LONG-TERM ADAPTIVE FLOOD RISK MANAGEMENT

Investing in coastal protection and stormwater management under deep uncertainty

TU Delft

H.J. van den Broek
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PREFACE

While initially challenging to find a thesis topic that would satisfy both masters, the topic I eventually found proved to be very engaging and rewarding. I gained a lot of knowledge in a field that was completely new to me, robust decision making, and combined it with the flood risk manaegment field.

This thesis serves to conclude my double degree in Hydraulic Engineering and Construction Management and Engineering. While initially challenging to find a thesis topic that would satisfy both masters, the topic I eventually found proved to be very engaging and rewarding. I gained a lot of knowledge in a field that was completely new to me, robust decision making, and combined it with the flood risk management field. The result is a newly designed and tested addition to the flood risk management approach for dealing with long-term uncertainty, which I think is especially necessary in a time of ever greater uncertainty due to climate change. It is a result I am proud of and I am happy that this is the culminating of years of studying.

I want to use this opportunity to thank the members of my committee for helping me to write this thesis. My gratitude goes to Erik van Berchum for his daily supervision, support in using FLORES and writing the thesis. I would also like to thank Jos Timmermans for introducing me to the topic of robust decision making, for advocating my thesis and arranging for me to speak at the Africa Works conference. I want to thank Matthijs Kok for chairing the committee and his view on robust decision making methods, which made me analyse and understand the topic in greater detail. Finally, I would like to thank Jan Kwakkel for always responding within minutes to my questions on robust decision making, his Exploratory Modelling Workbench and python related problems.

I want to thank my family, friends and girlfriend for their support and interest in the work. Especially my younger brother, with whom I could discuss the hydraulic engineering aspect of the work and discuss and check the written language. Finally, I want to thank and commemorate my grandfather for inspiring me to become a civil engineer.

Hidde van den Broek
Delft, August 2019

ABSTRACT

Flood risk management is the process of analysing, assessing and (if required) reducing flood risks, in terms of economic costs and affected population or loss of life. The analysis is performed through a probabilistic approach in which the factors are represented by a probability distribution function to address uncertainties. However, relevant factors in the analysis, such as mean sea level and the population living in the area, often are deeply uncertain on the longer term, resulting for example from climate change and changing socio-economic conditions. Generally, FRM explores these conditions through scenario analysis. However, the way FRM creates and analyses the scenarios is subjective and leaves open a lot of uncertainty. Often, only a limited set of subjective qualitative scenarios is made, which risks not taking scenarios into account that turn out to be important later. Quantitative scenarios become increasingly uncertain as the time horizon over which these are used lengthens, due to uncertainty in the trend.

This research investigates a new addition to flood risk management to support it in dealing with long-term deep uncertainty. It uses robust decision making approaches as an addition to the usual FRM approach, by analysing results for a much larger set of scenarios to increase robustness, both static and flexible, to different scenarios. It combines aspects of dynamic adaptive policy pathways (Haasnoot, Kwakkel, Walker, & ter Maat, 2013) and aspects from robust decision making (Lempert, Popper, & Bankes, 2003), with the FRM approach to create an eight-step iterative approach called Flood Risk Adaptation Pathways, which was later tested in a case study. The approach starts by analysing the current situation and possible futures, after which it determines the difference between those situations and the preferred state. Based on this, possible flood risk reduction measures are designed, and then tested on their performance in a flood risk screening model, to create so called effectiveness regions, which show under which conditions which solutions are effective in reducing the gap between states. Based on the effectiveness regions, pathways of actions over the different possible futures are created. A monitoring plan is then created, which defines the signposts and their trigger values. Finally, the situation is monitored and actions are implemented when required.

The Flood Risk Adaptation Pathways approach aims to provide policymakers with the ability to anticipate different futures, by creating actions, which meet the objectives, for a wide range of tested futures. It should allow policymakers to plan the implementation of measures ahead of time. The long-term situation is investigated, including the measures required at that point, and linked to the current situation, including the currently required measures. This should ensure that measures remain implementable by actively assuring the conditions for implementation are not violated, thus reducing negative effects of path-dependency. The link between the long-term measures and the current measures should also allow for an improved cohesion of the sequence of measures, with short-term measures providing a starting point for long-term measures. Finally, it narrows down the measures to the ones highlighted by the approach for later on in the process, when an action needs to be implemented.

The approach has been tested in a case study, on Beira, Mozambique, which is prone to severe rainfall and coastal flooding. Furthermore, compound flooding problems arise when high sea water levels coincide with rainfall events. The Flood Risk Reduction Evaluation and Screening model (van Berchum, van Ledden, Jonkman, Timmermans, & van den Broek, 2019) was used to model the current flood risk, as well as the effect of flood risk reduction measures on the flood risk, affected population and construction costs. For this research, the model was adapted to test specific actions over a set of changing conditions, to test their performance for the longer term. The approach was then used in the case study, following the steps (described above). The data was gathered from local sources and reference projects. After the completion of the case study, the approach was reflected upon: The main limitation arising from the case study, is the considerable computation time and time-consuming analysis of the results. Overall, Flood Risk Adaptation Pathways strengthen the FRM approach in dealing with long-term deep uncertainty, and thereby enhance the performance of flood risk reduction strategies under different than expected conditions.

GLOSSARY

Action/ Strategies	Actions (DAPP terminology (Haasnoot et al., 2013)) or strategies (FLORES terminology (van Berchum et al., 2019)) are a combination of flood risk reduction measures which, when put in sequence, form pathways.
Adaptation tipping point	"A point where the magnitude of change due to changing conditions is such that the current action will no longer be able to meet the objectives" (Haasnoot et al., 2013; Kwadijk et al., 2010).
Adaptation pathway	An adaptation pathway is "a sequence of water management policies enabling policymakers to explore options for adapting to changing environmental and societal conditions" (Haasnoot, Middelkoop, Offermans, van Beek, & van Deursen, 2012).
Adaptive/ dynamic policy	Incremental and adaptive policy, allowing uncertainties to be resolved over time and to adjust to the uncertainties as necessary by being dynamic (Walker, Rahman, & Cave, 2001).
Adaptive policymaking	An approach for the analysis and creation of an adaptive policy (Kwakkel, Walker, & Marchau, 2010; Walker et al., 2001).
Dynamic Adaptive Policy Pathways (DAPP)	Combination of adaptation pathways and adaptive policymaking (Haasnoot et al., 2013).
Deep uncertainty	"the condition in which analysts do not know or the parties to a decision cannot agree upon (1) the appropriate models to describe interactions among a system's variables, (2) the probability distributions to represent uncertainty about key parameters in the models, and/or (3) how to value the desirability of alternative outcomes" (Lempert et al., 2003).
Direct search	An approach in which optimization of operating policies is accomplished directly by the model by finding optimal parameters of the policy using system simulation results and performing iteration until an optimum is found (Momtahen & Dariane, 2007).
Drainage measure	Flood risk reduction measure which is specifically designed to improve the drainage capacity in the area of its construction to reduce flood risk from rainfall.
Effectiveness region	Range of the external factors in which a certain solution is an effective option for the study at hand.
Emergency measure	Flood risk reduction measure which aims to facilitate early evacuation to reduce the number of people affected by a flooding event.
Exploratory modelling	"The use of series of computational experiments to explore the implications of varying assumptions and hypotheses" (Bankes, 1993).
Exploratory modelling workbench	Python library, based on the XLMR framework, which uses models as functions to describe the relationships in the system. The library supports the input of external factors and policy levers, to run the model which then gives the performance metrics as output (Kwakkel, 2017).
External factor	Factors outside of the control of the policymaker, which influence the success of any policy or measure (Kwakkel, 2017; Lempert et al., 2003).
Feature scoring (FS)	Tool in the EMA-workbench, which is used to analyse the dependency of a performance indicator on policy levers.
Dynamic robustness/ Flexibility	Performance indicator, a high flexibility means that a solution is able to adapt well to different than expected conditions (Walker, Haasnoot, & Kwakkel, 2013).
Flood risk	Flood risk is flood probability times consequence, where the consequence is determined by the flood hazard and the flood vulnerability.
Flood risk management	The process of managing flood risks in order to satisfy a certain objective, which may or may not result in the use of flood reduction measures.
Flood risk reduction measure	These are measures designed to reduce flood risk (where flood risk, can be economic risk or in terms of affected population).

FLORES	Flood risk Reduction Evaluation and Screening model, a flood risk screening model (van Berchum et al., 2019).
Full factorial subspace sampling	Sampling with equal interval over the subspace of external factors.
Hydraulic boundary conditions	The external conditions that act upon the modelled region. In the FLORES model these are the influence of tide, storm surge, wave height, and rainfall (van Berchum et al., 2019).
Flood proving measure	Flood risk reduction measure that is implemented at the local level, thus influencing the vulnerability of the area at risk of flooding.
Long-term	In the context of this study long-term means a duration of 80-100 years or longer.
Performance metrics	Outcomes of interest for the study in question (Kwakkel, 2017; Lempert et al., 2003).
Patient Rule Induction Method (PRIM)	Tool in the EMA-workbench, which is used to find conditions under which certain performance thresholds are satisfied.
Policy lever	Individual measures, which are input for the model (Kwakkel, 2017; Lempert et al., 2003)
Rainfall intensity	Rainfall in mm/hour.
Relationships in system	The ways in which factors relate to one another, which is the core of any model (Kwakkel, 2017; Lempert et al., 2003).
Retention measure	Flood risk reduction measure that reduces flood risk in an area from pluvial flooding by improving the storage capacity of that area.
Risk analysis	The determination of the hazards and the vulnerability to the hazards to calculate the risk.
Risk assessment	Assessment of the calculated risk, to determine whether this is acceptable or not.
Robustness/ Static robustness	Performance indicator, a high robustness means that a solution is able to deal well with different than expected conditions (Walker et al., 2013).
Robust decision making (RDM)	An approach in which solutions are tested on the basis of robustness instead of optimum expected utility, with the aim of creating a robust strategy over different possible futures (Lempert et al., 2003).
Signpost	Information that should be tracked to monitor the adaptive plan (Haasnoot et al., 2013).
Structural measure	Flood risk reduction measure which is specifically designed to prevent coastal flooding.
Trigger	Value of a signpost at which an action should be implemented (Haasnoot et al., 2013).
Uncertainty region	The ‘area’ that falls within the ranges of uncertainty of the main external factors.
XLRM framework	A framework that uses exogenous uncertainties, policy levers, relationships, and measures to organise and analyse a situation to be modelled, see Figure A-2 (Kwakkel, 2017; Lempert et al., 2003). It is the basis of the set-up of the used EMA-workbench.

TABLE OF CONTENTS

1. INTRODUCTION

Flooding is a major problem in many low-lying coastal and riverine areas. Flooding can cause significant economic damage, fatalities and displacement of population. The three main types of flooding are coastal flooding, fluvial flooding and pluvial flooding. Coastal and fluvial flooding occur when high water levels in seas and rivers flood land adjacent to it. Pluvial flooding occurs when insufficient drainage or storage capacity is available to deal with high intensity rainfall events.

This study focusses on the conceptual design phase of flood protection projects, see Figure 1-1, and in particular on how to resolve the negative impact of long-term deep uncertainty of external factors, e.g. the impact of climate change on mean sea level. In the conceptual design phase, flood risk management is performed to analyse the situation and if required start the implementation process of flood protection measures, moving on towards the preliminary design phase.

Robust decision making approaches will be investigated, in order to find out if these can aid in reducing the negative impact of long-term deep uncertainty for the flood risk management approach. For this the study employs a model-based approach, meaning that a model will be central to the exploration of the flood risk and the uncertainties influencing it.

