has been used to determine the present value of the risk. This was possible due to the exclusion of maintenance costs, so that every future cash flow only consists of the risk reduction. Important assumption is also that the lifetime of the measures is infinite. This is of course not the case. Both the inclusion of a maintenance scheme as the discounting to present values would require extended computations. This is possible, but not performed in this research.

7.2.2. Inclusion of uncertain parameters

The effect of uncertainty in the used parameters has been examined by the use of distributions around the used variables and functions. The choice of distributions and the processing of the uncertainties has led to two shortcomings of the method, affecting the reliability of the results: the use of symmetrical uncertainty distributions and the disregarding of dependencies between the used parameters.

Symmetry of uncertainty distributions
For most uncertainty distributions a symmetrical shape is used, either uniform or triangular. With lack of better information, the uncertainty is often embedded with equal percentages for lower and upper boundaries. A similar approach is applied for the uncertainty around the Gumbel probability distribution and other used functions. This choice implies that the expected mean value is correct. The mean values of the curves that returned from the Monte Carlo analysis are therefore still the same as without the inclusion of uncertainty, only now with a specific deviation around this mean value. However, the expected value does not necessarily have to be correct. It might be the case that for some parameters the uncertainties are better expressed with right- or left skewed distributions. In these situations the mean value does not equal the value with the highest probability of occurrence any more. For the Gumbel distribution, uncertainty is even present in the shape of the curve, which has not been taken into account. Possible effects on the outcomes of the used methods are given in the following.

Effect on reliability of risk quantification
In the Chapter 5, the uncertainty around the risk quantification has been examined by looking at the uncertainty in total costs in the case of doing nothing (see Figures 5.9 up to 5.12). The uncertainty in the quantification is already large and increasing with higher valuation of life and a higher expected number of fatalities. With the use of asymmetrical uncertainty distributions, but equal lower and upper boundaries, this uncertainty will remain large. Only the shape of the curve might skew to the left or right instead of being almost symmetrical, as is the case now. In other words, the expected value might change, but the uncertainty is already high and will remain high.

Effect on reliability of optimal design
In comparison to the risk quantification, the determination of an optimal design was more robust under the inclusion of uncertainties. The question is whether this would still be the case with asymmetrical uncertainty distributions. The answer is twofold: the effect on the choice of measure and its optimised specifications. In this case study, the choice for dike heightening will probably remain robust. This choice was ultimately made based on comparison of needed investments, since total costs alone were not decisive. Looking back at the effect of uncertainties on the optimal investments (see Figure 5.13), the curves of the different measures are so far apart that any change in shape of the curve would not affect the choice of most appropriate measure. Only the expected values of the options of dike heightening or dike heightening combined with shelters might move closer to each other.
As regards to the size of optimal dike heightening, more care has to be taken. So far the shape of the Total Costs curve was hardly affected by the inclusion of uncertainties. However, this shape can change if the shape of the Gumbel distribution changes. When higher water levels at the Ayeyarwady River become less or more likely than they are now, the Risk curve declines faster or slower respectively. If the investment curves remain the same, the location of the minimum value of the Total Costs

curve might change. Some quick calculations are performed to verify the extent of this effect. When the shape parameter of the Gumbel distribution is reduced, higher water levels than its mean value become less likely than they are now. With a reduction of the shape parameter of 10%, dike heightening between 0.5m and 1.0m results in almost the same Total Costs. Increasing the shape parameter with 10%, thereby making higher water levels more likely, makes 1.0m to 1.5m dike heightening almost equally attractive in terms of Total Costs. The optimal specifications are therefore sensitive to this shortcoming of using symmetrical confidence intervals around the Gumbel distribution.

Interdependency of uncertain parameters
Within the uncertainty analysis, all parameters were treated as being independent on each other. Most really are independent, two are however dependent on each other, as discussed in the following.

Different land use cells
The flooded raster cells of crops, fish ponds, bushes/trees, built up and water in the geographic information system are dependent on each other, as the total amount of cells does not change. If one land use type has decreased in flooded cells, this is at the expense of another. For simplicity this is not taken into account. It is therefore possible that some iterations of the Monte Carlo analysis have calculated with the maximum (or minimum) amount of flooded cells of all types, thereby overestimating the risk (or underestimating). However, when there is looked back at the sensitivity analysis, the effect of the flooded cells of crops and fish ponds is relatively small. As regards to the flooded built up cells, the influence is larger. However, looking at the uncertainty within the land use maps, built up cells are mostly interchangeable with bushes and not with crops or fish ponds. Bushes are not taken into account in the uncertainty analysis, so that the flooded built up cells is a parameter that is practically independent of any other included variables. The simplification of assuming independent land use cells is therefore allowed in this case.

Saved population by shelters and loss of life
The influence of shelters is based on the fatalities around the shelter location. It is therefore dependent on the components of loss of life: flooded built up cells, population densities, shelter/evacuation rate, dose-response function and inundation depths. The largest contributor of uncertainty in both elements is the dose-response function. Monte Carlo iterations that use a low mortality rate, but high numbers of saved population are therefore not logical due to their dependency on each other. Such calculations result in an underestimation of the risk, while high mortality rates combined with a small saved population leads to an overestimation of the risk. Following this reasoning, the spread around the mean values of minimum total costs should be larger for those options that include shelters than those without. When there is looked at Figures 5.09 to 5.12, showing the Monte Carlo results, this is phenomenon is not visible. Apparently is the effect of this interdependency too small to be of influence.

7.3. Reflection on derived methods

The most important shortcomings within the used methods have been described in the above. Combining this information with the use of data and the effects of the quantifiable uncertainties, the workability and reliability of the methods can be assessed. Again the separation is made between the risk based approach and the economic optimisation that follows upon this.

7.3.1. Risk based approach

Workability
In general it can be said that there is enough open data available to make a risk estimation for any comparable area in the world: around 100 km^2. Comparable areas are equal in size, so that the assumptions that are necessary for the inundation mapping are valid: surface roughness has little effect on the flood propagation over the land and the river will not recede before the area is filled up to the river water level. The first assumption implies that the water surface level is horizontal and that the floodwave contains enough water to fill up the area. For such cases, flood events can be mapped and the corresponding consequences can be derived from developed land use maps, all based on open source information. The flood risks can however not be quantified without information about the river. The amount of information that can be obtained will differ per location, but it is expected that there

should be at least a short time series available to base the probabilities of flooding on. The derived working method of risk determination in a geographic information system is therefore applicable to other data scarce areas of similar size.

Quantitative reliability
Besides the workability of the method, its reliability is also important in assessing the applicability of the risk based approach. This reliability is twofold: the spatial and quantitative reliability of the derived risk. The present value of the risk for the Nyaungdon area that is found when no uncertainties are taken into account amounts $18.7 million. When all used input parameters turn into uncertainty distributions, the mean value remains almost the same, but carries a standard deviation of $6 million. This spread arises for the set up in which a relatively low valuation of life is used and the Digital Elevation Model is used as it is, not adapted to a potential overestimation of the elevation of built up areas.

For the other set ups (higher valuation of life, adapted DEM or a combination) this uncertainty increases significantly. The derived method can therefore not be used straight away to make a clear quantitative estimation of the risk of the area. The uncertainties around the used variables are too large, especially for those that are used in the estimation of fatalities. When a higher valuation of life is used or more fatalities are expected by adaptation of the elevation model, the total economic risk value becomes unreliable. More reliable results can be obtained when only the material risk is examined and the economic damage due to loss of life is disregarded. For further reliability, the uncertainties have to be reduced by means of field work.

Spatial reliability
As regards to the spatial reliability, the method is more suitable. Small floodplain areas are suited for the easy method of inundation mapping, as long as they can be verified with flood events on satellite images. The presence of embankments makes it however less reliable. Therefore, land use maps can be constructed with good spatial accuracy, as long as the area meets up to two important requirements: comparable in size as the current case study and with knowledge on the current embankments. Although the Danger Level is known, it is unclear to what flood dangers this applies. Furthermore is the current embankment height important information that will not always be available. In this case study the reliability of the results is drastically reduced by the embankment around the eastern part of the scope, from which the height is not known.
Important to notice is also that overtopping is used as only failure mechanism by the current way of flood modelling. Fortunately, embedding uncertainty in the probabilities of flooding can capture some of the notion that embankments can fail before the water level has exceeded its crest. This would however not lead to any insights in how the probability of dike failure is distributed over the total section. Only with more information on the current dike system such analyses could be performed. This information was not available now and is probably also not available for other data scarce areas. Some field work is again needed to increase the reliability of flood risk assessment in of diked areas.

7.3.2. Economic optimisation

Workability
The workability of the optimisation method can be assessed in a brief way. Contrary to the risk estimation, no extra data is needed except for the investment costs. With sufficient computing power the process can be undertaken anywhere in the world.

Reliability of optimisation results
With the used data and uncertainty distributions, the choice of optimal design turned out to be quite robust. The change that any other measure than dike heightening is more attractive was low and the optimised dike heightening remained stable under the inclusion of uncertainties. The uncertainties in risk estimation changed the risk values, but the shape of the risk curve corresponding to dike heightening stayed more or less the same. The location on the Total Costs curve that corresponds to the lowest value was therefore also stable. It must be mentioned that this was partly due to the discrete set of flood events, resulting in jumps in the risk curve. More flood events would lead to a more fluent risk curve, so that other locations can become minima as well. In this case the shape of the risk curve

was as such that even with more flood events the optimal design is probably still relatively stable. With the current high flood probabilities, the total costs curve decreases significantly within the first meter of dike heightening. After that the Total Costs curve flattens out, before slowly climbing again. The difference between 1.0m or 1.5m is small in this case, while investment wise the 1.0m heightening is of course more attractive.

An important factor that reduces the reliability of these results is the use of mostly symmetrical uncertainty bounds. Within this method, the shape of the Total Costs curve remained the same, but this is not the case when the shape of the Gumbel distribution changes. Quick calculations have shown that small changes in the shape parameter of the Gumbel function leads to changes in optimal dike height. However, it is because of the flat shape of the Total Cost curve around its minimum value that the differences in total costs are not very large. The quick risk reduction within the 0.5m dike heightening will remain present. The optimality calculations therefore still give a good indication of suitable measures and design specifications. More case studies need to be performed to explore whether this robust behaviour is present more often.

7.4. Reflection on the used approach

The technical applicability of the risk based economic optimisation approach in flood risk management of data scarce areas has now been discussed. As final part of the discussion, a brief reflection is presented on the principles of the used approach.

7.4.1. Added value of systems engineering

Within this case study, an integral approach has been used to draft the measures. This systems engineering approach is based on Wasson (2006), who provided an analysing framework to translate a problem into physical solutions. The added value of this approach in flood management is that it supports the drafting of measures in a systematic manner. This way all important constraints and opportunities can be found and assessed. Subsequently this results in a complete set of requirements.
The social constraints are difficult to analyse without investigation at the location site. Much of the requirements for the current case study are derived from previous researches of Van Meel et al. (2014) and Steijn et al. (2015). If this information would not have been available, it was more difficult to draft requirements. Therefore, although much of the risk based assessment and economic optimisation can be performed with open data, the design of suitable measures still requires insights that can only be found on location.

7.4.2. Need for risk based economic optimisation

The insights that are given by the risk assessment are of use for the area. It shows where the highest risks are located and therefore where measures can be placed to reduce the risk most efficiently. This used method can furthermore be applied in areas comparable in size as well, since most of the data is openly available. The risk estimation shows large spreads in quantity, which can only be reduced by exploration on site. Despite this uncertainty, the optimal design was quite robust. The shape of the risk curve was as such, so that the outcomes remained stable under the influence of uncertainties. It is however the uncertainty within the shape of the Gumbel distribution that can reduce this robustness.

A separate discussion can be conducted on whether all the analyses and calculations weigh up to the results. If the highest risk locations are found with the derived method, the choice can also be made to reduce this risk with the use of design standards. For instance, the current embankment can be heightened with a particular amount without further calculations. The optimality calculations have shown that the difference in total costs are not very large around 1.0m dike heightening. However, this might be applicable within this case study, where a small scope is used. When the practice of dealing with flood safety becomes more advanced over the years in developing countries as well, economic optimisation will probably become of use. When larger system boundaries are chosen, the size of measures also increases. Large amounts of money might be spent in an inefficient way when crude design standards are still used in that situation. However, this does require more advanced ways of flood modelling, as the currently used inundation mapping is only applicable to smaller areas. This is only possible when more data becomes available.