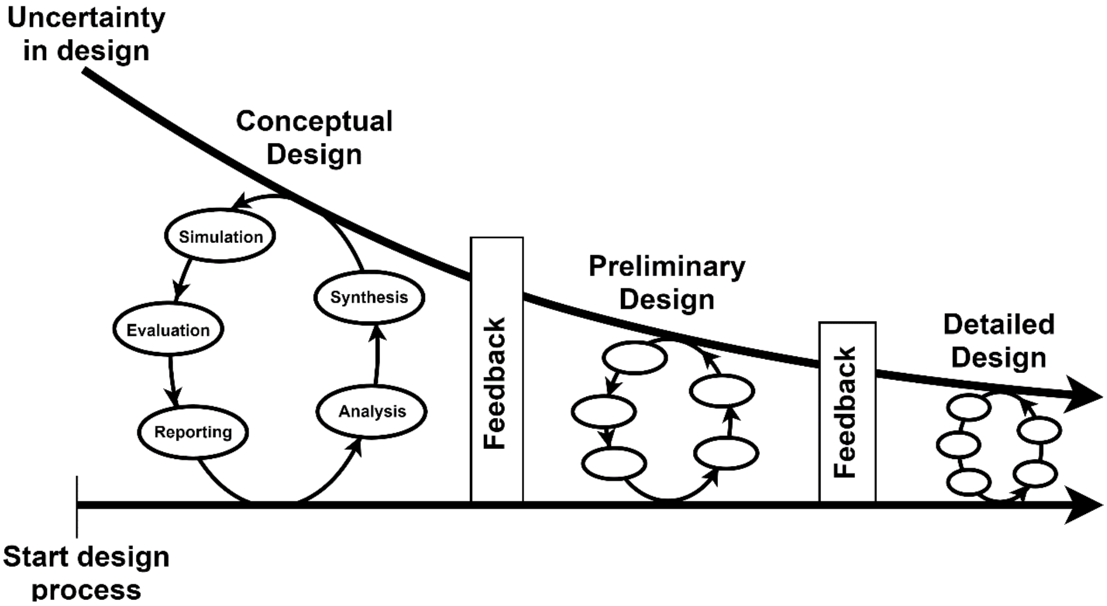


Figure 1-1: Design phases for a construction project. Image adapted from: Berchum and Mobley (2017).

1.1. Background

This section first introduces flood risk management, after which it introduces the problem flood risk management faces, when confronted with deep uncertainty. Thirdly, it will introduce robust decision making approaches, which the study will use to try and resolve the flood risk management problem with deep uncertainty. Lastly, flood risk screening models are introduced, which are needed to use robust decision making approaches in a flood risk management context.

Flood risk management

Flood risk management (FRM) is the process of managing flood risks so that these stay acceptable in relation to the goals set by policymakers. In flood risk management, risks relating to flood events are first analysed, then assessed and finally, if necessary, reduced (Schanze, 2004). Risk is the consequence of an event times the probability of this event. Consequence and risk are both in terms of economic damage and affected population or loss of life. Risk analysis in the FRM approach uses joint probability distribution functions to account for uncertainty in parameters, e.g. hydraulic loads and rainfall intensity and duration, the risk can then be calculated through either numerical integration or Monte

Carlo simulations (Jonkman, Steenbergen, Morales-nápoles, Vrouwenvelder, & Vrijling, 2016). There are three types of options to reduce flood risks; pre-flood intervention, flood event management and post-flood intervention (Schanze, 2004). In this study pre-flood intervention and flood event management are considered.

Risk analysis, the basis of the FRM approach, often relies on scenario-based approaches for determining future risks. Scenarios can either be based on quantitative modelling of the future or on qualitative storylines, which describe a certain future world (Merz, Hall, Disse, & Schumann, 2010; Schanze, 2004). Scenarios are used to analyse the consequences these possible futures have on the flood risk and on the performance of candidate strategies. These scenarios give a limited set of possible futures, but it is hoped that overall, the set of scenarios will provide a good picture of the possibilities. However, under long-term deep uncertainty the scenario analysis may not perform satisfactorily, which is further introduced in the next part.

Problem

In their respective papers, Merz, Hall, Disse and Schumann (2010) and Lempert, Popper and Bankes (2003) warn that scenarios are subjective and cannot thoroughly describe all possible futures while Schanze (2004) warns that scenarios often have a large degree of uncertainty. This uncertainty forms an important problem, because when a design is subjected to conditions it was not designed for, it can be less effective or even have detrimental effects (Hamarat, Kwakkel, & Pruyt, 2013; Hamarat, Kwakkel, Pruyt, & Loonen, 2014; Löwe et al., 2017; Walker et al., 2001). Such detrimental effects can be an increase in flood risk, but can also mean that the implemented measures block the implementation of other measures required later on due to unforeseen conditions (i.e. path dependency), limiting the ability to reach policy goals (Walker et al., 2013). Furthermore, by not exploring possible futures, important opportunities could be missed. If these possible futures would have been mapped, together with the requirements these pose, it could have helped with the planning of the implementation of measures in terms of the financial, political and technical challenges involved.

As the time horizon over which the assumptions are used increases, these assumptions become increasingly uncertain. Thus, making useful assumptions on uncertainties and managing flood risk becomes increasingly difficult when done over a longer term (Haasnoot et al., 2013).

Often the external factors are governed by deep uncertainty. An external factor is governed by deep uncertainty when ''analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes'' (Lempert et al., 2003).

Climate change is an important driver of deep uncertainty (Hallegatte, Shah, Lempert, Brown, & Gill, 2012). It has a major impact on the requirements on all aspects of flood risk management. For many developing countries this is combined with an uncertain economic and population growth, which are also governed by deep uncertainty.

Robust decision making approaches

In policy sciences, robust decision making approaches have been suggested as an effective approach for planning under deep uncertainty. Walker, Rahman and Cave (2001), Lempert et al. (2003) and Lempert and Collins (2007) describe the need for adaptive policy making in contrast with other approaches such as designing for optimum expected utility (Morgan & Henrion, 1990; Vrijling, van Hengel, & Houben, 1995), because of their tendency to perform poorly under different conditions than designed for.

Therefore, in policy sciences it has been advocated to make policies adaptive and robust (Lempert & Collins, 2007; Lempert et al., 2003; Walker et al., 2001). This is to enable them to perform under a range of possible future scenarios. Walker et al. (2001) propose adaptive policies as a concatenation of policy options which are to be implemented or not, depending on conditions at some point in the future. The adaptive policy should have contingency plans and specified conditions under which the policy should be reconsidered. Lempert et al. (2003) describes an approach in which a large ensemble of possible futures is used to analyse all possible futures and test solutions on. Both approaches are based on exploratory modelling, which is a way of using computational experiments to explore the consequences of varying assumptions and hypotheses (Bankes, 1993).

The key to creating these policies are flexibility and robustness, where flexibility aims to keep options open to be able to react to changing conditions and robustness is aimed at allowing a strategy to function under many different conditions (Faturechi & Miller-Hooks, 2014; Walker et al., 2013).

Multiple robust and adaptive planning methods have been proposed based on the definitions of Walker et al. (2001) and Lempert et al. (2003), such as Robust Decision Making (Lempert et al., 2003), Adaptive Policymaking (Kwakkel et al., 2010), Adaptation Pathways (Haasnoot et al., 2012) and Dynamic Adaptive Policy Pathways (Haasnoot et al., 2013). Adaptive Policymaking and RDM optimise the strategies over a large ensemble of possible futures to create robust and flexible strategies. Meanwhile, Adaptation Pathways and Dynamic Adaptive Policy Pathways create pathways (sequences of actions) to allow adaption to changing conditions, see Figure 1-2. The figure shows the possible actions, combinations of measures, and the timeline in which they are able to meet the policy goals. An action is implemented, after which it is kept in place until an adaptation tipping point is reached, at which point this action is no longer able to meet the policy goals, after which a new action is selected. The path that is followed, in time, over the possible actions is called a pathway. An example of a pathway: Action D is selected in 2022 and kept in place till its adaptation tipping point in 2030, at this point, action E is selected until 2050, when action F is selected. These three actions combined, form one of the possible pathways in this period.

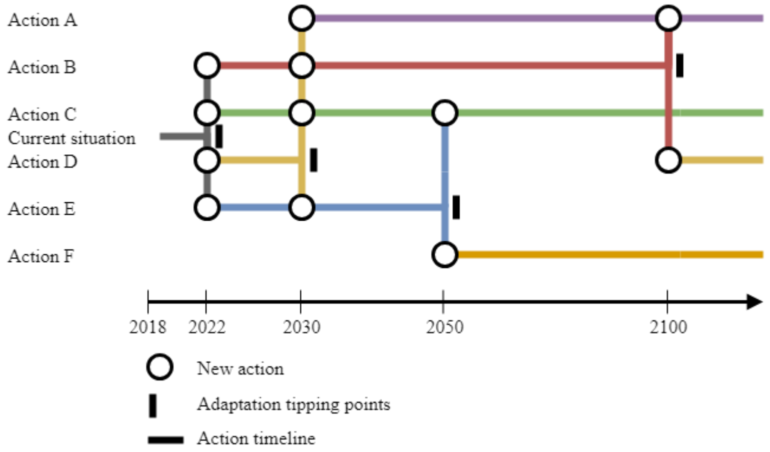


Figure 1-2: Example of adaptation pathways, based on Haasnoot et al. (2012).

Using robust decision making approaches in FRM could contribute in dealing with uncertainty through the incorporation of the flexibility and robustness performance measures and the more exhaustive exploration of the possible futures. Robust decision making approaches rely on fast, simple policy analysis models (Walker et al., 2013), for which this study uses flood risk screening models, these are introduced in the next part.

Flood risk screening models

A flood risk screening model is a model that is used to provide a first assessment of flood risk and potential flood risk reduction measures. This type of model is less computationally demanding than more detailed models, which allows them to analyse more scenarios and combinations of measures. More detailed models can then be used, later in the assessment, to analyse the remaining options in more detail. Flood risk screening models are flexible and simple in their use and can handle lack of data well. This study uses the Flood Risk Reduction Evaluation and Screening model (FLORES) (van Berchum et al., 2019).

1.2. Research Goal

The goal of this research is to *develop an approach for long-term adaptive flood risk management planning under deeply uncertain conditions.*

The research aims to realise this goal by combining robust decision making approaches with flood risk management. In order to reach this goal, a main research question along with supporting sub questions have been formulated. The main research question focusses on finding the steps that would be required to create such a long-term adaptive flood risk management and on what the result is of performing these steps.

In what form can robust decision making approaches be used for long-term flood risk management planning under (deep) uncertainty?

The following sub questions will be researched to support the main question:

1. *How do current approaches in flood risk management account for deep uncertainties? What are its strong and weak points?*
2. *How does robust decision making account for deep uncertainties? What are its strong and weak points?*
3. *Can and how can robust decision making improve flood risk management in dealing with deep uncertainties?*
4. *What components does a long-term adaptive flood risk management planning consist of?*
5. *Can and how can this method in practise be used for the design of long-term flood risk management plans?*
6. *What are the strengths and weaknesses of the long-term adaptive flood risk management approach?*

1.3. Research method

In order to answer the research question, a new adaptive policy planning approach for use in the hydraulic engineering field is to be created. To design this new approach, flood risk management, robust decision making approaches and flood risk screening models are researched first. Based on this literature research, a new model based planning approach will be created by combining strong points from the robust decision making and flood risk management approaches. The new planning approach will be applied to a case study in Beira, Mozambique, to test and finetune the approach. This will be done with the flood risk screening model FLORES, which needs to be adapted for use in the case study and for use with the approach. The performance of the approach in the case study is then evaluated. This will finally lead to a discussion of the results and conclusions and recommendations for further research. The steps are shown in the flowchart in Figure 1-3.