8

Conclusions & Recommendations

This research has been conducted to explore the applicability of risk based economic optimisation of flood safety. Floods are likely to occur more often in the future and especially for developing countries the effects can be disastrous. Such areas are in need of appropriate flood management approaches. The economic optimisation of multi layer flood safety offers potential to spend every penny efficiently. However, the remaining issue is if this approach fits the circumstances of such areas. Therefore the following research question was set up:

How can risk based economic optimisation in multi layer flood safety be applied under budget constraints and uncertainty due to data scarcity?

The case study of Nyaungdon, Myanmar has been used to make sure that all variables and functions needed for a risk based assessment and subsequent optimisation of measures are included. Over the course of the main report a method has been developed that assesses the flood dangers of the scope area through a risk approach. Thereafter, measures have been drafted that would fit the environment, after which the specifications of these measures have been optimised. The inclusion of uncertainties has tested the robustness of the approach and its outcomes. All key results have been examined and discussed in the previous chapter. The conclusions and recommendations that can be drawn from the total research are presented now.

8.1. Conclusions

In the introduction at the start of the report, it was stated that the applicability of risk based optimisation will lie between two extremes. The first extreme corresponds to a reliable outcome of the economic optimisation under the sensitivity to uncertainties. This implies that the uncertainties have little effect and a reliable flood management design can be presented. The other extreme represents a situation where the spread of optimal design specifications under uncertainties is so wide, that the derived values are not meaningful at all. An intermediate result would be that the process can only serve as preliminary assessment of measures. After the answering of each sub question, it is concluded which end of the hypothesis is true.

8.1.1. Sub conclusions

1. How can the economically optimal design be determined, assuming certainty in used variables and functions and fixed budget?

An extensive overview of the derived method is given in Chapter 6. It is mostly based on open data to assess the risks of the area. Suitable measures were drafted, based on an integral approach: dike heightening, placing houses on poles and/or the construction of shelters. Each measure had its own effect on risk reduction. Combining this risk reduction with the investment costs, the specifications of (combinations of) measures have been determined by finding the minimum total costs.

2. What effect do the uncertainties have on the optimal distribution of investments?
Within this case study, the uncertainties have little effect on the optimal distribution of investments. Taking both the total costs as the required investments into account, dike heightening alone is the most attractive. This is to such an extent that with the inclusion of uncertainties in risk estimation and investments dike heightening remains the best option. Only the option of dike heightening combined with shelters is comparable in results. Combinations with pole heightening are cost inefficient: it is expensive and relatively low in risk reduction.
Also the amount of dike heightening remained robust under the inclusion of uncertainties. The shape of the Total Costs curves in the Monte Carlo analysis are always as such, that its minimum location is always between 1.0m and 1.5m dike heightening. The differences in Total Costs within this range are low, while 1.0m of course requires the lowest investments. Since one measure turned out to be the most appropriate and most cost effective, a smaller budget will not lead to any differences in optimal distribution of investments in this case study. Also future changes did not lead to much uncertainty in the optimal dike height.

Important to notice that there are some shortcomings to this method that reduce the reliability of the uncertainty analysis and its results concerning the robustness of the optimal design. First, a discrete set of flood events is used, which led to jumps in the Risk and therefore Total Costs curve. As a result, dike heightening by lower than one meter will never turn out to be the best option from the optimality calculations. If a smooth curve is used, some more uncertainty in the optimal dike height can be expected. Second, within the uncertainty analysis mostly symmetrical distributions are used. As a result, the shapes of the Total Cost curves of the Monte Carlo analysis remained comparable in shape. This shape will change when the shape of the Gumbel distribution can change as well. However, because of the distinctive flat shape of the Total Costs curve around its minimum, the differences in Total Costs will not be very large. The quick risk reduction within the 0.5m dike heightening will remain present. Although it reduces the robustness of the 1.0m dike heightening, it will remain a good indication.

3. Can the expected uncertainty in optimal design specifications be reduced?
Some uncertainties within the case study can simply be reduced by more extensive analysis of the variables. This is the case for the construction of land use maps and therefore also the population densities. For other variables and functions it is still required to perform field work or questionnaires on location. The expected errors in the Digital Elevation Model can be verified by comparing the elevation of the built up areas with its surroundings. Variables such as the land use values of rice and fish ponds values can better be estimated by interviewing the owners. Local contractors can reduce the uncertainty around the investment costs. More extensive questionnaires are needed to give more insights in the evacuation and shelter processes. Also the attractiveness of shelters can be deduced from this. Experiments can be used to reduce the uncertainty in depth-damage functions. This is mostly the case for fish ponds, from which a depth-damage function is not available yet. The uncertainty around the discount rate and valuation of life is simply a matter of choice. However, all these uncertainties cannot be completely diminished. When the uncertainties are heavily reduced, the choice for dike heightening will become even more reliable.

Two functions remain whose uncertainty is difficult to reduce. These are the dose-response function and the Gumbel distribution. The mortality rates will always embed a lot of uncertainties, amongst others due to the differences in human behaviour during flood events. The Gumbel distribution will remain uncertain due to the relatively short time series. Changes in shape are still possible, which can affect the optimal design specifications. However, as explained in the previous sub question, the optimality calculations can still give a good indication for the best option.

4. Which learned lessons with respect to the applicability of risk based economic optimisation can be generalised to other data scarce areas?
In this case study, the economically optimal flood management system could be determined with sufficient confidence. Even though the uncertainties in risk values are large without further field work, the optimal design turned out to be quite robust. This does not have to be true for other cases as well, but has to be examined in every situation. The derived method is nevertheless still applicable on any case that is comparable in size. This means that the study location should be in the order of 100 km^2,

otherwise the assumptions that are necessary for the inundation mapping are not valid any more. If the risk declines fast with the implementation of measures, but flattens out when the size of the measure is increased even further, it can be expected that the outcome of the optimality calculations is robust. The minimum of the Total Costs curve will always be around the same location. Slightly higher design specifications are likely to result in the same amount of total costs. However, in that case it is of course wiser to construct the lower limit of the optimal design specifications if higher values would result in the same total costs.

Multi layered flood safety turned out not to be the optimal solution for this case study. Dike heightening alone resulted in the lowest total costs and also lowest investments most of the times. This conclusion cannot simply be drawn for other cases as well, since this is situation and measure specific. In this case, the issue of limited budget was easy to deal with: heighten the dike as much as possible. Their might however be situations where combinations of measures are most attractive. When in that case the budget is limited, there should be started with the measure that reduces the risk most cost efficiently. Or in other words, start with that measure that has the highest benefits/costs ratio. If the budget is even too low to invest in large operations of first and second safety layer measures at all, the construction of shelters is a good start. This becomes especially the case when a high valuation of life is used.

8.1.2. Main conclusion

Throughout the research a method has been derived to make a risk assessment and economically optimise flood safety measures in data scarce areas, mostly based on open data. The applicability of both aspects is elaborated in the following.

Risk based approach

In general it can be said that a spatial risk based assessment is well executable in data scarce areas that are comparable in size as the current case study: in the order of 100 km^2. For larger areas, the validity of the made assumptions for the inundation mapping should be considered again. There is a large amount of open source data and literature to work with for any area in the world. Especially for floodplain areas, the risk assessment is spatially accurate with the derived method. Land use maps can be constructed with high accuracy as long as this is given sufficient attention. Moreover, based on comparison with actual flood events, the simple method of inundation mapping provides good results. If a diked system is in place, the estimation of the risk becomes less reliable with the current method of flood modelling. This has two reasons. First, the design of the embankments, amongst others the height, is probably not well not known in data scarce areas. The real probabilities of flooding are therefore hard to estimate. Second, other failure mechanisms than overtopping are not included. Again this affects the probabilities of flooding.
The quantitative aspect of the risk assessment is less reliable. With the inclusion of uncertainties, a large spread around the risk value for the case study area was found. The uncertainty in used variables and functions is too large to acquire a single confident estimation of the risk. Especially the uncertainty around the economic loss due to fatalities is large. When only the material damages are taken into account, a more reliable estimation can be given. However, without further reduction of the uncertainties by means of field work, a confident value for the material risk can also not be given.

Economic optimisation

Unexpectedly did the large uncertainty in risk quantification have little effect on the optimisation results of the case study. Despite the uncertainty in risk and investment costs, the Monte Carlo analysis showed that the choice between optimal (combination of) measures and subsequent optimal design specifications are robust under the sensitivity to uncertainties. Combinations with pole heightening mostly turned out to be unattractive due to its high investment costs and relatively low risk reduction. Dike heightening turned out to be the best option from an economic perspective. Dike heightening can efficiently reduce the current high probability of flooding of the diked area within the first meter of heightening. Combining this with shelters becomes attractive when a high valuation of life is used.
After the choice has been made to continue with dike heightening, the optimal height was also stable in the used method. The shape of the Risk and Total Costs curve was as such that the locations of the minima were always around the same location. Only between 1.0m and 1.5m the distinction is low, but

based on investments the lower limit is of course more attractive. For this case study it can therefore be concluded that risk based optimisation of flood safety measures can well be applied with the derived method. The derived optimal design remained stable under the inclusion of uncertainties. Moreover, due to the high attractiveness of dike heightening compared to the other measures, budget constraints did not change the choice nor the specifications of the optimal design.

The reliability is however reduced by keeping in mind that the uncertainty bounds around the parameters are not necessarily symmetrical. Within this case study, the differences in total costs and investments between the different measures were as such, that the choice for dike heightening will still be the best case from an economic perspective. However, a change in shape of the Gumbel distribution can change the Total Cost curve and therefore also the location of optimal design specification. The best dike heightening can therefore not be given with high accuracy, but the optimality calculations still give a good indication. The differences between 1.0m and 1.5m will probably not be large, and the steep decline within the first 0.5m will remain present. How much the dike should be heightened cannot be based solely on economic optimisation any more, but changes into a decision problem. The specifications will mostly depend on the available budget. Risk is most reduced within the 0.5m heightening, and this will probably remain the case.

8.2. Recommendations

With the conclusions in mind, some recommendations can be provided. The recommendations are twofold. First the recommendations related to the outcomes of the case study are given. After that, recommendations for further research are presented that will increase the reliability of the conclusions.

8.2.1. Recommendations for Nyaungdon

For the current case study of Nyaungdon is 1.0m dike heightening most likely to be the optimal solution, increasing the Danger Level to 8.5m +MSL. The shape of the Total Costs curve was as such that its minimum value is mostly located at this design specification. Due to the current high probability of flooding the risk can drastically reduce within the first meter of dike heightening. After that, the curve flattens out before slowly rising again after 1.5m dike heightening. The difference in total costs between 1.0m and 1.5m is small. Based on the required investments it is logical to heighten the dike by only 1.0m. Compared to the high level of uncertainty in the quantified risk assessment, these results of the optimisation process are more stable and reliable. However, a remaining issue that needs to be verified at location first, is if the diked area would flood as it is presented in the derived inundation maps. Since it is not located directly next to the Ayeyarwady River, the results of the inundation mapping need to be verified.

8.2.2. Recommendations for further research

A few recommendations for further research can be made to increase the reliability of the used method and to support the current conclusions.

- The estimation of loss of life has been a large contributor to the uncertainty. The expected number of fatalities is low for floodplain flood situations, but when the economical valuation of life increases, the economic losses can still become significant. Especially in the estimation of risk, the current method of determining the expected loss of life is not sufficient for reliable results. Although the used method of Jonkman works, the uncertainty in the dose-response function is large. To apply the total scheme of loss of life estimation, including evacuation and shelter rates, there was not sufficient information available. There is need for another work method that makes estimation of loss of life more reliable.

- Another large source of uncertainty was the presence of fish ponds. Hardly any information is available for this, both on its economic value as how they get damaged by floods. Better risk estimations can be made when a depth-damage curve for fish ponds is available. Especially since large amounts of fish ponds are in place in Myanmar and the rest of Asia, increased knowledge on the consequences of flooding on fish ponds can greatly improve the risk assessments of such areas.

- In this case, the robustness of the economic optimisation process turned out to be high under the influence of uncertainties. More case studies should however be performed to verify is this is more often the case. If so, the uncertainty analyses becomes less important, which saves a lot of effort.
- The case studies should furthermore be extended to include the effect of maintenance costs and lifetime of the measures. In the current case study both are disregarded, so their effect cannot be assessed. It needs to be investigated whether this can change the choice of optimal design.

8.3. Wrap up

To summarize, the derived method is suitable for risk assessments in data scarce areas that are comparable in size as the current case study. The spatial accuracy can be high, as long as there is sufficient effort put into the derivation of inundation and land use maps. However, the reliability decreases when there is worked with diked areas instead of floodplains without embankments. The uncertainty in the quantification of risk is currently too large, especially due to the loss of life. Despite the amount of open data, some field work is still needed to make more confident statements. However, the economic optimisation turned out to be quite robust under the sensitivity to uncertainties. It is especially the uncertainty in the water level distribution that can reduce the reliability.

In short, it can be said that risk based economic optimisation of flood measures is possible in data scarce areas in the order of 100 km^2, therefore being equal in size as the current case study. For a small area as the current case study, it is questionable whether it is necessary to design the flood protection this way. If larger areas are examined, efficient spending can save large amounts of money compared to when crude design standards are used. However, extra care has to be taken for the inundation mapping in that case, as the made assumptions for the inundation mapping are not valid for larger areas. Also the choice between measures can be based on economic comparison. It must however still be kept in mind that the economic motive is not the only motive in designing flood management systems. The suitability of measures also largely depends on social opportunities and limitations. There is a connection between multi layer flood safety, economic optimisation and the environment which must always be taken into account.

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A
System analysis

In order to find suitable measures for the Nyaungdon area, the environment has to be analysed. As written in Chapter 2.2.1, this is done through the framework that is designed by Wasson (2006). Some background information about Myanmar is already given in the Chapter 2.2.2. This appendix complements the background information by presenting a short elaboration on the history of Myanmar, since this might affect the way people think and handle nowadays. After that, the system analysis zooms in on the Nyaungdon case and requirements are drafted for the to be designed flood management system.

A.1. History of Myanmar

Various ethnic groups from China and India migrated to the area of modern day Myanmar long before Christ and formed competing kingdoms. The first unification of the regions that would later form Myanmar took place in the eleventh century. In 1044 the first comprehensive kingdom was established, also known as the Kingdom of Pagan, named after the settlement from where the empire had grown. The social, economic and religious reforms that were implemented in this era have had a large impact on the current culture of Myanmar. Important developments were the introduction of Buddhism and with that the construction of large amounts of famous temples that still exist today. After 250 years of unity, the empire fell back into several smaller states with the invasion of the Mongols in 1287. In the sixteenth century, the ambitious king of the Taungoo Kingdom succeeded in reunifying several of these states and declared a new unified kingdom, which was the start of the Taungoo Dynasty (1510–1752). In the eighteenth century the kingdom deteriorated and the dynasty was ended by an invasion by the Mon minority. Due to this event the kingdom entered the Konbaung Dynasty (1752–1885), which turned out to be the last. (Myanmars.NET, n.d.)

During the last decades of the Konbaung Dynasty, several wars have been fought with British India. In 1885 the total country had been annexed by the British Empire. The conquered region was called Burma, after the largest ethnic group in the country: Bamar or Burman. After the annexation Burma was incorporated as province of British India with Rangoon as its capital city. During British rule, the economy grew and Burma became the wealthiest region in Southeast Asia. In 1948 Burma regained their independence from Britain and from a short reign by Japan after World War II. The new, independent Union of Burma was unstable. Several ethnic minorities demanded autonomy and communistic riots took place, as they felt excluded from the government. The internal conflict that started shortly after Burma's independence, is seen as one of the world's longest ongoing civil wars. In 1962 general Ne Win, a nationalist from the majority Bamar people, staged a coup and replaced the civilian government with a military dictatorship. Even more discontent, some ethnic minority groups formed rebel fractions. In the meanwhile, Ne Win's goal was to transform Burma into a socialist state, isolated from the rest of the world. His focus on the now nationalised industries had adverse effects on the agricultural sector. The food shortages and inflation that originated led to strikes and anti-government demonstrations, suppressed by the military. Famous is the so called '8888 Uprising', a series of nationwide pro-democracy protests with its key events on 8 August 1988. General Ne Win resigned in this year, but the military regime remained in power. (Szczepanski, n.d.) A year after, in 1989, the regime changed several names of cities and rivers that had been transliterated by the British. Also the country's official name was changed from Burma to Myanmar to get rid of its references to the colonial past. Although these seem two complete different names in the Latin alphabet, the local pronunciation and notation is comparable. However, the use of Myanmar is controversial and not used by governments that have not acknowledged the military regime. Some western countries still use Burma, the United Nations have accepted the name change (BBC News Magazine, 2007). Other important name changes are the following (Lemere and West, 2011):

- Burma → Myanmar
- Rangoon → Yangon
- Pagan → Bagan
- Arakan → Rakhine
- Karen → Kayin
- Karenni → Kayah
- Burman → Bamar
- Tenasserim → Tanintharyi
- Pegu → Bago
- Irrawaddy River → Ayeyarwady River
- Salween River → Thanlwin River
- Sittang River → Sittaung River

After decades of protest and economic crises, multi-party elections were kept in 1990 in which the National League for Democracy (NLD) won over the National Unity Party (NUP, the successor of Ne Win's party). However, the military regime did not acknowledge the results and put the democratic leaders under house arrest. One of the two leaders is Aung San Suu Kyi, awarded with the Nobel Peace Prize in 1991. It took two more decades of internal and international pressure for the military regime to undertake democratic reforms. In 2011 Aung San Suu Kyi was released and the democratic party won the vast majority of seats in the parliament in 2015. Although she is constitutionally barred from presidency due to her marriage with a British citizen, she obtained a lot of power in parliament in the new created function of State Counsellor (BBC News, 2016). Despite the first civilian government in decades, the internal conflicts are still running. The main minority fronts against the majority Bamar people are formed by the Kachin, Kayah/Karenni, Kayin/Karen, Rakhine/Arakan and the Shan. A nationwide ceasefire agreement has been drafted in 2015, but only 8 out of the 15 insurgent groups that took part in the negotiations signed the agreement (Myanmar Peace Monitor, n.d.).

A.2. System analysis by Wasson

This section complements the selection of measures in the main part of the report. The requirements for suitable measures are derived by the method of Wasson, as presented in the Chapter 2.2.1. Before the the requirements are drafted, the system is analysed and defined at the start of this section.

A.2.1. System definition

According to Wasson (2006), a system is defined as *"an integrated set of interoperable elements, each with explicitly specified and bounded capabilities, working synergistically to perform value-added processing to enable a user to satisfy mission oriented operational needs in a prescribed operating environment with a specified outcome and probability of success"*. In this case the system of interest to be designed is a cost effective flood management system for the area of Nyaungdon, as defined by the physical scope. The owner of this system will be the government. Depending on the management system the responsibilities are owned by national or lower level authorities. Each part of the system that is mentioned in the above definition is further elaborated below.

Interoperable elements of the system

The integrated set of elements could be any possible combination of the three layers of safety. The three layers working together creates synergy, but all layers have their own capabilities. The preventive layer is used to reduce the probability of a flood situation. This implies that the measures in this layer reduce the probability of material damages due to floods as well as the probability of loss of life. Thus, the preventive layer can reduce both types of direct losses. Depending on which measures are implemented in the spatial planning layer, this safety layer can affect both types of direct losses as well. The measures in this layer reduce the consequences by, for instance, adaptation of assets to make them more flood resistant or moving assets to less flood prone areas. Making assets more flood resistant does not necessarily reduce the loss of life as well. The third layer, crisis management, mostly focusses on reducing the loss of life in flood situations. Depending on the measures, this safety layer could reduce the material losses as well. Improved warning could in theory reduce the material losses, when people can move their belongings to safe places. Improved evacuation will not affect the material losses. In short, it will depend on the specific measures that will be chosen later on which kind of losses are prevented or mitigated. Since these three elements of the flood management system are systems on their own, they can also be further divided into interoperable elements. It depends on the measures that are chosen if this is necessary for the purpose of this research or that this first subsystem level is sufficient.

System mission

Every system has two roles: it pursues its own mission and at the same time supports other systems in achieving their mission, implying that a mission is also supported by other systems. The mission system and the support system(s) together form the system of interest. The current mission is to realise a cost efficient flood management plan, fitting the needs and boundaries of the environment it has to operate in. It thereby supports the development of the area, by reducing the costs and other disadvantages of flooding and offering a safer place to live. Support systems for the flood management system are the three layers of safety, including the people involved.

Operating environment

The operating environment the system will be working in consists of both the physical environment as some higher order systems. The physical environment is defined by the natural environment, human-made systems environment and the induced environment. All operating environments can have different levels of abstraction, such as global, national, regional and local environments. Both the elements of the physical environment as the higher order systems are described in more detail in the following.

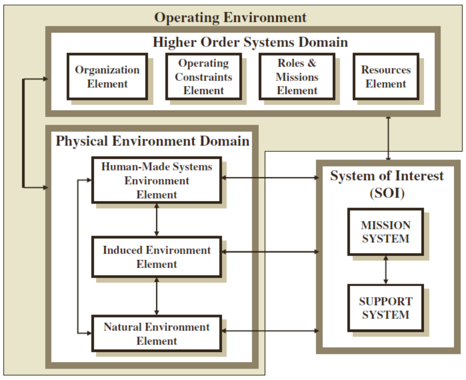

Figure A.1: *Operating environment according to Wasson (2006)*

Natural environment

The natural environment consists of all *"all non human, living, atmospheric, and geophysical entities"*, placed into different levels of abstraction. For the natural environment, the regional and local abstraction level are most relevant. On regional level the climate can be defined, since this will be the same for all lower abstraction levels. The climate for the current region has already been described in Chapter 2.2.2. For the local abstraction level, the Nyaungdon scope is located in the lowlands of Myanmar created by rivers such as the Ayeyarwady River. This has resulted in a soil class of so called Gleysol, a wetland soil saturated with groundwater for longer periods, if not drained (Blom et al., 2016). In tropical climates this soil is suitable for rice production, as is also the case in Nyaungdon. Most of the area consists of rice paddies, combined with smaller spots of bushes and trees. The elevation of the area mostly amounts between 7.5-9m +MSL (USGS, 2017).

Former river bends, or so called oxbows, of the meandering Ayeyarwady River are also located in the area, indicating the dynamic behaviour of the river. This behaviour also effects Nyaungdon Town, where the embankments located in the outer bend of the river are getting undermined by the river. Another effect of this changing flow path is the extra land that is being created in the inner bend, located in the west part of the scope. This is however at the expense of the bank located on an outer bend at the other side of the river. In short, it can be noticed that the natural environment is not static, but changing over the years.

Human-made environment

The second element of the physical environment are the human-made systems, which are defined as *"external organizational or fabricated systems created by humans that interact with your system entity at all times"*. This broad definition implies that a lot can be gathered under the human-made environment: nine sub elements in this environment can be distinguished. Again the human-made environments can work in different abstraction levels. The nine sub elements below are in principle given on a local level, unless stated otherwise. Furthermore, only the elements that are most relevant for this study are discussed explicitly.

- *Historical and heritage systems.* These include all relics, traditions and important locations. In this case, important locations as the pagodas distributed over Nyaungdon Town can be of influence. Especially the pagodas near or on the current embankments, since they affect the dike heightening design.
- *Cultural systems.* These systems are closely related to the previous sub element of human-made environment. Things as religion and the way people interact with each other can be gathered under this element. Relevant for the current region are the Buddhist monasteries, whose monks offer shelter and protection to vulnerable people, also in case of flood situations (Win Min Oo, 2017).
- *Urban systems.* Urban systems consist of all entities where humans can group into communities. Nyaungdon Town is the major urban cluster within the scope area. The majority of the dwellings are located within the embankments, some are however placed on or at the riverside of the dike (Blom et al., 2016). This can affect the dike stability, but it also complicates potential dike heightening. For the remaining urban systems, several villages are divided over the area, which is also visible in the land use map of Figure 3.7.
- *Business systems.* This element includes everything related to how humans produce products and services for use in the marketplace to sustain a livelihood. An important sector within the business system is the fishery, which is also an export product of the area (Blom et al., 2016). The other important sector is rice production; most of the land use is assigned to the rice production, both for own use as for trading. About one quarter of the population works on their own account, slightly less than a quarter is a household worker and about the same amount is employee. Other major groups are unpaid family workers and students. The small rest group is employer, retired or unemployed (Ministry of Population, 2015a).
- *Educational systems.* This system comprises all institutions used for educating. Nyaungdon Town holds one school with primary and secondary education. Furthermore four smaller schools are present (Blom et al., 2016).
- *Financial systems.* This element applies to all entities that support financial transactions. This includes banks and investment entities and their links with the population. How they are present within the scope area is not clear. On a larger abstraction level other financial systems arise. Several institutions are active within Myanmar. Regarding the water sector, commercial banks, national governments and international institutions such as the EU, Asian Development Bank and the World Bank provide grants and other ways of financing (Van Meel et al., 2014).
- *Government systems.* All entities related to governing a human society fall into this sub element. On a national level, flood related government entities are the Ministry of Agriculture and Irrigation and the Ministry of Transport. These ministries are locally active in the Irrigation Departments (ID), Department of Meteorology and Hydrology (DMH) and the Directorate of Water Resources and Improvement of River Systems (DWIR). Departments used for crisis management are the National Institution for Disaster Management and Relief and Resettlement Department. However, due to conflicts of interests and policy gaps between local departments or between local and national entities, management of problems is not always conducted in an integrative way (Van Meel et al., 2014). Other local governmental bodies are the Evacuation Committee and the City Development Department (Blom et al., 2016).
- *Medical systems.* Including hospitals and other entities delivering healthcare. A hospital is present in Nyaungdon Town. Furthermore, several non governmental organisations cooperate with the area in case of crises. Examples are UNICEF and the Red Cross and Red Crescent.
- *Transportation systems.* The final sub element of the human-made environment are the transportation systems. Nyaungdon Town is on land connected to its surroundings by the Pathein Road. In the north west of the scope area, the Pathein Road crosses the Ayeyarwady River by

means of the Bo Myat Tun bridge (Google Maps, 2016). Situated further north the Ayeyarwady-Nyaungdon Bridge is constructed, to facilitate a two-lane road, two-lane rail road and two pedestrian lanes cross the river. Around half of the population owns a bicycle and about a quarter owns a motorcycle. Less than 1% owns a car, truck or van. Furthermore the Ayeyarwady River and Pan Hlaing River are used as waterways. About a quarter of the populations owns a canoe or motor boat (Ministry of Population, 2015a).