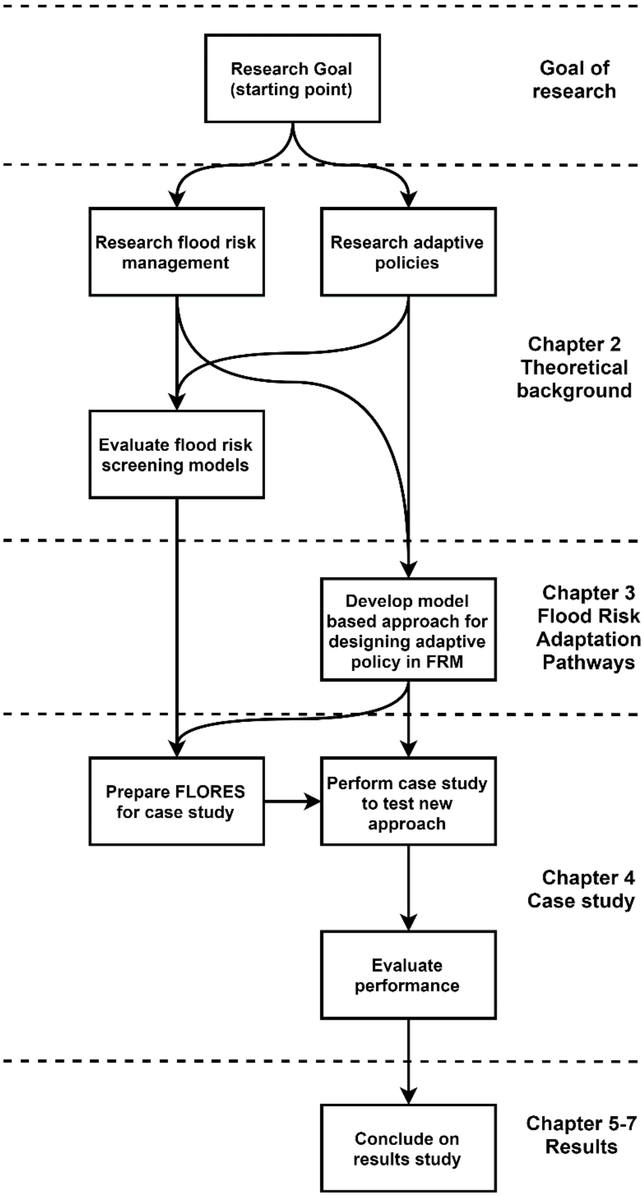


Figure 1-3: Flowchart of steps performed in the study.

1.4. Thesis outline

In chapter 2 flood risk management and adaptive policymaking are researched. Based on the weaknesses and strengths of both fields a new approach is defined and discussed in chapter 3. In chapter 4 a case study is performed to test the newly defined approach. In chapter 5 the results are discussed, and conclusions and recommendations are given in chapter 6 and 7.

2. THEORETICAL BACKGROUND

This chapter reviews and analyses the relevant literature on flood risk management and robust decision making. In section 2.1, the widely used practices in flood risk management are reviewed. Section 2.2 examines robust decision making approaches, focussing in particular on DAPP. Section 2.3 describes flood risk screening models. The findings of the literature review will be summarised in section 2.4.

2.1. Flood risk management

The activities in flood risk management are described through Schanze (2004) which describes the core elements of flood risk management and Plate (2002) which describes FRM in a more operational form. In flood risk management, risks relating to flood events are assessed for the current situation and several different possible futures in order to manage these risks. The risks are in terms of economic damages and affected population or loss of life.

In the past the main method for designing flood risk reduction measures was to optimise for a single estimate of the joint probability functions of the uncertainties (Lempert & Collins, 2007). A good example of this is striving for an economic optimum as done in Vrijling, van Hengel and Houben (1995).

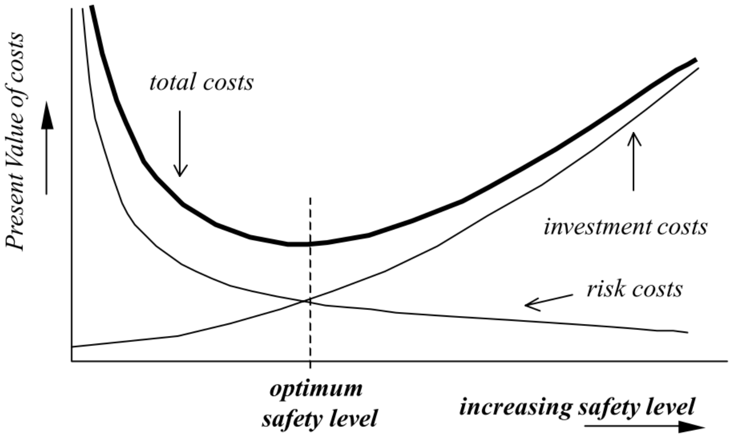


Figure 2-1: Economically optimal safety level (Arends, Jonkman, Vrijling, & Van Gelder, 2005).

Flood risk management activities Schanze (2004)

Schanze (2004), defines the three main activities of flood risk management, Figure 2-2:

The process starts with risk analysis, consisting of determining the hazard, the vulnerability and finally the resulting risk (Schanze, 2004). The risk analysis is a level IV probabilistic approach in which the risk (consequence times probability of event) is calculated and used as a measure for the state of the system. The risk is an expected value and is often calculated for economic damages and loss of life or people affected by flooding (Jonkman, Schweckendiek, Jorissen, & van den Bos, 2018; Schanze, 2004). In order to determine the consequence of a flood event the flood characteristics, the land use functions and their values and the damage functions of the land use functions per flooding level need to be analysed. The flood characteristics that are most often considered are location and depth of flooding, but other factors can have a significant influence on the damage as well, such as; flow velocity, moment of occurrence and duration of the flood event (Jonkman et al., 2018). The land use function gives information on the economic value and population at risk in the relevant area. The damage function of the land use functions represent the vulnerability of the land use type to flooding, these functions are often a relation between flood depth and damage, but other flood characteristics can be important as well (Jonkman et al., 2018). In a level IV risk analysis the uncertain parameters, such as the probability of failure of coastal defences and rainfall intensity, are represented through their joint probability distribution functions (Jonkman et al., 2016; Schanze, 2004). Mean values, a standard deviation and a distribution type are estimated for the probabilities/values of the relevant uncertainties. The risk is then calculated either with analytical expressions, numerical integration or Monte Carlo simulations. However, calculating risks analytically is only possible in a few simple cases. Numerical integration is only feasible when a small number of variables are involved (Jonkman et al., 2016). For example, the mean value of probability of failure, the standard deviation and distribution type of the different failure mechanisms of a dike can be estimated in order to calculate the overall mean value, standard deviation and distribution type of the probability of dike failure with a Monte Carlo simulation. Combining the probability with the consequences in a similar way then leads to the risk of the possible dike failure. This risk analysis should be a continuous process, updating the analysis as conditions change, and holistic, meaning that the flood risk system should be considered as comprehensive as possible (Schanze, 2004).

As a second step, a risk assessment can be made. First, risk weighing determines the level of accepted risk, which is a trade-off between the risk and the costs, monetary and others, of the required interventions to reduce the risk (Schanze, 2004). In the Netherlands for example, risk of loss of life is assessed on both an individual and societal level, where both must be within acceptable limits. Then, if the level of accepted risk is lower than the actual risk, the risk assessment leads to the decision to reduce the risk. The risk assessment depends on the risk perception of the policymaker. The risk perception will differ between individuals and societies as a whole, with different perceptions come different risk management choices (Schanze, 2004).

If risks have been assessed as not acceptable, then the risks can be reduced by implementing flood risk reduction measures in the third step. There are three forms of risk reduction; pre-flood reduction, flood event reduction and post-flood reduction (Plate, 2002; Schanze, 2004). Pre-flood interventions aim to prevent flood damage. This is done through structural protection, reducing flood severity, reducing vulnerable elements in flood prone areas and by preparing people at risk (Plate, 2002; Schanze, 2004). Flood event management aims to manage a flood event in such a way as to reduce adverse effects by as much as possible (Schanze, 2004). Forecasting flood events allows people to be warned and evacuated in a timely matter and allows flood control, i.e. controlling water levels, and flood defence measures, i.e. closing structures and temporarily heightening them, to be taken (Plate, 2002; Schanze, 2004). Post-flood interventions include relief and reconstruction efforts after a flood event has occurred (Schanze, 2004).

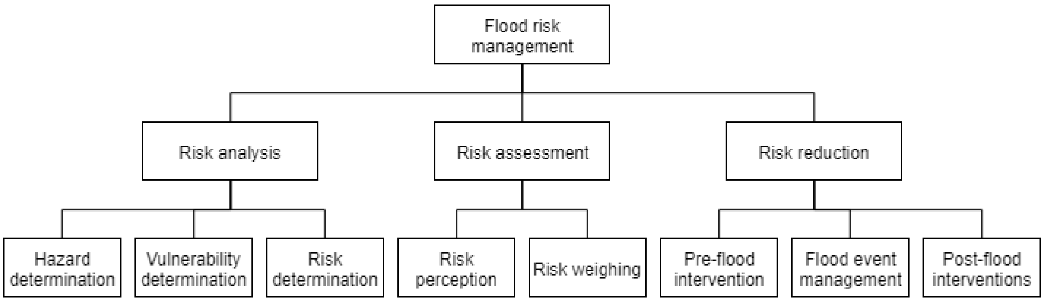


Figure 2-2: Diagram of FRM activities, the middle row shows the main activities and the lower row shows a further subdivision (Schanze, 2004).

Flood risk management process Plate (2002)

Plate (2002) describes flood risk management as an ongoing process with three different sets of actions, Figure 2-3:

The first is operation of the existing system with the aim of being prepared for a flood event and minimise its impact (Plate, 2002). This in turn consists of four elements (Plate, 2002): Periodical risk analysis, assessing the hazards and the vulnerability of the elements at risk. Plate (2002) does not state how the risk analysis should be performed, but it is expected this is the same as in Schanze (2004) and Jonkman et al. (2016). This forms the basis for the decisions on maintenance and improvements on the existing system. The third element is to create a decision support system for if the system fails or is going to fail. This aims to reduce residual risks, through emergency measures. The last element is disaster relief; providing humanitarian aid and reconstruction of the area.

The second action is planning for a new or revised system and deciding upon this system (Plate, 2002). This happens when the current system is no longer able to meet the requirements. These requirements are set by the governing body and reflect societies view on the acceptability of flood risk, financial resources and what can be done with the available technology. These factors change over time and thus the requirements of a flood risk management system will change accordingly.

The third action is obtaining an optimum design and construction of the selected flood risk measures (Plate, 2002). It further elaborates on the results of the second action and aims to reduce the flood risks to meet the requirements set in the second action.

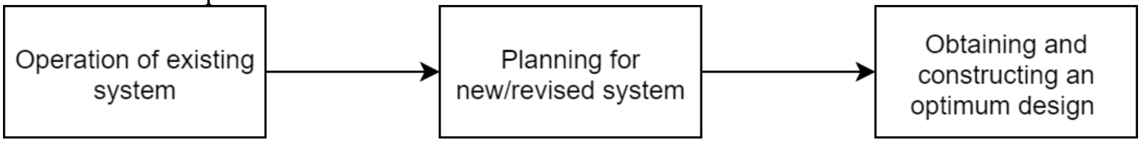


Figure 2-3: Operational phases FRM (Plate, 2002).

Synopsis Schanze (2004) *and Plate* (2002)

Recapping on both methods; flood risk management is the process of analysing risks and using this analysis to reduce risks when this is assessed as necessary. This analysis is performed, while operation of an existing system is ongoing, with the intend of revising the system in such a way that the goals set by policymakers are reached. Flood risk management is an ongoing process, which should aim to update its analyses when new insights come to light. Risks are calculated with a level IV probabilistic approach in which uncertainties are represented by joint probability distribution functions. This approach works very well for situations in which the joint probability functions can be estimated for the uncertainties. However, there are situations, with long-term deep uncertainties, under which this is not possible. The next part describes the approach which is most often used when the use of joint probability functions is not possible.

Flood risk management approach to long-term (deep) uncertainty

To assess the future risks, the change in external factors required for assessing these risks must be estimated. As mentioned above, FRM uses joint probability distribution functions to estimate uncertainties, but when this is not possible, because uncertainty is severe, e.g. long term socio-economic changes or factors influenced by climate change, scenario-based approaches are often used (Merz et al., 2010; Schanze, 2004).

Scenario analysis explores the flood risk over a number of contrasting possible futures without an applied probability (Merz et al., 2010). The scenarios differ based on the key drivers of change, such as economic development, climate change, societal values or technological changes.

There are two different approaches to creating the scenarios. This can be done through the creation of qualitative storylines or through quantitative modelling of the future developments.