Induced environment
The induced environment as part of the operating environment does not introduce new elements, but is used to isolate entities that represent the interactions between the natural and human-made environments. This third environment can therefore be defined as the "discontinuities, perturbations, or disturbances created when natural phenomenon occur or human-made systems interact with the natural environment". Among the induced environment could be any form of natural disaster, such as fire, floods, storms, cyclones, earthquakes, tsunamis, landslides or droughts. The Ayeyarwady Delta is not prone to all of these disturbances. The delta is mostly exposed to floods, storms, cyclones, earthquakes and tsunamis (Van Driel and Nauta, 2015). As regards to wars, an internal conflict is still ongoing between the different minorities and the military. However, most of this takes place along the border areas of the country. In the Ayeyarwady Delta, where most of the population belongs to the majority Bamar ethnic group, the situation is relatively stable.

Higher order systems
The current system of interest, the flood management system for the area of Nyaungdon, has to function in the operating environment, but is also placed within a hierarchy of systems. Each higher level of abstraction than that of the level of the system of interest, is in theory a higher order system that can affect the system of interest. Higher order systems can govern the flood management system through two application contexts. At first through the human-made systems context. Higher order organisations can have control over the system of interest via structures and policies, such as laws, regulations and public opinion. A further elaboration on water policy and laws is given later on. The second context is formed by the natural laws, that control all natural and human-made systems. Although this seems obvious, especially within civil engineering, it has to be included when the total operating environment is being described. After all, possible measures have to be physically realisable.
This first context mainly arises from the higher order organizations and their roles and missions. In this case the higher order ministries and their roles and missions can affect the policy of the flood management. Both contexts can work through the operating constraints element and the resources element. These elements govern and constrain the physical environment by policies and procedures, and by the resources that are allocated to the system respectively. Examples of resources are time and money, but also expertise. Further in the process this will return.

A.2.2. System design

Now that the system is defined and the environment it is operating in, the process of Wasson can be followed to determine physical designs of measures. This starts with defining the problem and the solution space that is able to manage this problem. The steps thereafter bound the solution space until a physical design is drafted.

Problem and solution spaces
The current mission (realising a cost efficient flood management system) is based on the problems the area has. Theoretically speaking the problems are captured in the so called problem space, which is part of the operating environment that poses some level of threat. In the Nyaungdon case the threat is an element of the induced environment: flooding of the Ayeyarwady River. A major assumption hereby is that the threat is really seen as problematic and unacceptable and that, although the population is used to flooding and have the capacity to partly adapt to it, a better situation is wished for. If after the economic optimisation of the specification of measures it turns out that the implementation of measures will reduce the total costs, at least a more cost efficient situation is possible. Another important concept of the problem space that has to be noted is that the problems cannot be eliminated completely. The problem space can at best only be managed and controlled. Fortunately, the whole risk based approach

supports this concept. Furthermore, the problem space is usually not static. The operating environment is dynamic and therefore so may be the problem space. Drivers of change within the problem space are amongst others the dike erosion, land subsidence and climate change. The first two will definitely increase the threat of flooding, climate change will likely do that as well. Furthermore the land use might change when certain areas become less or more exposed to flooding.
The threat creates risk on a financial, safety, health or emotional level. Financial risk is produced by the potential damages due to material damage and loss of life. Although this is the only factor that will be included in the economic optimisation, the other factors should be used to design a suitable flood management system that is supported by the people involved. The counterpart of the problem space is the solution space. The solution space represents an entity that, when implemented, can solve (a part of) the problem space. However, the possible solution space is bounded by its operating environment. It has to fit the physical environment, but also the laws and policies commissioned by the higher order systems and the resources that will be assigned to the system. The solution space or spaces can be determined by specifying it in more detail in the requirements domain, operational domain, behavioural domain and at last the physical domain. The starting point of the solution space is a multi layered flood safety system, to be further specified in the next steps.

Requirements Domain
The first step in bounding the solution space is by determining the requirements for the system. If a list of requirements is not provided by the client in advance, they have to be established from scratch. Some requirements can be based on the National Water Policy (NWP). In 2014 the NWP was released, proposing a framework for the regulation of watersheds, rivers, lakes and reservoirs, aquifers and coastal and marine water (Van Meel et al., 2014). It should work as guidance for the development of water policies, legal instruments and strategies concerning water resources in Myanmar. All these are being developed since 2014, via the following goal of the National Water Policy (Van Meel et al., 2014):
”To develop, share and manage the water resources of Myanmar in an integrated, holistic and socially inclusive manner, to contribute significantly to the poverty alleviation, to the green growth and sustainable development of the nation, by providing access to water of equitable quantity and safe quality for all social, environmental and economic needs of the present and future generations.”
Although the second part of this statement is mostly relevant for water resources allocation issues, three relevant requirements for the development of a flood management system can be deduced from this goal:

- The system should be designed through an integrated and holistic approach, meaning that all relevant factors should be included. Water problems are inter-disciplinary and should be managed that way.
- The system should be sustainable in a social, environmental and economic way.
- The system should be designed in a socially inclusive manner. In other words, with the involvement of all the stakeholders and their wishes. Current stakeholders are amongst others the citizens within the Nyaungdon scope, which are mostly fishermen, farmers and the inhabitants of Nyaungdon Town.

The latter requirement can be further specified, following the needs and wishes of the stakeholders. Normally this would be done in consultation with the stakeholders, to validate that the drafted requirements indeed reflect how they would like to see the system to be designed. In this case the requirements are based on literature and consultation with citizens and experts from Myanmar, though not from the Nyaungdon area. Since they are still only top level requirements and abstract wishes, they cannot be formulated in a SMART way (specific, measurable, agreed upon, realistic, time-related). However, it will suite the function of drafting an appropriate flood management system. Requirements and wishes related to farmers are:

1. Minimal decline in the yield of rice fields due to the new flood management system. The current regular floods deposit fertile alluvium on their land and moreover, can serve as irrigation (Steijn et al., 2015). The to be designed flood management system has to take these benefits of flooding in the form of fertility and sufficient water resources into account or at least be compensated for it.

2. Protect farmers/rural citizens against severe floods. The regular events are floodplain flooding without embankment failure. This implies that the water rises slowly and no high water velocities are reached, resulting in hardly any casualties (Steijn et al., 2015). With severe flooding, events are meant that have the ability to make fatalities. However, when farmers are commended by the authorities to evacuate to diked areas, they often choose not to, since they do not wish to leave their properties (Win Min Oo, 2017). The new system has to take this behaviour into account.

Requirements and wishes related to fishermen are:

3. Enabling to remain close to the river and their fishery assets. As with the farmers, fishermen are located close to their assets, meaning that they currently often live on the outer side of the dike. This way they are close to the river and their boats. Furthermore, the land is cheaper than on the inner side of the dike (Blom et al., 2016).

4. Protect fishermen against floods. Since fishermen often live outside the dike protected area, their dwellings flood regularly. Although they seem to accept this situation, a higher protection level is always desirable.

Requirements related to urban citizens:

5. Protect urban citizens against flooding. The town of Nyaungdon is densely populated, which means that the risk related to flood events is high, both economic as in loss of life. The town is already protected with a dike that is recently heightened. However, the current erosion process is reducing its strength. This should be taken into account when choices are made for the preventive safety layer.

Operations Domain
The solution space can be further bounded by envisioning how the system should be deployed, operated and, when there is looked at the whole life cycle of the system, disposed. This is called the operations domain solution. The requirements that can be deduced within this domain for deploying the system are the following:

6. Fitting the current measures. Several safety measures are already in place within the scope, which might be improved instead of starting from the beginning. As noted before, the town of Nyaungdon is protected by a dike. Different types of dike sections are present, namely an earthen dike covered with revetments, a dike combined with concrete walls or a combination of the two. The concrete walls were used when houses were located too close to the dike and the choice has been made to keep the houses in place instead of removing them to enable traditional dike heightening. Some third layer measures are also present, although crisis management is not worked out in detail. Most of the communities in the delta region have experience with regular floods and they evacuate to monasteries and schools when needed (Win Min Oo, 2017). The responsible institution for water level measurements on a national level is the Department of Meteorology and Hydrology, which also sends out early warnings. Their warnings can be broadcast via the governmental MRTV, the Myanmar Radio and Television organisation, or commercial media. On a local level, every morning the water levels of the upstream towns of Mandalay (7 days upstream) and Hinthada (1 day upstream) are gathered. If the water level reaches a critical level, the chairmen of the different villages discuss what to do. A local disaster plan is provided by the nationwide evacuation committee, but the level of detail is low and the plan is not concrete (Blom et al., 2016). If early warning is needed, a car with microphones informs the area.

7. Little disturbances to the inhabitants of the scope area. Deduced from the National Water Policy the flood management system should be developed in an integral and socially inclusive way. This is needed for the measures themselves, but this can also be applied to the deployment/construction of measures.

Requirements related to how the system should be operated and supported are as follows:

8. Maintainable with the local knowledge and capacity. Due to its history and the closure of Myanmar from the rest of the world, the water resources knowledge and expertise is lacking behind (Van Meel et al., 2014). Measures should be maintainable with an appropriate level of knowledge.

9. Coping with changes in the natural environment. Ongoing changes are amongst others the global climate change and the resulting sea level rise, leading to relative land subsidence. If absolute land subsidence already is or will be a problem is not clear due to lack of data (Van Meel et al., 2014). Climate change is likely to result in more severe storms, higher river discharges and thus higher flood risk. Also the dynamic behaviour of the Ayeyarwady River, that is able to erode river bends and create land somewhere else, should be taken into account.

Behavioral Domain

The last step before translating the solution space into a physical design and selecting the best alternative is working out the behavioural domain solution. In this domain solution the required capabilities are identified, in other words the functions and performance of the system. This also includes how the system is to react to external stimuli arising from the operating environment. In this case the performance covers amongst others the safety levels of the preventive layer, but this will be determined on the basis of the cost benefit analysis. A behavioural requirement concerning external stimuli from the operating environment is the following:

10. Robust to changes in administration. Although Myanmar has already undergone its democratic reforms several year ago, further changes in the administration on national, regional or local level are not unlikely. Water resources management and flood protection should however be able to function for a longer period beyond the influence of politics.

B

Floods

This appendix elaborates on flood related analyses. Its first part shows how the Gumbel water level distribution is found. It thereby supports Section 3.2.1. The second part provides the historic flood events that are used as benchmark values for the estimation of loss of life.

B.1. Water level distribution

Two methods exist to approximate measured data by a distribution: considering all measured water levels or only those higher than a certain threshold. In the main report, both options are provided. This appendix gives the underlying data.

B.1.1. All water levels

An Extreme Value Analysis on the annual water level data has been used to be able to say something about the probability of water levels to occur. The total range between the measured water levels can be divided into small interval classes. In this case an interval of 5cm is chosen. The measured water levels are subsequently placed in their corresponding class. By counting the frequency of occurrence of an interval and dividing it by the total number of measurements, the probability of a river water level to fall within that interval is found. This process is given in Table B.1. The total number of measurements is 31, the probability p of a water level falling in a specific interval is found by dividing the counted number per interval by 31. To find the cumulative density function P, the cumulated counted number is divided by 31. Subsequently the probability of exceedance P_{exc} is determined by $1 - P$. The corresponding return period T is given by the inverse of the probability of exceedance.

A distribution that fits this data is now needed to be able to say something about the water levels with lower probabilities of exceedance/higher return periods. The Gumbel distribution was used for this in the main report. The location and scale parameter have been derived through the Method of Moments. This lead to the equation for the probability of exceedance:

$$P_{exc}(h) = 1 - e^{-e^{-\frac{h-709.23}{34.08}}} \tag{B.1}$$

When the interval water levels are filled in into this equation, the Gumbel P_{exc} in column eight of Table B.1 are found. By comparing column six and eight or seven and nine it can be seen that the Gumbel approximation differs more from the measured data as the probabilities decrease (or return periods increase).

Table B.1: *Water level statistics (all levels)*

Interval	Counted	Cumulative	p	P	P_{exc}	T	Gumbel P_{exc}	Gumbel T
630-634	1	1	0.0323	0.0323	0.9677	1.0333	1.0000	1.0000
635-639	0	1	0	0.0323	0.9677	1.0333	0.9999	1.0001
640-644	0	1	0	0.0323	0.9677	1.0333	0.9995	1.0005
645-649	1	2	0.0323	0.0645	0.9355	1.0690	0.9986	1.0014
650-654	0	2	0	0.0645	0.9355	1.0690	0.9966	1.0034
655-659	0	2	0	0.0645	0.9355	1.0690	0.9926	1.0074
660-664	0	2	0	0.0645	0.9355	1.0690	0.9856	1.0146
665-669	0	2	0	0.0645	0.9355	1.0690	0.9743	1.0264
670-674	2	4	0.0645	0.1290	0.8710	1.1481	0.9577	1.0442
675-679	1	5	0.0323	0.1613	0.8387	1.1923	0.9348	1.0697
680-684	0	5	0	0.1613	0.8387	1.1923	0.9054	1.1045
685-689	0	5	0	0.1613	0.8387	1.1923	0.8695	1.1501
690-694	1	6	0.0323	0.1935	0.8065	1.2400	0.8277	1.2082
695-699	2	8	0.0645	0.2581	0.7419	1.3478	0.7809	1.2805
700-704	3	11	0.0968	0.3548	0.6452	1.5500	0.7305	1.3689
705-709	0	11	0	0.3548	0.6452	1.5500	0.6777	1.4756
710-714	2	13	0.0645	0.4194	0.5806	1.7222	0.6238	1.6030
715-719	1	14	0.0323	0.4516	0.5484	1.8235	0.5701	1.7539
720-724	0	14	0	0.4516	0.5484	1.8235	0.5177	1.9318
725-729	1	15	0.0323	0.4839	0.5161	1.9375	0.4672	2.1405
730-734	1	16	0.0323	0.5161	0.4839	2.0667	0.4194	2.3844
735-739	0	16	0	0.5161	0.4839	2.0667	0.3747	2.6690
740-744	0	16	0	0.5161	0.4839	2.0667	0.3333	3.0003
745-749	1	17	0.0323	0.5484	0.4516	2.2143	0.2954	3.3856
750-754	3	20	0.0968	0.6452	0.3548	2.8182	0.2609	3.8331
755-759	3	23	0.0968	0.7419	0.2581	3.8750	0.2298	4.3524
760-764	0	23	0	0.7419	0.2581	3.8750	0.2018	4.9548
765-769	2	25	0.0645	0.8065	0.1935	5.1667	0.1769	5.6534
770-774	2	27	0.0645	0.8710	0.1290	7.7500	0.1547	6.4630
775-779	1	28	0.0323	0.9032	0.0968	10.3333	0.1351	7.4013
780-784	0	28	0	0.9032	0.0968	10.3333	0.1178	8.4884
785-789	1	29	0.0323	0.9355	0.0645	15.5000	0.1026	9.7478
790-794	0	29	0	0.9355	0.0645	15.5000	0.0892	11.2066
795-799	1	30	0.0323	0.9677	0.0323	31.0000	0.0775	12.8963
800-804	1	31	0.0323	1	0		0.0673	14.8535

B.1.2. Peak over threshold

The second method is the Peak over Threshold (PoT). The Peak over Threshold (PoT) method filters out the extreme values by only taking water levels into account above a certain threshold. In this case the threshold was set to be 700cm +MSL. The same process as described above can be walked through. The results are given in Table B.2. In the main report the PoT Gumbel distribution was derived to be the following:

$$P_{exc}^{PoT}(h) = -0.74 * e^{-e^{-\frac{h-734.29}{23.90}}} + 0.74 \tag{B.2}$$

Its results are again given in the most right two columns. Compared to the method that used all values, this seems a better approximating for higher return periods. However, small return periods are less accurate. Since the flood events have higher return periods, this method is still seen as the best approximation for the measured water levels.

Table B.2: *Water level statistics (peak over threshold)*

Interval	Counted	Cumulative	p	P	P_{exc}	T	Gumbel P_{exc}^{PoT}	Gumbel T^{PoT}
700-704	3	3	0.1304	0.1304	0.8696	1.1500	0.7308	1.3684
705-709	0	3	0	0.1304	0.8696	1.1500	0.7173	1.3941
710-714	2	5	0.0870	0.2174	0.7826	1.2778	0.6951	1.4386
715-719	1	6	0.0435	0.2609	0.7391	1.3529	0.6630	1.5082
720-724	0	6	0	0.2609	0.7391	1.3529	0.6215	1.6090
725-729	1	7	0.0435	0.3043	0.6957	1.4375	0.5722	1.7477
730-734	1	8	0.0435	0.3478	0.6522	1.5333	0.5177	1.9316
735-739	0	8	0	0.3478	0.6522	1.5333	0.4609	2.1697
740-744	0	8	0	0.3478	0.6522	1.5333	0.4044	2.4730
745-749	1	9	0.0435	0.3913	0.6087	1.6429	0.3503	2.8549
750-754	3	12	0.1304	0.5217	0.4783	2.0909	0.3001	3.3325
755-759	3	15	0.1304	0.6522	0.3478	2.8750	0.2547	3.9267
760-764	0	15	0	0.6522	0.3478	2.8750	0.2144	4.6637
765-769	2	17	0.0870	0.7391	0.2609	3.8333	0.1793	5.5759
770-774	2	19	0.0870	0.8261	0.1739	5.7500	0.1492	6.7034
775-779	1	20	0.0435	0.8696	0.1304	7.6667	0.1235	8.0957
780-784	0	20	0	0.8696	0.1304	7.6667	0.1019	9.8139
785-789	1	21	0.0435	0.9130	0.0870	11.5000	0.0838	11.9335
790-794	0	21	0	0.9130	0.0870	11.5000	0.0687	14.5476
795-799	1	22	0.0435	0.9565	0.0435	23.0000	0.0563	17.7710
800-804	1	23	0.0435	1	0		0.0460	21.7452

B.2. Historic flood events

As a benchmark value for the expected loss of life, historic flood events in Myanmar are used. The United Nations Office for the Coordination of Humanitarian Affairs (OCHA) has been providing humanitarian information on global crises and disasters since 1996 on the website `ReliefWeb.int`. All monsoon flood events since 1991 are presented in Table B.3. Tropical storms, cyclones and flash floods are not included, since those events do not represent the flood scenarios comparable to flooding from the Ayeyarwady River near Nyaungdon.

Table B.3: *Fatality rates of Myanmar floods 1991-2016*

Period	Location	Population affected	Fatalities	Fatality rate	Source
July 1991	Sagain Region	359,976	23	$6.39 \cdot 10^{-3}$ %	OCHA (1991)
July 1997	Mon State; Bago and Ayeyarwady Regions	103,650	68	$6.56 \cdot 10^{-2}$ %	OCHA (1997)
July 2013	Kayin, Mon and Rakhine States; Tanintharyi and Ayeyarwady Regions	73,300	6	$8.19 \cdot 10^{-3}$ %	OCHA (a) (2013)
September 2013	Across the country	22,000	0	0 %	OCHA (b) (2013)
October 2013	Bago Region	50,000	2	$4.00 \cdot 10^{-3}$	OCHA (c) (2013)
July 2015	Across the country	178,000	48	$2.70 \cdot 10^{-2}$	OCHA (2015)
June 2016	Chin and Rakhine States; Ayeyarwady, Bago and Sagain Regions	26,000	14	$5.39 \cdot 10^{-2}$	OCHA (2016)
			Average	**$2.36 \cdot 10^{-2}$%**	

C
Population and housing

This appendix elaborates on how the population and housing densities have been derived for the Nyaungdon case study area. Although a recent census is available, it cannot be used straight away in the estimation of population and housing densities.The census makes a distinction in the urban and rural population. However, the scope area of Nyaungdon does not match the townships of the census, since the scope is chosen to be smaller than the township. Moreover does Nyaungdon township has multiple urban areas.

Another location nearby is used to determine the population and housing densities: Dala. The township of Dala has the benefit that it only consists of one urban area, the rest is rural area. By combining the data from QGis and the census, an estimation of the population and dwellings can be made. The area of Dala is depicted in C.1. In the left picture the urban area of Dala township is bounded, which has an area of 9,264,367 m^2. The right picture displays the land use map for the area. If the assumption of the urban area is correct, a population of 119,366 should live within this area according to the census of the Ministry of Population (2015b).

Figure C.1: *Dala population determination. Left: urban scope, right: land use map*

The distinction between normal building density and high building density is made on sight. The high density built up area within the town clearly distinguishes itself from the rest, when there is looked at satellite images. Within the urban scope, the normal built up area amounts 4,012 raster cells in QGis, the high density built up area 3,667 raster cells. Still a guess has to made about the difference in building density. By counting dwellings and comparing both types of built up area, it is estimated that 1/3 of the urban population lives in the normal configuration and 2/3 of the population lives in the high density built up area. This means the following for the population densities:

$$\text{Population in normal configuration} = \frac{119,366 \times \frac{1}{3}}{4,012} = 9.92 \text{ inhabitants/cell}$$

$$\text{Population in HD configuration} = \frac{119,366 \times \frac{2}{3}}{3,667} = 21.70 \text{ inhabitants/cell}$$

The normal population density has been applied to the rural area of Dala. The estimation of normal built up cells times the population density matches the rural population of 53,491 from the census quite well. Now, to make an estimation of the housing densities, the above values of population densities are combined with the average size of households. According to the census this is 4.5 persons for Dala. It is assumed that one household shares one dwelling. For the housing densities this implies:

$$\text{Housing in normal configuration} = \frac{9.92}{4.5} = 2.20 \text{ dwellings/cell}$$

$$\text{Housing in HD configuration} = \frac{21.70}{4.5} = 4.82 \text{ dwellings/cell}$$

These are the housing densities that are used for Nyaungdon as well.

D

Shelter efficiency

If all three measures are combined in the optimisation process, there are certain interdependencies between the different measures. The loss of life in the open area is affected by both the houses on poles as shelters, since the mortality rate reduces when the poles get longer. This reduces the efficiency of the shelters A and D to H. The loss of life in the diked area is affected by the dike heightening and the shelters that are located in that area. This implies that shelters B and C become less efficient when the dike is heightened. This also means that the order of most efficient shelters changes continuously for different combinations of measure specifications.

This appendix provides an overview of how the different shelters reduce in efficiency for all possible pole lengths. This information is used in the optimality calculations. If the specifications of measures is such that the order of efficiency differs from the original situation, this information is needed to see which shelters need to be constructed. The overview of efficiency is presented in Figure D.4 on the next page.