Qualitative scenarios are usually constructed with the help of experts or stakeholders, with the aim of integrating different perspectives and possibilities (Merz et al., 2010; Middelkoop et al., 2004; Raadgever & Becker, 2008). The storylines describe a possible future world, which results in certain values for the external factors. A limited set of scenarios is usually used, as it is often not feasible to make more than a few, because it depends heavily on the insight and judgement of their creators (Merz et al., 2010). The scenarios do not always represent the most likely future, in which case they give a limited set of possible options, to take the possible futures into account that are relevant to the policy goals.

Quantitative scenarios often rely on regression techniques to predict the future external factors based on the datasets of the past. For example, non-stationary frequency analysis can be used to extrapolate flood trends into the future. A long enough dataset of sufficient reliability has to be available to perform the regression analysis on (Merz et al., 2010).

Quantitative scenarios are often used if datasets are available to extrapolate on. Qualitative scenarios are used for factors for which there is no dataset available or when it is not possible to extrapolate because of high uncertainty in the expected trend. Often quantitative scenarios are best used for the not too distant future, as the uncertainty in the trend increases as the time over which is extrapolated increases. For example, trends are often calculated for factors governed by climate change, population growth and economic growth, for the shorter term, but scenarios are often used for the highly uncertain (long-term) estimates.

Limitations of FRM approach in dealing with (deep) uncertainty

Lempert et al. (2003) and Merz (2010) indicate that the scenario analysis approach is subjective and cannot be thorough in the description of the possible futures. Schanze (2004) states that the large degree of uncertainty in scenarios means that the outcomes of risk reduction strategies can only partly be estimated.

It is not impossible to take the uncertainties into account correctly through the use of qualitative scenarios. However, because of the limited number of scenarios used there is a real risk that important situations and extremes are not tested for. An example of problems related to underestimation of uncertain external factors can be found in the 2013 Delta Programme (Deltacommissie, 2013). It used four scenarios to base its future estimations up to 2100 on. Six years later its estimation of the maximum sea level rise for 2100 (85cm) has been subjected to doubt as reports emerged that a sea level rise of 3m for 2100 is possible (Haasnoot et al., 2018). While this does not mean the programme will be incorrect necessarily, it does reveal the difficulties intertwined with predicting the unknown.

For quantitative scenarios a major problem is that the trend can be very different in the future than in the past or present and regression techniques can thus lead to under- or overestimation of the factors (Merz et al., 2010). Trend shifts are often difficult to predict and thus it can become difficult for quantitative scenarios to predict the range of possible future conditions.

For cases with limited data availability, which is often the case in developing regions across the world, even the current situation becomes difficult to establish. Quantitative scenario creation is then often not possible, due to the lack of datasets. Qualitative scenarios creation can also become more difficult, as the local situation is less well understood, due to a lack of local experts and unfamiliarity with the region of foreign experts.

When a design is made based on the created scenarios and is exposed to conditions it was not designed for, it can be far less successful or even have undesired effects (Hamarat et al., 2014; Merz et al., 2010; Pahl-wostl, 2008; Walker et al., 2001). Furthermore, the already constructed solutions create a path dependency for new solutions taken in the future which can have further detrimental effects. It is possible that decisions taken today will have to be reversed in the future (Pahl-wostl, 2008).

2.2. Robust decision making

Robust decision making approaches take long-term deep uncertainty into account, by optimising over a large ensemble of possible futures, through this, they aim to improve performance of measures taken under these circumstances. They originated in the policy sciences, see Walker et al. (2001) and Lempert et al. (2003). In this research these methods are applied to flood risk management.

Walker et al. (2001) and Lempert et al. (2003) use exploratory modelling (Bankes, 1993), as a basis for their robust decision making approaches. Exploratory modelling is the use of “series of computational experiments to explore the implications of varying assumptions and hypotheses” (Bankes, 1993). This is important because, when faced with deep uncertainty, the consequences of the uncertainties should be explored to aid decision making (Kwakkel, 2017; Lempert, Groves, Popper, & Bankes, 2006). To be able to perform such an extensive series of model runs a fast, simple policy analysis model is required (Walker et al., 2013).

Several robust decision making approaches are described in section 2.2.1. In section 2.2.2, the adaptive approach selected as the main point of reference for this study, dynamic adaptive policy pathways, is described in more detail.

2.2.1. ROBUST DECISION MAKING APPROACHES

The approaches that are described in this section are robust decision making (Lempert et al., 2003), adaptive policy making (Kwakkel et al., 2010; Walker et al., 2001), adaptation pathways (Haasnoot et al., 2012) and dynamic adaptive policy pathways (Haasnoot et al., 2013).

Central to these approaches are two forms of robustness which can be used to create a robust strategy. These are static robustness and dynamic robustness (also called flexibility) (Faturechi & Miller-Hooks, 2014; Hashimoto, Stedinger, & Loucks, 1982; Walker et al., 2013): Static robustness aims to reduce the vulnerability of a certain measure to changes in conditions. Dynamic robustness is the ability of a strategy to adjust to changing conditions, it aims to keep options open and have those options available for when these are required. Robust and flexible measures differ from optimal performance solutions, as these trade optimal performance for better performance under a range of other scenarios (Pahl-wostl, 2008).

Robust decision making

Lempert et al. (2007; 2003) describes an approach in which solutions are tested on the basis of robustness instead of optimum expected utility, with the aim of creating a robust strategy over different possible futures. Three different ways of creating this robust strategy are described. The first defines a robust strategy as a trade-off between a small amount of optimal performance in return for a strategy that is less sensitive to unexpected conditions. The second defines a robust strategy as one that has reasonable performance over a wide range of possible future conditions. The third defines a robust strategy as a strategy that keeps options open, which is thus flexible. The RDM approach is an iterative approach consisting of four steps (Lempert & Collins, 2007; Lempert et al., 2003):

The first step is the participatory scoping step. In it, the system is conceptualised, the key uncertainties are identified, the strategies created, and the outcomes of interest defined.

The second step is the case generation step. This step explores the behaviour of one or several models describing the studied system and the performance of possible strategies over the range of identified possible conditions. This provides information to help choose candidate strategies, which can be used to iterate on the strategies (Lempert & Collins, 2007; Lempert et al., 2003). The first and second step combined are comparable to the FRM approach.

The third step is scenario exploration and discovery, which analyses the performance of the candidate strategies using statistical machine learning algorithms (Lempert & Collins, 2007; Lempert et al., 2003). It aims to reveal situations in which the performance of the strategies is poor. A large ensemble of scenarios is analysed, no probability is assigned to each scenario, instead all are deemed equally possible for the analysis. Through this analysis, information on the vulnerabilities of the strategies is found. If required the process can go through an iteration by going back to participatory scoping to redefine the strategies. Step two and three combined are comparable to the exploratory modelling approach.

The fourth step is a trade-off analysis, which compares the performance of the strategies on the basis of the different performance indicators (Lempert & Collins, 2007; Lempert et al., 2003). This again enables the user to iterate on the designed strategies. The steps can be repeated until a robust strategy materialises.

RDM does not describe how vulnerabilities should be addressed, it only helps to locate them but leaves open how to deal with them (Kwakkel, Haasnoot, & Walker, 2016). It can be used to increase static robustness (Kwakkel et al., 2016; Walker et al., 2013). But it can also be used to create dynamic robustness through a system of signposts and triggers (Bloom, 2015; Groves, Fischbach, Bloom, Knopman, & Keefe, 2013; Lempert & Groves, 2010), where a pre-specified action to adjust the strategy is taken when a trigger value is reached (Kwakkel et al., 2016).

RDM has been further developed into many different similar approaches such as objective robust decision making (Kasprzyk, Nataraj, Reed, & Lempert, 2013) and adaptive robust policy design (Hamarat et al., 2013).

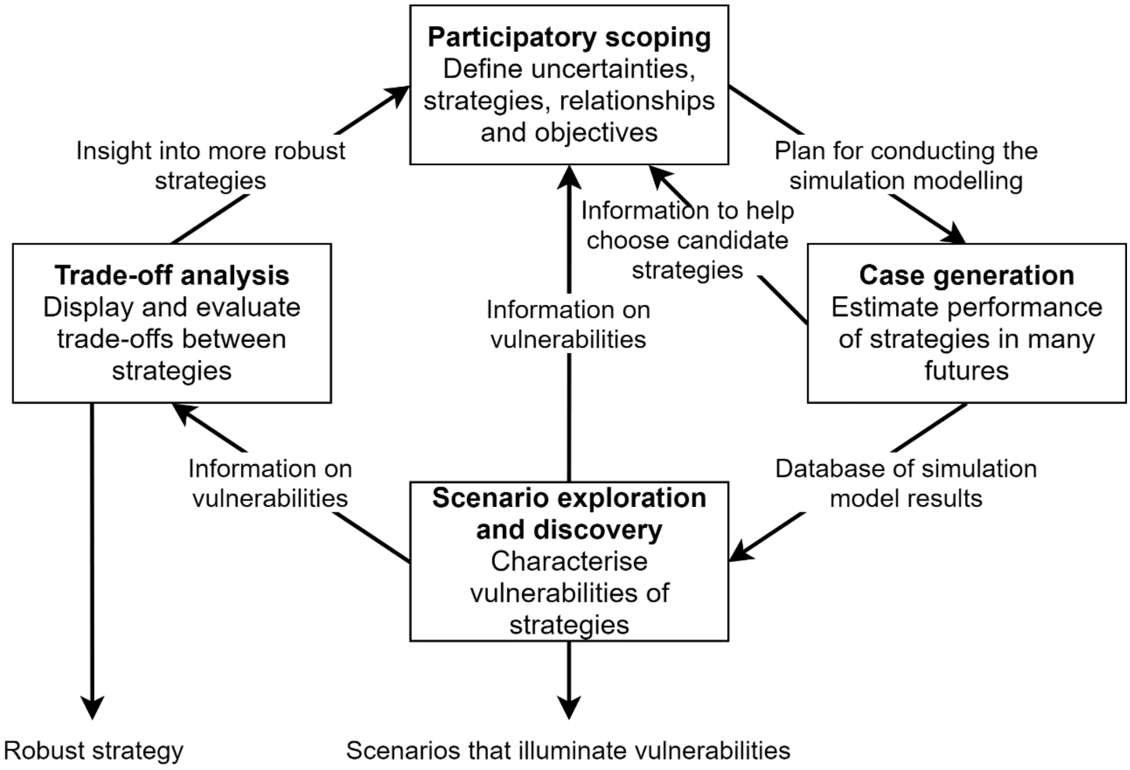


Figure 2-4: RDM process (Lempert et al., 2003).

Adaptive policymaking

Walker et al. (2001) specified the basic steps to creating an adaptive policy. Kwakkel et al. (2010) developed this approach further, Figure 2-5, which works along the same lines as the adaptive policy-making process proposed by Walker et al. (2001).

Adaptive policymaking aims to provide a structured approach to handling uncertainty. The approach as defined in Kwakkel et al. (2010), Figure 2-5, is shortly explained here. It starts with 'stage setting', which describes the existing system and sets objectives, this is similar to the first step of RDM. Then, a basic plan is defined in the second step. Step three is to make the basic plan more robust, through hedging, mitigation, seizing actions and shaping actions. This step is similar to the third and fourth step of RDM. Step four creates a monitoring plan, through stating the required signposts and triggers. Step five specifies the possible corrective, defensive and capitalizing actions and when reassessment of the plan is required. The main focus of this approach is to make the selected options more robust through steps three, four and five.

The steps of adaptive policymaking approach are much more detailed than the ones in the RDM approach. Adaptive policymaking gives a clear guideline on how to improve the performance of the strategy, through several types of actions and a monitoring plan. RDM is less detailed and does not specify how to change the strategy, only how to test it. Nonetheless, their results can be similar, but this does depend on how the RDM approach is used.

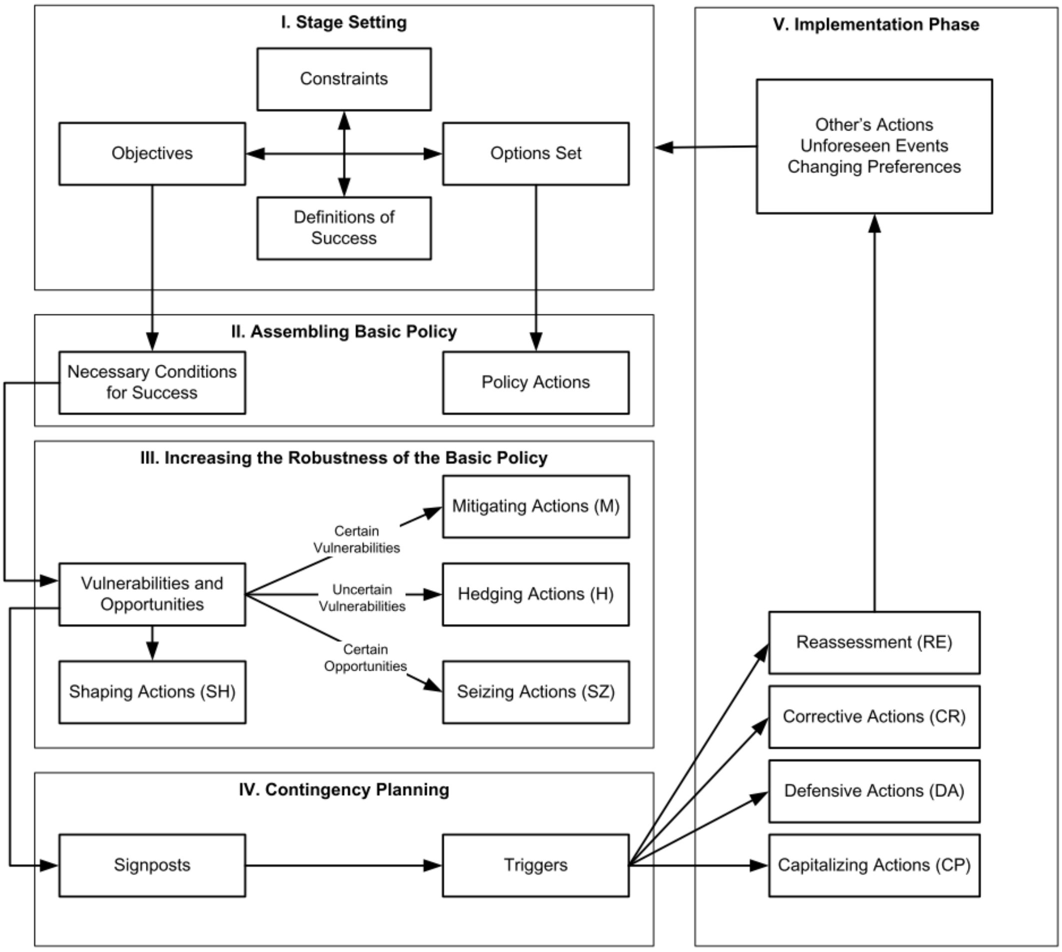


Figure 2-5: Adaptive policymaking (Kwakkel et al., 2010).

Adaptation pathways

Adaptation Pathways is an adaptive approach that aims to provide a greater amount of flexibility through selecting many more basic actions and using adaptation tipping points to define their sell-by date. Adaptation trees, or pathways, give possible sequences of actions which together fulfil the minimum set objectives over the plan duration (Haasnoot et al., 2012). Flexibility is created through the pathways, as depending on the changing conditions, the plan adapts by selecting a new action. An overview of the pathways is given in a pathways image, see Figure 1-2. A scorecard can be added to give scores on the relevant factors for each pathway (Haasnoot et al., 2012). The steps as defined for Adaptation Pathways are shown in Figure 2-6.

The adaptation pathways approach is markedly different from the adaptive policymaking and RDM approaches, as it focusses specifically on creating flexibility, static robustness is not used. Neither RDM nor adaptive policymaking prescribe the type of robustness to be used. Furthermore, the result of the approach is shown in one figure which gives an overview of all actions and pathways in the plan, which makes the plan insightful.

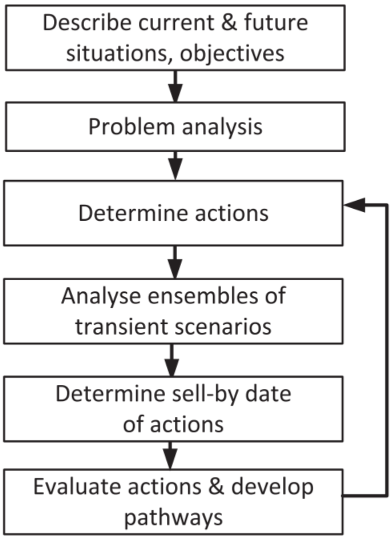


Figure 2-6: Adaptation Pathways (Haasnoot et al., 2012).

Dynamic adaptive policy pathways

DAPP is a combination of adaptive policymaking and adaption pathways. It has the strong (visual) representation of the possibilities from adaptation pathways and its high level of flexibility. The adaptation pathways (Haasnoot et al., 2012) create a level of flexibility that is not matched by other adaptive policy methods such as adaptive policymaking (Kwakkel et al., 2010; Walker et al., 2001). Adaptive policymaking chooses a solution and makes this more robust by means of preparing actions to safeguard against possible failures and a monitoring system to implement these actions when required (Haasnoot et al., 2013). The steps from adaptive policymaking are also more clearly worked out and provide a better roadmap to reach the intended results. These additions from adaptive policymaking make DAPP a more matured version of adaptation pathways.

Choice of robust decision making approach for FRM

The robustness indicators, and the structured exploration of many possible futures in order to analyse the robustness, is what robust decision making approaches, in general, have to support the FRM approach. The dynamic robustness performance indicator of the robust decision making approaches is one that combines well with flood risk management. Often flexible measures, such as sand suppletions, are used which combine well with the dynamic robustness performance indicator. Static robustness can then be used when more permanent measures are needed.

Kwakkel et al. (2016) concludes that both DAPP and RDM are valid approaches for designing flexible strategies, but that DAPP leads to flexible measures explicitly. DAPP is more computationally expensive than RDM, but in return it explores the design options more thoroughly. RDM shows under which conditions adaptation is required, while DAPP develops sets of pathways which each have their own trade-offs (Kwakkel et al., 2016). DAPP has a more detailed approach and leads to a more well-defined result with pathways, signpost and triggers and a monitoring plan. Both DAPP and RDM are equally capable of providing static robustness in their outcomes (Kwakkel, Haasnoot, & Walker, 2015; Kwakkel et al., 2016).

It is thought, that DAPP is the best approach to use for the current study, because of its clearly defined approach with a clear intended end result. This gives a clear structure to the analysis, which makes it clearer for users what should be done and what the result should look like, which is something RDM lacks. RDM can also be useful in the flood risk management process, but as the process is not so clearly defined, it is not capable of giving an equally structured approach to dealing with uncertainty. Furthermore, DAPP investigates the long-term situation explicitly and links this to the current situation and the effect of solutions, taken now, on the future availability of options is analysed. This creates a coherent set of actions over time and makes the effects of path-dependency visible before implementation. This explicit linking of the long-term situation with the current situation can aid the FRM approach, under (deep) uncertainty, to achieve policy goals and prevent unwanted side effects. Finally, DAPP presents its main results visually in one image, this could prove to be very helpful in the communication between engineer and policymaker (and other stakeholders).

The DAPP approach is thus chosen to form the cornerstone of the new adaptive flood risk management approach, with elements of other approaches incorporated as deemed required.

2.2.2. DYNAMIC ADAPTIVE POLICY PATHWAYS

This section describes DAPP in more detail, it starts with describing how the approach works and then describes the results of using such an approach and finally the section concludes with discussing the strengths and weaknesses of DAPP.

DAPP Approach

Haasnoot et al. (2013) provides a framework for creating the DAPP, an overview of the approach is given in Figure 2-7. It will be further elaborated upon here.

Figure 2-7: Dynamic Adaptive Policy Pathways approach (Haasnoot et al., 2012).

1. The first step in DAPP is to describe the current and future situation, describing the characteristics of the system, the objectives to be met and the current and potential future constraints. It specifies the desired outcomes with indicators and targets to evaluate the potential solutions on performance and on 'sell-by date' (Haasnoot et al., 2013). This step also includes the listing of the major uncertainties regarding the future, data and model.
2. The second step is to analyse the problem; the gap between objectives and the current and future situation should be assessed. The gaps that are identified are the problems that need to be solved. Opportunities and vulnerabilities should be identified in this stage, which should be done by analysing the reference case through a computational model (Haasnoot et al., 2013).
3. Step three is to list possible actions to solve the problems and to take advantage of opportunities or defend against vulnerabilities. The possible actions are based on the action types from the Adaptive Policy framework (Kwakkel et al., 2010) .
4. In step four the effect of the actions on the closing of the problem gap are evaluated. The 'sell-by date of the solutions is assessed and the effect on the opportunities and vulnerabilities is evaluated (Haasnoot et al., 2013). The existing opportunities and vulnerabilities can have been altered by the solutions and new ones can have been created. The effective solutions will proceed to the next step.
5. In step five the effective solutions are put together to create pathways. The creation of the pathways is based on the information from all previous steps. The pathways can be selected by hand, but it is also possible to explore all possible pathways through the use of computer models which has been done in Kwakkel et al. (2015) and Zeff et al. (2016). Opportunities and

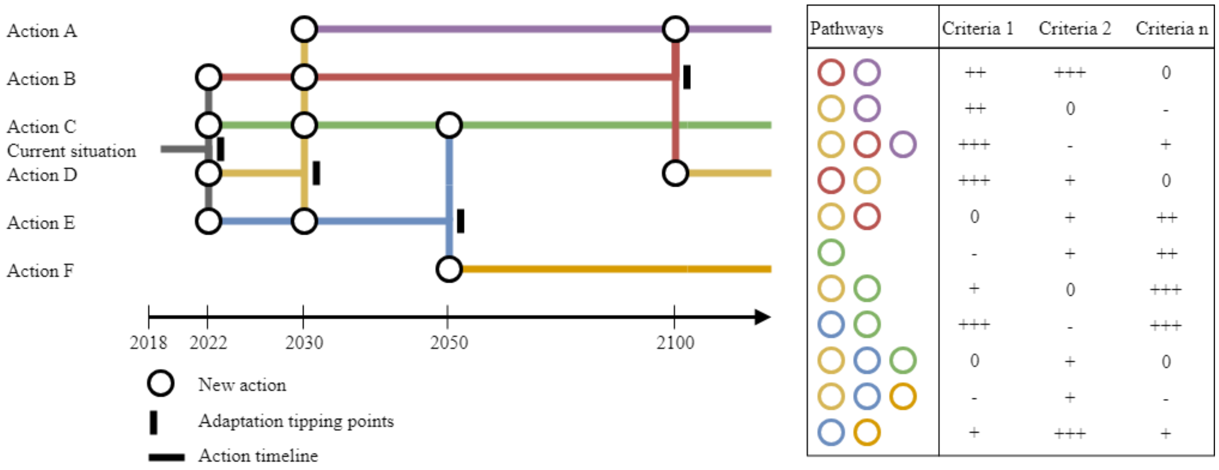
vulnerabilities should again be considered, as combinations of the solutions will have different effects than solutions on their own. The process can go back to step three to select new actions if it becomes clear the pathways could benefit from additional actions.

6. Step six then selects preferred pathways from the list of possible pathways (Haasnoot et al., 2013). To create socially robust pathways, the preferred pathways should be selected such that each perspective has at least one pathway (Offermans, Haasnoot, & Valkering, 2011). So preferred pathways should be selected for optimal performance and for representing the different perspectives. As mentioned in Haasnoot et al. (2012) the perspectives can be based on the social perspectives as applied to water management (Hoekstra, 1998; Offermans et al., 2011). Ideally the perspectives could be based on a stakeholder analysis, to make sure the actual perspectives of stakeholders are taken into account in order to create support for the plan.
7. In step seven the robustness of the preferred pathways is improved through contingency planning from Adaptive Policymaking (Kwakkel et al., 2010). Through corrective, defensive and capitalizing actions in combination with a monitoring system and trigger values, the actions are made more robust. When a trigger value is reached the associated action should be taken.
8. Step eight creates the dynamic adaptive plan, it summarizes the information gathered in the previous steps including the preferred pathways (Haasnoot et al., 2013). A plan should be drawn up that keeps the options as open as possible for as long as possible to reduce path dependency so as to remain flexible. No-regret measures can be listed, with which implementation can begin. Other measures should be implemented only when necessary and should thus be shifted to a later date, when they are triggered by an adaptation tipping point from the monitoring system. Trigger values and associated hedging actions will also be defined.