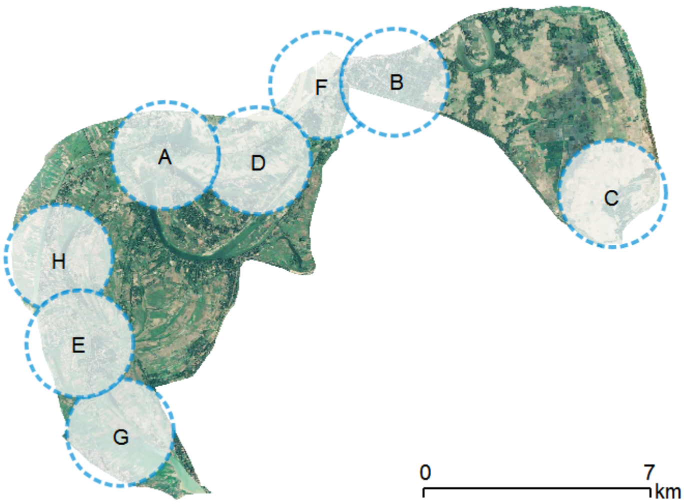

Figure D.1: *Shelter map*
Source underlying map: Google Maps (2016)

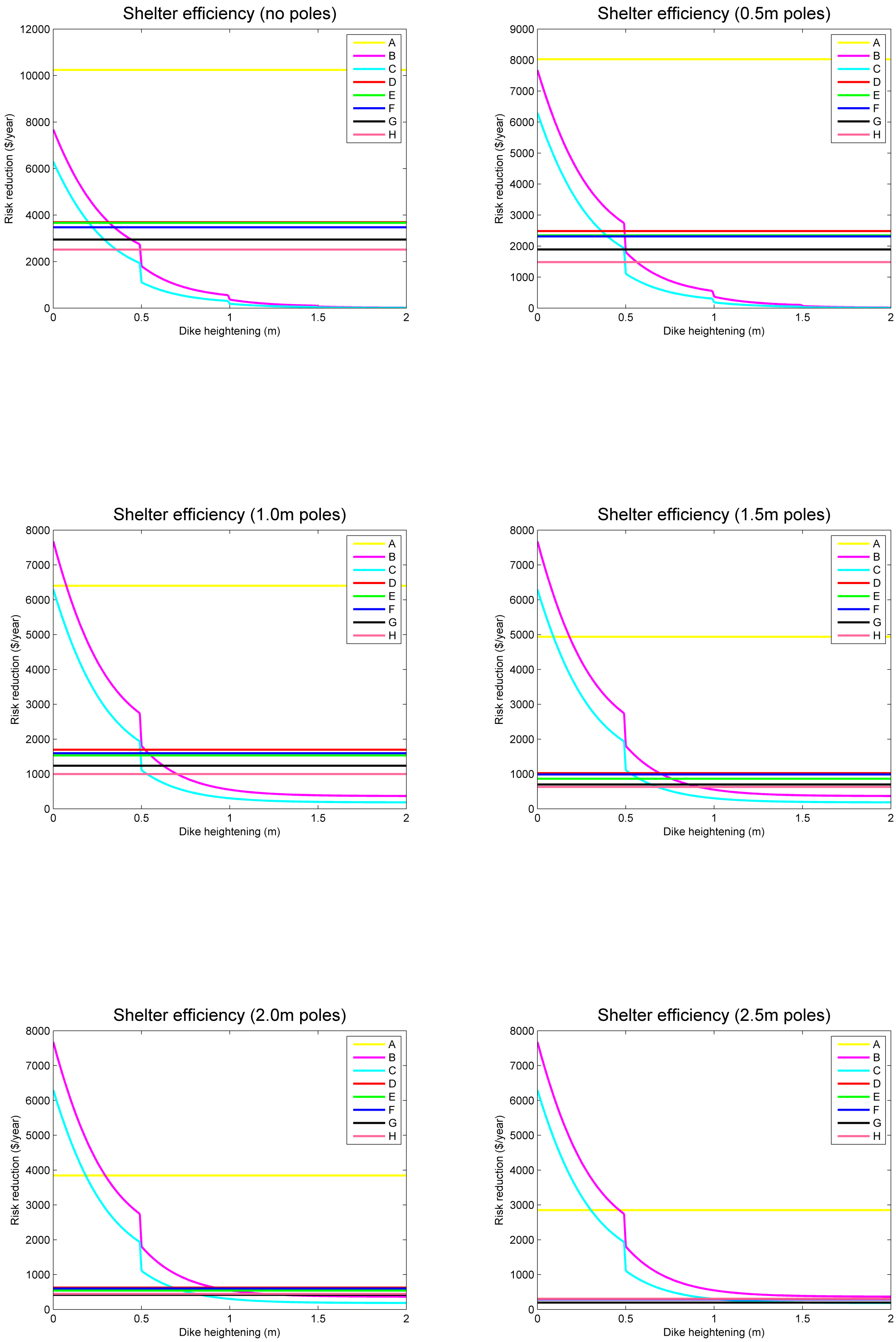

Figure D.4: *Effect of dike and pole heightening on shelter efficiency*

E

Uncertainty distributions

In the main report an overview of the used uncertainty distributions for the Monte Carlo analysis is given. This appendix provides the derivation of these uncertainties. Some are based more on grounded analyses than others. In the case that no indication of the uncertainty could be found, mostly boundaries of ± 30% were used.

Land use

The land use map is based on the satellite images from the Landsat program of NASA. These images have a resolution of 1 arc-second or around 30.87m. The most recent image was subsequently analysed in QGis, where the land was classified into the main land use types: crops, fish ponds, bushes/vegetation, built up area, high density built up area and water. Since the tool that was used is semi-automatic and the resolution is relatively coarse, some differences between the real land use and the classified land use might be present. The accuracy can be determined simply by comparing the Landsat image with the composed land use map. This is done in Figure E.1. It shows a piece of the scope, located west of the fish ponds. The upper right map shows the satellite image, the lower right picture the land use map. The large, left, picture shows the satellite image with an overlay of the land use map.

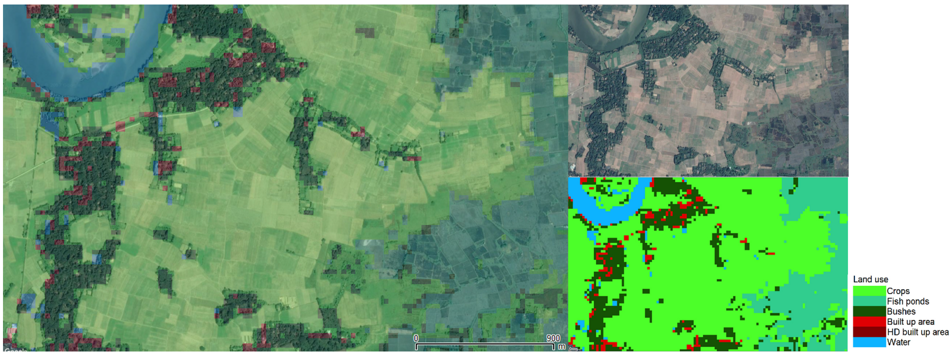

Figure E.1: *Comparison of satellite image and land use map. Left: land use map overlay. Upper right: satellite image. Lower right: land use map. Source underlying maps: Google Maps (2016)*

It can be seen that the land use type of water gives a good match between the generated land use map and reality, apart from some inaccuracies around the plots of vegetation and housing. In general the boundaries between the field of crops and the fish ponds are well set. Only the lower left part shows a difference between the satellite image and the land use map: the crops extend to far into the ponds. However, also from the satellite image it cannot be clearly see where the fish ponds start and the crops end. The same problem holds for the groups of houses and bushes. Such groups are well distinguished from the other land use types, but since bushes are present around the dwellings, both types are difficult to distinguish from each other. Even on satellite images the distinction is not clearly visible.

There needs to be zoomed in to clearly separate the houses from the bushes. Then it can be seen that at some locations the bushes are overrepresented in the land use map, at other locations the dwellings.

Over all the land use maps gives a good match when it is compared to the satellite image. A small uncertainty is present in the fish ponds and therefore also the crops. After all, if the fish ponds increase in size this is at the expensive of the crops land use type. To be able to model the uncertainty in amount of crops and fish pond cells, the choice is made to put a uniform spread of 5% around both types of flooded land use cells. In reality, their quantities are dependent on each other, but this is not taken into account here. Most uncertainty arises in the built up cells, which might be present in greater or smaller extent than depicted in the land use map. A uniform spread of 25% is put around the amount of flooded built up cells. Both the 5% as the 25% are based on observation and not on extensive analysis. These uncertainties could be reduced when more time is spend on the land use map construction in QGis. Google Maps (2016) provides new satellite images on a regular basis, so this is a good source of open data. With increased effort the land use maps can match these images more and more, thereby reducing the uncertainty around this parameter.

Land values

Crops

So far the rice production costs and yield of Tin Htoo Naing (n.d.) have been used, as that article provides the information that is specific for monsoon paddy rice in the Ayeyarwady Region. The assumption was that the rice fields would be halfway the main growing season when the monsoon floods take place in July/August. This would imply that the total revenue of $541/ha can get lost and half of the production costs of $379/ha, so $190/ha, will be lost. This, however, includes some uncertainties. First of all, the used values are average values for the Ayeyarwady Region according to a survey in 2012. Amongst others the yield differs per rice variety from 2.80 to 3.85 ton/ha, with a weighted average of 3.30 ton/ha (Tin Htoo Naing, n.d.). If the yield of $541/ha corresponds to the weighted average of 3.30 ton/ha, than the yield corresponding to the 2.80 ton/ha is $459/ha and the yield corresponding to 3.85 ton/ha is $631/ha. These are however based on one source. Other sources mention $392/ha for rice in Cambodia (Shrestha et al., 2014) or even $840/ha for the Philippines (De Padua, 1998). Furthermore, even the average rice price is fluctuating over the years. Figure E.2 shows the price trend of Indica rice from 1960-2009, together with two other cereals. Although linear regression will show a slightly positive slope over the years, the price of rice can highly fluctuate (Global Rice Science Partnership, 2013).

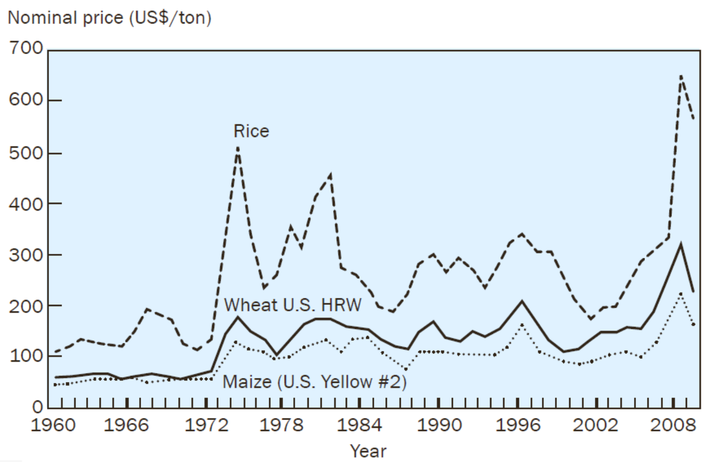

Figure E.2: *Price of Indica rice trend 1960-2009. Source: Global Rice Science Partnership (2013)*

Second, more expert knowledge is also required to validate how the production costs are spread over the growing season. Most labour is probably needed at the start of the growing season (planting seeds, transplanting the seedlings to the paddy) and the end of the season (harvesting). If flooding halfway the season also implies that half of the production costs is lost is uncertain. It might well be that the planting phase is more labour intensive than the harvesting phase, or the other way around. Flooding halfway

the season could therefore mean that roughly $100/ha or $250/ha of the production are wasted.
Summarising, the average yield of $541/ha based on Tin Htoo Naing (n.d.) is most likely, since it is location specific and based on a fairly recent research. This is however an average value for the Ayeyarwady Region and $459/ha or $631/ha are possible as well. Based on historic trends the price can fluctuate heavily and other sources mention higher or lower values, although for different countries. As regards to the lost production costs $190/ha is most likely, but that might well be $100/ha or $250/ha. Adding the lost yield and wasted production costs, the most likely value is $731/ha. The lower bound is based on the lowest production costs and yield, corresponding to $492/ha. The upper bound is based on the highest values, leading to $1090/ha. The intention is that the intermediate values are still quite likely. When a triangular distribution is chosen between the lower and upper bound with $731/ha as most likely value, this is the case. The boundaries could get closer to its mean value when the rice sector is better explored or when the values originate from the farmers in the Nyaungdon area. The fluctuation of the rice price remains however unstable, so some uncertainty will always remain.