Finally, the plan is implemented, and the system monitored until actions need to be taken. When the plan is no longer sufficient, the process can go back to step 1.

DAPP Result

The final plan will be as shown in Figure 2-8, with additional content such as the monitoring plan, trigger values and hedging actions. The timeline as given in the figure, would merely serve as an initial estimate. The decision to implement a new action should be taken only when the actual tipping point will soon be reached. There will be far less uncertainty relating to the future on this short timescale, but there is also still enough time to implement the action. Through this, DAPP seeks to keep options open for as long as possible (Haasnoot et al., 2013). For example, if action B was chosen in 2022, the situation can then be monitored until the adaptation tipping point is reached. A few years before the tipping point is expected to be reached, the final decision can be made to either implement action A or C. Thus, that choice will be made under much less uncertainty than if it would have been made in 2022 already, while the basic plan is already in place. In the meantime, a few trigger values could have been reached which would have triggered the appropriate hedging action. It is not only beneficial from an uncertainty point of view, but economically it is also desirable to perform actions as late as possible because of the time value of money. The plan also makes policy ‘lock-ins’ clearly visible, which allows policymakers to reduce unwanted path dependencies (Haasnoot et al., 2013).



Pathways	Criteria 1	Criteria 2	Criteria n
🔴 🟣	++	+++	0
🟡 🟣	++	0	-
🟡 🔴 🟣	+++	-	+
🔴 🟡	+++	+	0
🟡 🔴	0	+	++
🟢	-	+	++
🟡 🟢	+	0	+++
🔵 🟢	+++	-	+++
🟡 🔵 🟢	0	+	0
🟡 🔵 🟠	-	+	-
🔵 🟠	+	+++	+

Figure 2-8: Example of adaptation pathways, based on Haasnoot et al. (2012).

DAPP Strengths and Weaknesses

An important strength of the pathways approach is the high level of flexibility automatically incorporated into the plan, which enables it to handle deeply uncertain factors better. The flexibility is created by the pathways of actions, combined with the monitoring plan. Comparing this to FRM approach, this can be done as well, but it is not part of the approach, thus leaving it open to the user whether or not to consider it. By postponing the decisions that can be taken later and only implementing the solutions as they are required, the long-term uncertainties regarding factors that are important for the success of a measure are reduced.

It creates an environment in which stakeholders can participate successfully in the decision making process, as the plan leaves open which pathway is to be taken. Since all the pathways satisfy a set of minimum requirements which are deemed satisfactorily, the resulting solution will be satisfactory for the client. But it will leave room for discussion and change so that the other stakeholders have reason to participate (De Bruijn & Ten Heuvelhof, 2008; De Bruijn, Ten Heuvelhof, & In 'T Veld, 2010). This strength is further enhanced, because the main results of the approach are visually represented in one image. This has the ability to improve the interaction with policymakers and stakeholders, by clearly showing the available options.

The long-term situation is explicitly investigated and linked to the current day situation and the effect of solutions taken now is linked to future options. This makes the future consequences of actions taken now explicit. This strengthens the temporal cohesion of measures and makes the effects of path-dependency visible prior to the implementation of the measures instead of after. This is further enhanced, because the approach shows it in one image, making the effects of path dependency visual and clearly interpretable.

A weakness of the approach is the lack of guidance on how efficacy of pathways and solutions should exactly be investigated. The approach names adaptation tipping points as points after which certain solutions are no longer possible. However, when a policy is no longer possible can be difficult to assess. Boundaries between possible and not possible are often not that strongly present in a situation.

A further weakness in the current approach is that there is an estimate of the time factor, even though the approach acknowledges that this cannot be predicted because of the uncertainty in the involved factors. This is done through the creation of different scenarios, in which different changes occur under differing timescales.

2.3. Flood risk screening models

Section 2.2 mentioned that robust decision making approaches require a fast, simple policy analysis tool. This section describes a type of model which is able to fulfil this role in flood risk management, which are called flood risk screening models. Furthermore, these models can operate in situations with very limited data availability. Only a few of these models exist today, see Gouldby, Sayers, Mulet-Marti, Hassan and Benwell (2008) and Van Berchum et al. (2019). The purpose of this type of model and the benefits of using them is described. After this the model that was used in this study is described.

Flood risk screening models

Flood risk screening models are models that simulate the local situation in a simplified manner. Relatively simple 1D formulas are used and it uses simplified geographical and demographical information, by dividing the area into basins with a certain height and land use. Flood risk reduction measures are represented in a simplified fashion, e.g. coastal defences are schematised with a height and fragility curve.

Flood risk screening models are capable of running a large number of different simulations, for different scenarios and different strategies, in a short timeframe (Berchum & Mobley, 2017; Gouldby et al., 2008). They are designed to be able to model the effect of flood management strategies on flooding and resulting risk.

Flood risk screening models fall in between conceptual risk optimisation models on the one hand and detailed risk simulation models on the other, see Figure 2-9. This type of model is needed for robust decision making approaches because of the large amount of runs that are required for the adaptive approach. The large number of required runs makes the use of a detailed risk simulation model too computationally demanding, while a conceptual risk optimization model is too simplified to properly analyse the situation (Berchum & Mobley, 2017; Gouldby et al., 2008).

The main strength of flood risk screening models is that these can give a first assessment of which flood risk reduction measures are needed (if needed at all) and effective. After this initial assessment detailed risk simulation models can then simulate a more limited number of solutions in depth. In this way, flood risk screening models are able to guide the decision making early on in the design process and reduce computation times (Berchum & Mobley, 2017).

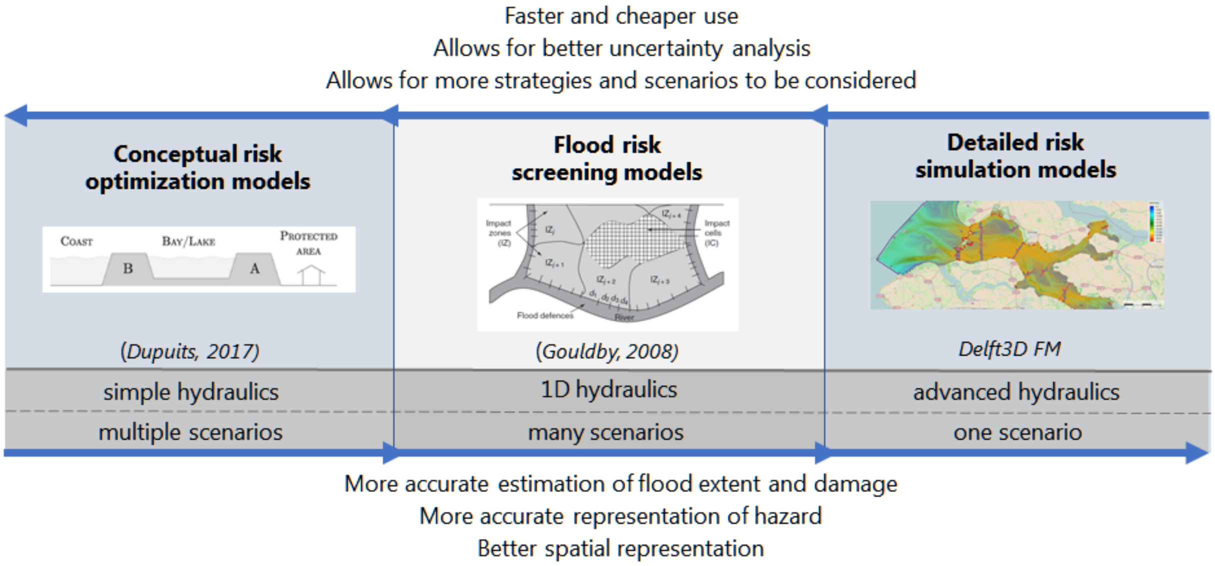


Figure 2-9: Flood model types used in flood risk management (van Berchum et al., 2019).

Benefits of using flood risk screening models

The flexibility and simplicity of the models mean they can handle uncertainty and lack of data well. The data that is required for the model to function is limited to demographic and topographic data. A digital elevation map, combined with data about land usage type, intensity and vulnerability would be enough to run the model. Extra information can then be added to make the model more inclusive and more precise data will improve the predictive power of the model (Berchum & Mobley, 2017). The low level of required data means that this type of model can still be used under data conditions where many models would not be able to produce satisfactory results.

The importance of the shortcomings in the data can easily be investigated and if required taken into account when analysing the model outcomes. The relative simplicity of the model makes the internal relationships more understandable and the relatively short computation time allows investigation into the effects of changing input (Berchum & Mobley, 2017). This would be impractical in more complex models as the effect on the results caused by shortcomings in the data will be more difficult to predict, because of far more complex relationships inside the model.

FLORES

In this study, the flood risk screening model 'Flood risk Reduction Evaluation and Screening' (FLORES) was used. FLORES was originally constructed to simulate flooding damage and structural and nature-based solutions for the Galveston Bay area in the United States. The model was designed to be flexible in order to enable it to be adapted to other cases easily. Recently, it has been adapted to be used for the city of Beira, Mozambique (van Berchum et al., 2019). It uses the Exploratory Modelling and Analysis (EMA)-Workbench enabling it to simulate a large number of strategies over a wide range of scenarios. The EMA-Workbench is a toolbox designed to assist in the generation and execution of series of computational experiments and to aid in the analysis and visualisation of their results (Kwakkel, 2017). This is to enable easier exploratory modelling, using (existing) models, and to identify promising policies for a wide range of scenarios (Kwakkel, 2017). Both FLORES and the EMA-workbench are python-based. It is a relatively simple model that requires only limited input, more information can be found in Appendix A and in Van Berchum et al. (2019).

2.4. Concluding remarks

In this chapter we described that a possible weakness of flood risk management lies in the way it uses quantitative or qualitative scenario analysis. The scenario analysis, as used in FRM, has a large amount of uncertainty and cannot thoroughly describe all possible futures, which risks forgetting important scenarios, under which the performance of the selected solution is poor. This can lead to less optimal performance of the flood risk management approach.

Robust decision making approaches actively take long-term deep uncertainty into account, by optimising over a large range of scenarios, and aim to create robust solutions, which have a satisfactory performance over a large range of scenarios, and flexible solutions, which can adapt to a large range of scenarios. The explicit exploration of the uncertainties and the consequences these have, can help guide the flood risk management approach to achieve better results under different than expected conditions. For this research, the robust decision making approach DAPP was chosen to form the basis of a new adaptive flood risk management approach, which is described further in chapter 3. The main benefit of incorporating DAPP into the FRM approach is that it explicitly links the future situation with the current situation and the effect of solutions taken today on the future options, which strengthens the cohesion of the overall plan and reveals the effects of path-dependency before solutions are implemented.

It was found that robust decision making approaches need a fast, simple policy analysis tool in order to analyse a large amount of possible futures. Flood risk screening models, can fulfil this role in a flood risk management setting. For this study FLORES is the used flood risk screening model.

3. FLOOD RISK ADAPTATION PATHWAYS APPROACH

This chapter describes the adaptive long-term flood risk management approach as suggested by this report. It is based on the analysis of the flood risk management approach and the robust decision making approaches in chapter 2. It aims to combine the strengths of the flood risk management approach with the strengths of the adaptive approaches.

3.1. Description of flood risk adaptation pathways

The Flood Risk Adaptation Pathways (FLORAP) approach is designed to act as a planning method for flood risk management far into the future. Through the use of a flood risk screening model, an initial estimate is made of the effectiveness of flood risk reduction measures under differing future external factors. A wide range of possible futures is considered to examine which measures work under which conditions. These conditions are decoupled from timelines and scenarios, the result will show under which conditions which measures can be used. This is done because the timeline is uncertain. So, the result is not based on this uncertain timeline, but instead shows what is possible under which conditions. The likelihood of these conditions occurring and when is removed on purpose, because of the large amount of uncertainty involved. These measures can then be used to create suitable actions for each possible future.

The selected measures are then combined into pathways, which are sequences of actions, which adapt to the changing external factors, such as sea level rise or population growth in the area under consideration. The focus in linking the actions is to create a flexible plan that can adjust to changing conditions. This is done by creating stepwise improvements between the sequences of actions.

A monitoring plan is then created, consisting of signposts and triggers, which signals when actions should be implemented. This allows the situation to be monitored, and to implement actions as the conditions require. During the monitoring phase further research can be done into likely required actions and the plan can be updated as new insights arise.

The approach aims to give the ability to anticipate for any possible future. This reduces the risk of not analysing futures, that are thought to be unimportant for the success of the measures, which later turn out to be important. This is realised by investigating a large range of possible future conditions with the flood risk screening model. It prepares a plan which is used as a frame of reference and basis for any action taken. It should allow policymakers to anticipate the implementation of measures, which would allow them to plan for investments and for making sure that nothing will block the implementation of those measures. This means making sure the solutions of today do not block the measures of tomorrow (preventing path dependency) and also actively making sure that areas that would be needed for measures later on remain available for these measures when the need arises. The approach thus reduces possible negative effects of path dependency, by making the future needs visible early on and keeping the required options open.

By planning over this longer timeframe, there should also be an improved coherence between successive actions in terms of measures used. Whereas normally, measures are implemented and revisited occasionally, now a long-term plan is created where the successive actions can be optimised to succeed each other. This means every action taken can be a building block and steppingstone for the next, reducing the costs of implementation of the next action.

Further by creating this plan, with the envisioned measures at each stage in advance, it will reduce the number of measures that need to be explored when we reach a point where the implementation of a measure is required. Normally when the point to act is reached, a broad spectrum of possible options is available and needs to be explored. With this plan, however, a preliminary result on which measures are effective is available. This would allow the remaining measures to be investigated in more detail.

It will leave room open for different preferences as it is possible to create several pathways based on different optimisation preferences or by indicating preferences for measures. This could be useful to investigate the wishes of policymakers, and to show them when the use of certain measures leads to unsuccessful pathways later on. And by allowing different preferences the plan is expected to be decoupled from uncertainty in the decision making, because it gives policymakers actions to choose which align with their preferences.

By combining the flexibility of DAPP with an evaluation over a large ensemble of possible futures it is expected that the approach will lead to a robust and flexible plan for almost every imaginable future. Through this approach long-term deep uncertainty should then be fully accounted for, as the plan has been tested for every eventuality and can be adapted to them.

Place in design process

The approach creates plans in the conceptual design phase. Further detailing of the plan can be done as the process moves into the new design phase, with a more detailed model.

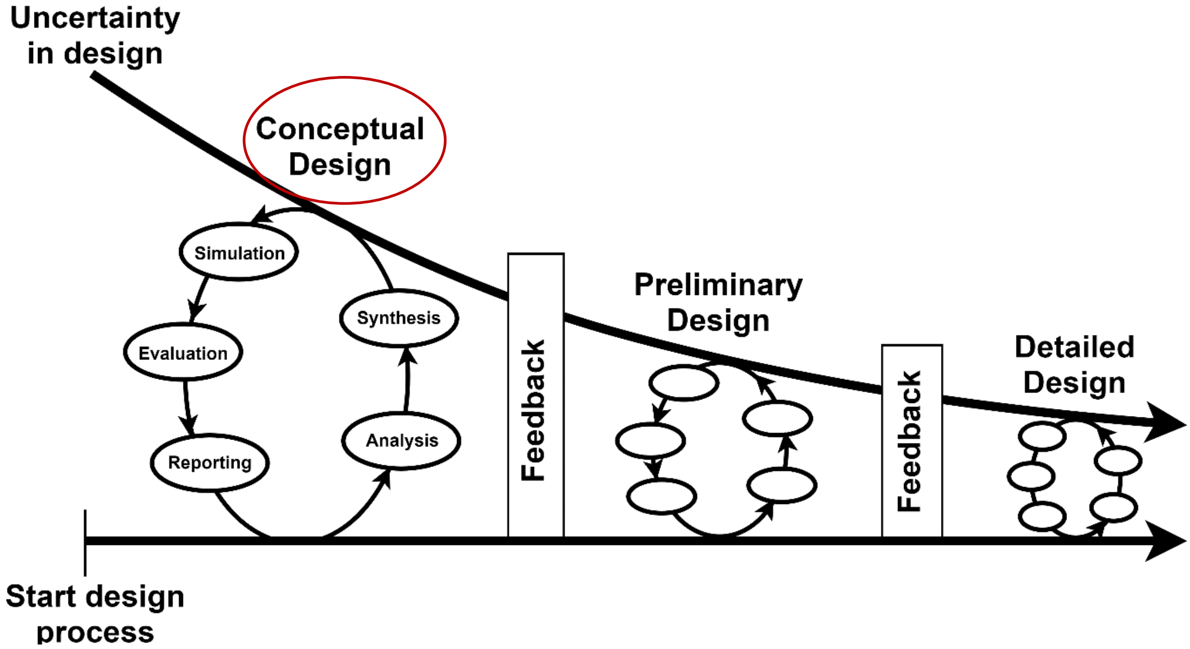


Figure 3-1: The flood risk adaptation pathways are designed to be created in the conceptual design phase. Image adapted from: Berchum and Mobley (2017).

3.2. Approach

The pathways are created through an eight-step process, which will be explained in this section. These steps are based on DAPP (Haasnoot et al., 2013), but several key changes have been made. The steps are shown in Figure 3-2. Multiple iteration moments are incorporated into the plan to improve the results, as is done in RDM (Lempert et al., 2003).

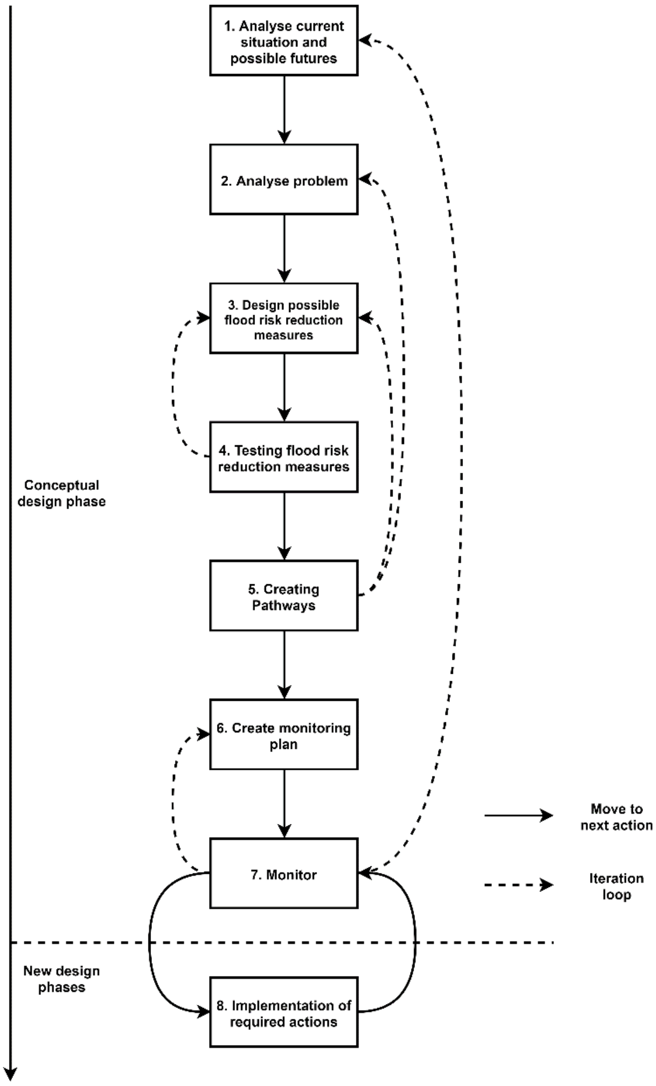


Figure 3-2: Flood risk adaptation pathways approach. Dotted lines are feedback loops which are used when required.

STEP 1. ANALYSE CURRENT SITUATION AND POSSIBLE FUTURES

The first step is to analyse the current situation and the range of possible future situations. This means collecting the data necessary to run the model for the current situation, such as data on the flood risks and topographic and demographic data. This data can be collected from available reports, literature and interviews of experts. Then based on the data of the current situation combined with future predictions (e.g. IPCC report (IPCC, 2014)) a range of possible futures can be created. In the next steps the possible futures within this range will then be examined.

STEP 2. ANALYSE THE PROBLEM

Secondly, the extent and severity of the problem must be analysed. What is an acceptable situation? How far is this from the current situation and possible future situations? What are the causes of this shortfall from the preferred state? The policymaker needs to specify what the goals are that need to be achieved by the plan. An optimisation problem or minimum performance requirements needs to be set in order to test measures to this standard and create actions. Examples are; setting a maximum accepted amount of risk or to strive towards the economically most optimal situation (risk and construction costs).

When applicable a stakeholder analysis needs to be performed to be able to take their interests into account in the plan. It is important to look at all the actors and determine their positions in terms of strength, wishes and demands. This will enable the engineer to take their preferences into account during the creation of the solutions and the pathways. This can be used to gain more acceptance and support for the plan by satisfying the goals of stakeholders. If these are incorporated into the plan, the discussion will be about which part of the plan should be implemented instead of whether the plan should be implemented. This leads to a much more constructive discussion and quicker and easier implementation and greater project success (De Bruijn & Ten Heuvelhof, 2008; De Bruijn et al., 2010).

STEP 3. DESIGN POSSIBLE FLOOD RISK REDUCTION MEASURES

Based on the previous steps a list of possible flood risk reduction measures can be created, which are possible candidates to be incorporated into the pathways.

As mentioned in step 2, the stakeholders need to be taken into account when creating the plan. The possible solutions should satisfy a wide range of the interests of stakeholders.

Possible flood risk reduction measures consist of pre-flood interventions and flood event management measures as defined in chapter 2.1. The resulting set of flood risk reduction measures need to have a wide range of applicability over the different possible futures, within the range as defined in step 1. They can be based on available sources, such as local reports and reference projects as was done in Van Berchum et al. (2019).

STEP 4. TESTING FLOOD RISK REDUCTION MEASURES

The next step is to test the flood risk reduction measures on their appropriate performance indicator and under which external factors this performance is attained. This should be done in a flood risk screening model to be able to test many solutions under many different combinations of external factors.

This leads to the creation of areas within the uncertainty range, where certain measures score strongly based on their performance indicators. Together these areas form a set of regions in which certain measures performs strongly, effectiveness regions, Figure 3-3. If areas are found where none of the flood risk reduction measures perform well, the process goes back to step 3 to create new measures which are expected to work in that area. It is important that every possible future has enough measures to create actions, because otherwise the resulting plan is not capable of dealing with these futures.

Investigation of the uncertainty range

There are two ways to test the flood risk reduction measures over the range of uncertainties. An open exploration (exploratory modelling) can be performed and a direct search can be applied, a combination of the two would also be possible. A full factorial subspace exploration would be a good option to sample over the uncertainty range, as this gives equidistant information on the performance of solutions over the uncertainties. Other ways to explore the subspace are also worth considering, since full factorial subspace exploration would be computationally expensive.

An exploratory modelling approach would involve running the model and analysing the results to come to a set of measures that can be used, this is explained in the next section.

Direct search engines, e.g. BORG (Hadka & Reed, 2013), can be used to computationally select the combination of measures that meet the policy goals. When this option is used, the model will be run and the direct search engine will select the best flood risk reduction measures and redirect new model runs in their direction.

Exploratory modelling

The steps of the exploratory modelling approach are explained in this section, they are listed in Table 3-1.