Fish ponds
Compared to rice, the information on aquaculture in Myanmar is much more limited. The only quantitative reports on fish ponds in Myanmar that has been found is that of the UN Food and Agriculture Organization (2003) and UN Food and Agriculture Organization (n.d.). The first estimation was based on average fish price and average yield. The average fish price comes from regions other than the Ayeyarwady Region, but are likely to be comparable. The yield is based on the yield in the southern regions of Myanmar. Both are uncertain by deviating from the average values. The same holds for prawn farming.
Although the average fish price was around 600 Kyat/kg, prices range from 200-980 Kyat/kg, depending on the type of fish. From satellite images it cannot be seen which type of fish is being grown, so the whole range is possible. As regards to the yield, further numbers besides the average value are not given. Literature concerning other countries show large varieties in yield. Fish production in China can range from 4 ton/ha for usual fish farming up to four times this amount for intensive farming (Mukherjee, 1992). Clearly the uncertainties in the maximum fish pond value are large. The lower bound is set at a fish price of 200 Kyat/kg and a production of 4 ton/ha per year, leading to $590/ha. The upper bound is a price of 980 Kyat/kg and a yield of 16 tons/ha, resulting in $11,500/ha. Most likely is the average value of $5,200/ha, as this number can be reached by multiple combinations of fish price and pond yield. The distribution between the three points is therefore chosen to be triangular, so that the average value has the highest probability. This large uncertainty can only be reduced when more information can be acquired from the fish farmers.

Built up
Until now, the value of a dwelling was based on the values of bamboo, wooden and concrete houses and how much of these houses are present in the Nyaungdon township. From this data the 'average' house within the case study was constructed. This average house has a value of $3,000. The individual values come from the Irrigation Department, the percentages of the different houses are based on the UN census. Both are probably a good indicator. The uncertainty that arises in this value is small compared to the uncertainty in the number of houses per built up raster cell in the QGis model, both in the normal configuration as the high density configuration. These density numbers were again based on the UN census, combined with satellite images and QGis, see Appendix C.

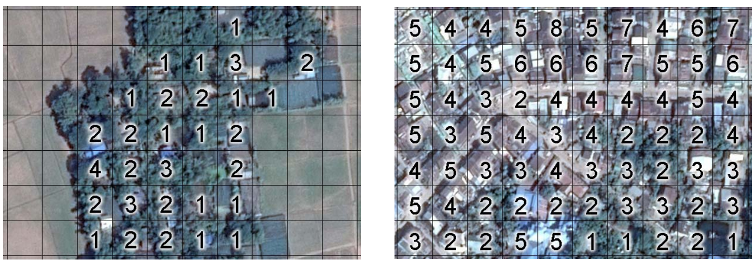

Figure E.3: *Counted houses on QGis grid. Left: normal configuration. Right: high density configuration. Source underlying map: Google Maps (2016)*

The pictures in Figure E.3 show an indication of how the houses are distributed over the grid. The left picture shows a normal configuration of houses in the rural area, the right is located in the middle of Nyaungdon Town. In each grid cell the number of houses is counted and displayed. It can be seen that the numbers fairly match the computed values of 2.2 and 4.82 houses in the normal and high density configuration, respectively. The averages of the depicted numbers are however 1.6 and 3.8 houses/cell. Although this does not mean that the computed numbers are wrong, since it are only small parts of the total scope area, it does show that there is some uncertainty in the numbers. To include this uncertainty, the number of houses per cell are set to be 2.2 ± 0.6 dwellings/cell and 4.82 ± 1.0 dwellings/cells for the normal and high density configurations respectively. For the values of normal built up cells, this means that they range from $4,800-$8,400/cell. For high density cells the value ranges from $11,460-$17,460/cell. Both are uniformly distributed, as no value is more likely as the other. As with the land use uncertainty, the uncertainty will reduce when the satellite images are explored more extensively, so that the housing densities can be estimated in a more profound way.

Population densities

The spread in housing densities also affects the estimation of fatalities due to floods. Up to now the loss of life was estimated with the number of inhabitants per cells, but if the number of dwellings per cell is uncertain, so is the number of inhabitants. According to the Ministry of Population (2015a), the average household size is 4.2 human beings and seen as a certain number. This resulted in population densities of 9.23 and 20.25 inhabitants/cell for the normal and high density built up configuration, respectively. With the spread in dwellings this turns into 9.23 ± 2.52 inh/cell and 20.25 ± 4.2 inh/cell for normal and high density. This is however not the only uncertainty in the estimation of economic loss of life, also the life valuation is uncertain, as given in the next paragraph.

Life valuation

In general, two methods exist to determine the value of statistical life: the behavioural approach and the non-behavioural approach. The first is based on willingness to pay, the latter on the macro-economic valuation of life. The latter will result in a lower valuation than the first. Until now the non-behavioural approach has been used, based on the macro-economic valuation of the productivity of an individual. This resulted in an estimated value of $58,000 per person. The difference in economic damage between both methods can be large. Which method will be used is a matter of choice; the spread between them cannot be seen as knowledge uncertainty. Both methods will be used separately in the uncertainty analysis. The individual methods do however include some uncertainties.

Behavioural approach

This approach is based on the willingness to pay by the public to reduce the risk of flooding. This means that the type of risk and the risk perception are of influence for the valuation of life (Jongejan et al., n.d.) The willingness to pay has to be determined through questionnaires. Such information is not available for Myanmar. A guess can however be made based on Dutch values.

A study of Bockarjova et al. (2009) has shown that the valuation of statistical life for flood events in the Netherlands is between €6.3 and €7.2 million. The uncertainty in this number is due to the fact that it is highly dependent on the context. As calculation value €6.7 million is often used. This number does not reflect the purchasing power of Myanmar and can therefore not be used one on one. By scaling it to its GDP per capita, a first indication can be found of the willingness to pay. The GDP per capita in the Netherlands is around $50,800, that of Myanmar $6,000 (CIA, 2016). If €6.7 million corresponds to the Dutch GDP per capita, by ratio the value for Myanmar is €790,000 or $860,000. However, this value would depend highly on the risk perception and might be completely different if it is actually based on questionnaires in Myanmar. A large uncertainty is therefore present in this value, since no information is available on willingness to pay. A uniform distribution of $660,000-1,060,000 will be used.

Non-Behavioural approach

The non-behavioural approach is based on people's productivity. The equation that was used for this included life expectancy, the average age and a discount rate. The first two values are fairly certain. The discount rate ranges in a uniform distribution from 9-13%, as will be shown later on. A lower discount rate values future expenses higher compared to higher rates. A 9% discount rate results in a valuation of life of around $64,000. Higher discount rates have the opposite effect. A 13% discount rate reduces the valuation to $45,700. The valuation of life with this approach is therefore uniformly distributed between these two values. This uncertainty will only decrease when a choice in discount rate is made.

Shelter and evacuation rate
The loss of life calculations are largely based by benchmarking with historic events. An average fatality rate of $2.36 \cdot 10^{-2}$% has been derived, see Appendix B.2. The shelter and evacuation rate were subsequently determined by backward reasoning: they were chosen as such so that the fatality rate of the Nyaungdon case would be around $2.36 \cdot 10^{-2}$%. As a result around 4.2% of the affected population should remain exposed, implying that 95.8% of the population evacuated or took shelter. Due to the background of the determination of this number, the uncertainty is large. Looking at the historic data, there were also events where no one lost their life, fatality rates among the population at risk up to $6.6 \cdot 10^{-2}$% also took place. To arrive at this number, an combined shelter and evacuation rate of 88% is needed for this. Without further analysis of the behaviour of the inhabitants of the area and the possibilities to take shelter or evacuate, better estimations cannot be made. A uniform distribution will therefore be used between 88% and 100% combined shelter and evacuation rate. To reduce the spread, the behaviour of the inhabitants has to be explored by means of questionnaires. This can be questionnaires for the inhabitants, but an indication can probably also be given by relief organizations.

Dose-response function
Another important factor in the estimation of fatalities is the dose-response function. Jonkman (2007) derived dose-response functions based on historic flood events, mainly the 1953 flood in the Netherlands and the United Kingdom and the 1959 flood event in Japan. Distinctions are made between different zones: the breach zone, the zone with rapidly rising water and the remaining zone, see Figure E.4.

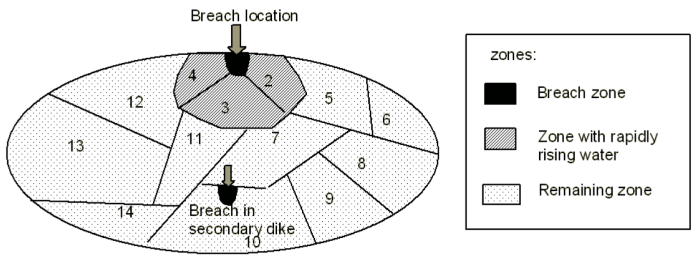

Figure E.4: *Floodzones according to Jonkman (2007)*

Until now the remaining zone was seen as most suitable, as for flood plain floods the water level rises slowly. However, this is only valid if there is no dike or when the river slowly overflows the embankment without letting it fail. If small embankments are made when high river levels are about to take place and such embankments fail during the floodwave, zones with rapidly rising water might be present. Furthermore, if the dike around the eastern part of the scope fails, such zones might be present. Figure E.5 shows the historic data and the best fitted trendline of both zones, together with a confidence interval. Moreover, Equation E.1 displays the trendline in lognormal equation form as derived by Jonkman (2007). Its parameters corresponding to the rapidly rising zone and remaining zone are given as well. Φ_N represent here the cumulative standard normal distribution.

$$F_D(h) = \Phi_N\left(\frac{ln(h) - \mu_{N,x}}{\sigma_{N,x}}\right) \tag{E.1}$$

$$\mu_{N,rapid} = 1.46 \qquad \sigma_{N,rapid} = 0.28$$

$$\mu_{N,remaining} = 7.60 \qquad \sigma_{N,remaining} = 2.75$$

Several things can be noted here. At first, the difference between the zone with rapidly rising water and the remaining zone in mortality rates runs up high for larger water depths. Where the remaining zone has mortality rates between 0 and 0.015 of the exposed population, the zone with rapidly rising waters

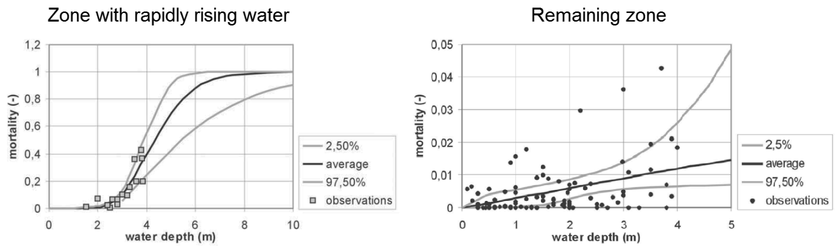

Figure E.5: *Relation between water depth and mortality rate. Left: rapidly rising zone. Right: remaining zone. Source: Jonkman (2007)*

has a mortality rate up to 0.6 for the same water depth of 5m. Fortunately, according to Equation E.1 and its parameters the mortality rates of both zones are comparable for water depths up to 2m. This implies that for this case study the choice between both zones is less important, since the average inundations for the different flood scenarios remain mostly below this level.
As second issue, the uncertainty around the remaining zone is large. The zone with rapidly rising water has an R^2 of 0.76, which indicates a fairly strong correlation between the data and the derived dose-response function. The R^2 of the remaining zone is only 0.09 (Jonkman, 2007). Although the choice between zones is considered less important for inundation depth up to 2m, this weak correlation results in significant uncertainty in the appropriate dose-response function. Important to notice is also that the data originates from more developed countries than Myanmar. Amongst others the difference in type of buildings (brick/concrete versus bamboo/wood) can be of effect in the mortality rate.

Since the exact data points are not available, an uncertainty analysis comparable to that of the flood probability function is not possible. The uncertainty still has to be quantified for the Monte Carlo analysis. Looking at the data points and the trendline of the remaining zone, the mortality rate can easily be half the amount less or more than determined by the distribution. The lower and upper bound for the uncertainty around the mortality rate are therefore $F_{D,remaining}$ ± 50%. Due to the weak correlation between data and estimator, a uniform distribution for the mortality rate is chosen. This gives all the possible values between the boundaries an equal probability. This uncertainty cannot easily be reduced. Similar research as that of Jonkman should be performed for flood events in countries like Myanmar. However, after that the uncertainty will probably still be large due to the spread in data points.

Depth-damage function

The uncertainty in depth-damage function is twofold: the choice for a specific function and the uncertainty within that function. Two start with the second: the functions are often derived from experiments or historic flood events. The curves are subsequently constructed by drawing a line through the scattered data points. This curve can only have a specific degree of goodness of fit and will always inherent some uncertainty bounds. The choice for an exponential or linear trendline can therefore already influence the damage estimations although they are both based on the same experiments, as shown by Notaro et al. (2014).
The uncertainty due to the choice for a specific function relates to the fact that it is not exactly known what kind of assets can get damaged. As an example, the depth-damage curve for houses in the flood risk analysis is the one constructed for rural dwellings in Cambodia. Whether the houses in Myanmar are comparable can only be assumed. Huizinga (2015) established an overview of depth-damage functions for different types of assets for every continent from literature. How the initially used depth-damage functions relate to others is given below.

Crops

The used function for rice is in most cases the upper boundary, based on the other depth-damage functions in the overview of Huizinga (2015). This might be due to the fact that the used function was derived specifically for rice in early in the growing season and more mature plants are less susceptible to inundation. To include uncertainty within the derivation of this function and the uncertainty due to the choice of this function, a lower bound is set by the values of the current depth-damage relation minus 0.3. The upper bounds are the current depth-damage values. A uniform distribution is chosen between the boundaries, so that the values in between are evenly likely. Of course can the damage not be lower than 0 or higher than 1. This uncertainty can in theory be reduced by extra experiments. However, a large amount of functions is already available for comparable situations and they still show deviations from each other. Some uncertainty will therefore always remain.

Fish ponds
The depth-damage function for the fish ponds could not be linked to any literature. The uncertainty is therefore large, but an indication of this uncertainty is also difficult to find. Therefore the current curve plus or minus 0.20 is used. Again the damage has to remain between 0 and 1. A uniform distribution between these boundaries is used. Better understanding of how fish ponds get damaged during floods can reduce this uncertainty. Experiments are needed for this, as historic data is probably not available.

Dwellings
Compared to the other depth-damage functions for rural houses in the overview of Huizinga (2015), the used function is intermediate. Furthermore is the spread between the functions for rural dwellings relatively small. The uncertainty bounds are therefore given by the current values plus or minus 0.15, as long as the damage remains between 0 and 1. The type of dwellings in the scope area should be verified in order to make a more sound choice between the different damage functions and thereby reducing the uncertainty. As with the other depth-damage functions, some uncertainty will always remain.

Digital Elevation Model
Within the use of the SRTM digital elevation model (DEM), three sources of uncertainty are present:

- *The vertical resolution of 1m*. The vertical resolution of the DEM is quite coarse. Especially when it is compared to the depth-damage functions and the discrete steps of the flood events. Imagine the flood scenario with water levels of 8.5m +MSL. If the true elevation of a rice field is 7.6m +MSL, this is rounded to 8m +MSL in de DEM. In reality , the land would be inundated with 90cm water, in the model it is only inundated with 50cm. For the crops, this would mean that in reality they would be damaged for around 40% (using the initial depth-damage function), while in the model there is no damage at all. It can however also work the other way around, so that there would be no damage in reality while there is significant damage in the model. It is expected that on average these two mechanisms counteract each other in the risk quantification. This is however not certain, so that a small spread around the flood depths is included: the flood depth is uniformly distributed around each mean with a deviation of 10cm on both sides.This uncertainty can only be reduced by working with a DEM that has a more fine vertical resolution.
- *The age of the DEM mission.* The DEM maps are based on the SRTM mission that took place in 2000. In the meantime, the bend of the Ayeyarwady River on the west side of the scope has moved more west. As a result the DEM displays water where there is land nowadays. Due to its large influence on the calculations, the DEM was already adapted. In the adapted DEM the former river bend matches the elevation of its surroundings. If in reality the elevation really equals its surroundings or if it has a lower elevation is not known. This can only be verified with a more recent DEM or an indication can probably also be given by field work at location. The effect of the age of the DEM is tried to be covered in the uniformly distributed flood depths with a deviation of 10cm, as it was derived for the error caused by the vertical resolution.
- *The error around elevated objects.* The DEM is constructed based on the duration between the moment a signal is send from the satellite, the signal gets reflected from the surface and this signal is picked up by the satellite again. If this signal hits plain ground, a good estimation of the elevation can be given. If however the signal reflects on other objects such as bushes and the roofs of houses, the elevation might be overestimated. In the DEM map that is presented before, the plots of bushes and houses (including Nyaungdon Town) have a higher elevation than its surroundings. This might be due to this reflection error. Such areas might therefore not flood in the QGis model, while they would flood in reality. The possible influence of this error will be

analysed by decreasing the elevation of built up area with 3m, as this is a reasonable elevation of dwellings. These means that the average inundation depth for built up land use increases with 3m. Subsequently the risks are compared to the initial situation. If this is really the case can only be found out with field work.

Influence of measures

The influence of measures on the risk reduction can also be uncertain. It is uncertain whether the dike and pole heightening have the desired effect. This is however an uncertainty due to the used schematisation of the measure and cannot be quantified. Contrary to these two measures, the efficiency of the shelters can be quantified. The efficiency of the shelters is dependent on the estimated number of fatalities within the scope of the shelters. The scope was estimated to have a 1.6km radius. The estimated number of fatalities is furthermore derived from the population at risk (so the flooded built up cells and the population densities), the evacuation/shelter rate, the dose-response function and the inundation depths:

$$N(h) = N_{PAR} \cdot (1 - F_E) \cdot (1 - F_S) * F_D(h) \tag{E.2}$$

The uncertainty of all these variables have been determined before in terms of percentages of its mean value in a uniform distribution. Only the deviation of the inundation depths h is in the order of ± 10cm, but this equals approximately ± 5%. The propagation of these uncertainties for such a multiplication function of the type $f = A \cdot B$ is (NIST/SEMATECH, 2012):

$$\sigma_f^2 = f^2 \left[\left(\frac{\sigma_A}{A} \right)^2 + \left(\frac{\sigma_B}{B} \right)^2 - 2\frac{\sigma_{AB}}{AB} \right] \tag{E.3}$$

In this equation σ_A or σ_B is the standard deviation of the variable and σ_{AB} the covariation between the variables. The latter can be disregarded here, since the variables are seen as independent from each other. As regards to the fraction of the standard deviation and the value of the variables, this is the same as depicting the uncertainty in percentages of its variable. To find the uniformly distributed uncertainty for the saved populations within the scope of a shelter, the square root of the sum of the squared individual percentages has to be taken. This results in an uncertainty of ± 56% for the saved populations. It is especially the uncertainty in the dose-response function (± 50%) that is of influence here. As this source of uncertainty is difficult to reduce, the efficiency of shelters will also remain dubious.
The scope of the shelters is uncertain as well. The 1.6km is based on research as presented by Paul (2009). Since the uncertainty of the dose-response function has such a large effect on the uncertainty of the saved population, it is assumed that the uncertainty in scope radius can be disregarded.

Discount rate

Choosing an appropriate discount rate can be an extensive process. The theoretical background is large and can in this thesis not be considered all to make a best estimate of the discount rate. The discount rate that is used in cost benefit analyses represents the time dependent value of money, including both the rate of time preference and the opportunity cost of capital (Carruthers, 2004). The first refers to the fact that some people prefer to have money earlier in the near future, while others care less. The latter means that having capital now instead of in the future is that extra capital can be produced by investing or earning interest on a bank. The effect of the size of the discount rate can be high. With high discount rates, the future benefits become less valuable. Since projects in flood management are aimed at the long term, this makes them less attractive in comparison to lower discount rates. The choice of discount rate can make the difference between accepting a project or disapproving it.

There is disagreement on whether to include a risk premium in the discount rate, to embrace uncertainty in the future (Harrison, 2010). When risk is disregarded, a good indicator for the discount rate is the interest rate on government bonds, since they are usually considered risk free. Looking at Myanmar's Government Treasury Bonds, the current interest rates are 8.75 percent for 2-year bonds, 9.0 percent for 3-year bonds and 9.5 percent for 5-year bonds respectively (Central Bank of Myanmar, 2017). A 10% discount rate is chosen as first estimate to fit long term investments. However, Myanmar is developing fast. Furthermore, it has only selling bonds through a public bidding system since 2015 (Aung Hla Tun, 2015). Historic trends are therefore not available and the stability of the Treasury Bonds is unknown.

Another factor influencing the choice of appropriate discount rate is that it is likely that investments in flood management systems come from international development banks. Examples are the World Bank, Asia Development Bank and the European Bank for Reconstruction and Development. All banks have established their own discount rate for infrastructure projects in developing countries, which are 10-12% (Harrison, 2010). The Handbook on Economic Analysis of Investment Operations of the World Bank states (Carruthers, 2004): *"Traditionally the World Bank has used 10% to 12% as the discount rate for all Bank-financed projects. This rate is but a rationing device for WB funds and should not be construed to reflect the cost of capital in borrowing countries. Task Managers are free to use higher or lower rates where warranted, as long as they provide a sound justification. A discount rate of less than 10% might be difficult to justify as most research has shown that the cost of capital for developing countries is higher than 10%"*. Fortunately the (estimated) discount rates for the government of Myanmar as the international development banks are in the same range. Based on the knowledge from above and the fact that Myanmar is a dynamic country where a lot can change in the future, the spread in discount rates is set at 9-13%. Since all values are equally likely, the discount rate is given a uniform distribution. An ultimate value can only be chosen in consult with the financing organisation, since the discount rate also represents their time preference with respect to investments.

Investment costs

Dike heightening

The marginal costs of dike heightening depend on how much earthen volume is added to the dike. The marginal costs are \$2.61/m^3, according to Nay Myo Lin (2017), employed at the Irrigation Department. These unit costs are therefore seen as relatively certain. Also the dike length can precisely be determined from satellite images. However, the assumptions that were made for the current shape of the dike and the shape of dike heightening are uncertain. The current shape is based on the earthen dike section around Nyaungdon Town, as collected by Blom et al. (2016). The cross section dimensions of the other dike sections around the town are not known. For the rest of the dike around the eastern part of the scope, even the shape is unknown. It is however established by Blom et al. (2016) that the current dike heights are not always at the standard crest height. Those current dike heights might well be half a meter below that of the idealized cross section, implying a current dike height of 2.5m instead of 3m. The effect on the extra needed volume due to this lower current dike height is to such an extent, that the current shape is probably of less importance. The uncertainty concerning the marginal costs are based on the uniform distribution of the current dike height, lying between 2.5m and 3m. Further certainty about the uncertainty in dike height cannot be given. The resolution of the DEM is too large to base the current dike heights on. Field work is the only way to gain more certainty in the current dike system.
As regards to the initial costs of \$2.67 million, this value was determined by benchmarking. Any better estimations are not available and neither are there any estimations on the uncertainty. To still include an uncertainty on this variable, it is given a triangular around its mean value with lower and upper bounds of the derived value minus or plus 30%, respectively. Consult with local contractors would result in a better estimation of this initial value and its uncertainty.

Poles heightening

Variables in the marginal costs of pole heightening are the amount of dwellings at risk, the number of poles per house and the costs of the poles. The dwellings at risk are dependent on the housing density, whose uncertainty has been given earlier. The number of poles was based on a traditional Bamar house, resulting in 21 poles per dwelling. Of course, not all houses are the same, some might be bigger, some might be smaller. Some houses might not even look like the traditional Bamar house. A triangular distribution of 21 ± 6 poles is used, as no further information is available on this matter. Field work would be needed to verify the type of dwellings and their number of poles. However, after that there will still be worked with an average value, thereby still embedding uncertainty. The costs of poles depends on the size and the type of wood. Poles of 20x20cm or 0.04/m^2 were assumed. No further information regarding this number is available, but it is seen as a fair size. The indigenous Pyinkado wood was seen as most likely construction material, costing around \$475/m^3. Wood prices of \$150/m^3 less or more than this value are however not uncommon (see for example Fordaq (2014)). Consult

with local contractors or suppliers are needed to reduce this spread. For now a uniform distribution is set on the wood costs of $475/m^3 ± $150/m^3.
Concerning the initial costs, the same ratio was used as for the dike heightening, resulting in initial costs of around $5 million. Again, not further information is available for this. The initial costs are given an triangular distribution around this mean value plus or minus 30%. A better estimation can only be given by local contractors.

Shelters
The costs of one shelter was based on the World Bank (2014), benchmarking with a shelter construction project in Bangladesh. The costs of $400,000 of these shelters is seen as a good estimate. However, a conversion was used, since the shelters in Bangladesh are larger than those required for the Nyaungdon case. This resulted in shelters of $62,000. Further information is not available, so again a triangular distribution around this mean value is used, with boundaries at plus or minus 30% of this value. The initial costs were estimated in a different way compared to the dike and pole heightening, but again benchmarked to the Bangladesh project. No further information is available, so also for the initial costs a triangular distribution around its mean value of $20,000 is used with a spread of plus or minus 30%. As with the other components of the investment costs, better estimations can only be made by those responsible for the construction: the local contractors.