Table 3-1: Iterative exploratory modelling process.

STEP	ACTIVITY
1	Run many possible combination of flood risk reduction measures for several external inputs, ranging from extreme to normal conditions
2	Remove badly performing combinations of flood risk reduction measures, go back to step three if required.
3	Run combinations of flood risk reduction measure for all combinations of possible futures
4	Perform feature scoring and PRIM analysis
5	Create effectiveness regions
(6)	Construction of pathways (this is step six, but also part of the exploratory modelling process)

Firstly, a large amount of combinations of flood risk reduction measures should be run on a few scenarios ranging from the most severe conditions to normal conditions. On this basis an initial assessment of the measures can be performed, which allows ineffective measures to be removed and to go back to the previous step to create new ones if required.

The resulting measures can then be run for all the possible futures. After which, the measures can be assessed in the Exploratory Modelling Workbench (Kwakkel, 2017) with feature scoring (Breiman, 2001; Geurts, Ernst, & Wehenkel, 2006) and the Patient Rule Induction Method (PRIM) (Friedman & Fisher, 1999). On this basis and by analysing the model run results, the effectiveness regions can be created by analysing under which conditions what measure performs well.

Feature scoring is a machine learning tool, which can be used to generate insight into the relative importance of external factors and policy levers on the model outcomes (Kwakkel, 2017). In the FLORAP approach, it is used to generate insight into the relative importance of the flood risk reduction measures on the flood risk, affected population and construction costs. It is an alternative to performing a global sensitivity analysis (Kwakkel, 2017).

The PRIM analysis is a type of scenario discovery, which is an approach to finding subspaces in the model input space that have a high concentration of results that fulfil a specified goal (van Berchum et al., 2019). In the FLORAP approach it is used to find which flood risk reduction most often fulfil the set thresholds, where the thresholds are used to limit construction costs, flood risk and affected population in order to find measures that are suitable for obtaining the defined policy goal. The PRIM analysis is further explained in Appendix C.

Effectiveness regions

The effectiveness regions show the effectiveness of individual measures under the differing external factors. Combinations of these effective measures can then be made in the next step to create effective actions and then effective pathways.

An example of what the result would look like is shown in Figure 3-3. The effectiveness of the flood risk reduction measures is depicted over the horizontal axis, which is rainfall intensity increase in this example. It shows under which circumstances which solutions is an option. Effective solutions should preferably overlap as this allows pathways to be constructed for multiple preferences of stakeholders. It can occur that there is only one solution available, in which case the figure can be used to show to stakeholders that there is no other feasible option available. The effectiveness areas are the basis for the creation of the pathways in the next step.

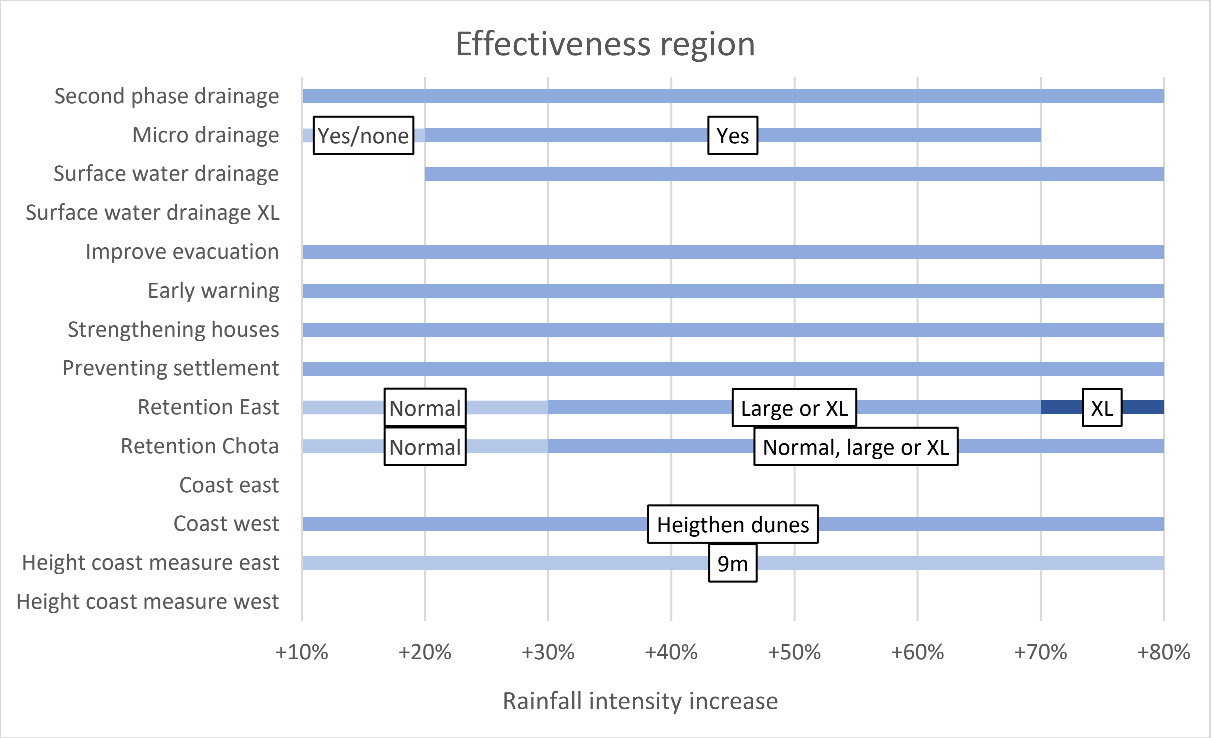


Figure 3-3: Effectiveness regions, each bar shows the region over which the flood risk reduction measures is effective. The relevant information to take away from the figure is under what condition which measure is an option to be part of the actions for the pathways. Three of the flood risk reduction measures are used to explain: The second phase drainage is effective (what is effective depends on the policy goal) in the current situation and will remain this for all increases of rainfall intensity, it will not be sufficient to reach policy goals on its own but it can make a valuable contribution. The surface water drainage system only becomes effective from a +20% rainfall intensity increase. The XL drainage system does not become effective for rainfall intensity increase alone.

STEP 5. CREATING FLOOD RISK ADAPATION PATHWAYS

Pathways can now be created by looking at the efficiency regions. Measures can be combined into actions, and sequential actions become pathways. The pathways should be constructed so that the resulting plan is flexible, and thus that switching from one action to another is easy (no conflicting measures).

The pathways should cover the whole region of the external factors and where possible multiple actions can be used for the same set of external factors, thus resulting in different pathways. The main external factors are used as the axes. Through the use of these axes, instead of a time axis as is done in DAPP (Haasnoot et al., 2013), policymakers are informed through clear visual information which solutions are required under certain external factors.

When there are multiple optimisation objectives, for example from different stakeholders and policymakers, more actions should be made based on these preferences. These differently optimised pathways can be shown in one figure, but if this becomes convoluted figures can be made per optimisation objective. An example of the resulting pathways is shown in Figure 3-4.

If a large number of pathways has been created, a select number of pathways should be selected as preferred pathways. These are the main outcome of the plan, with the other pathways as backup. Preferred pathways should be chosen on their performance and on the perspectives of the different stakeholders. Pathways should remain for all different combinations of external factors.

The result of this step determines if iteration loops should be used. When actions which meet the policy goals cannot be created, two possibilities exist: The process can go back to step 3, in order to create new flood risk reduction measures which would allow actions to be formed that meet the policy goals. The process can also go back to step 2, since new insight will have been generated by the testing of the solutions and creation of the pathways, and a possible conclusion is that the policy goals are simply unrealistic under those conditions. In this case the policy goals should be adjusted to reflect this new reality.

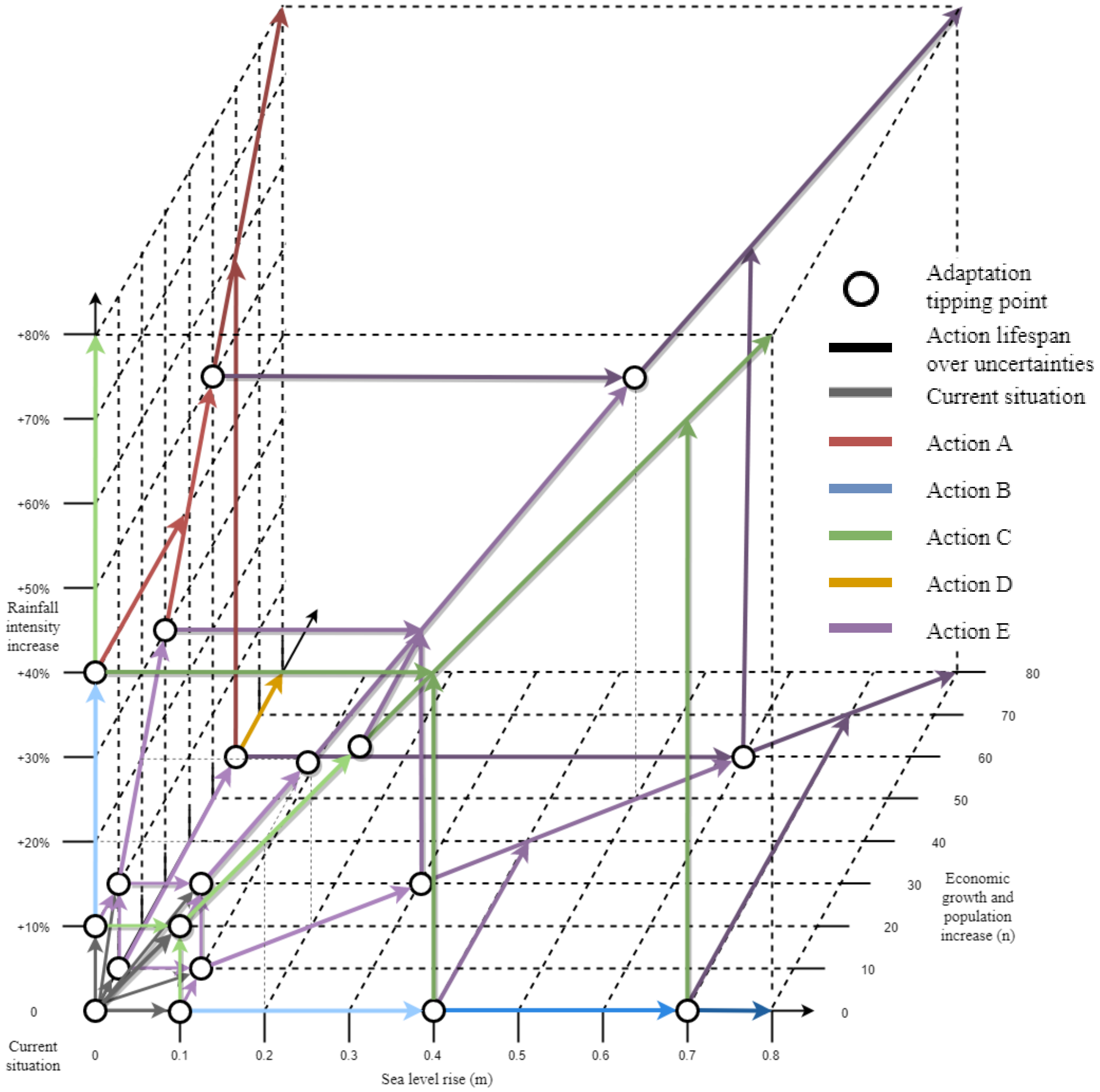


Figure 3-4: Resulting pathways over three main external factors, in this example these are rainfall intensity increase, sea level rise and economic growth and population increase. The pathways show what action should be taken under which combination of external factors. The origin of the graph is the current situation, from which point on the external factors can increase. This increase is uncertain and it is thus unknown at what point in the graph the situation will end up. The pathways show what happens under the different possible futures. There are more possible combinations of external factors than the pathways shown, in between pathways there are connection pathway arrows to show the transition between pathways.

STEP 6. CREATING MONITORING PLAN (CONTINGENCY ACTIONS, SIGNPOSTS AND TRIGGERS)

A monitoring plan should be created, as is done in DAPP (Haasnoot et al., 2013), which specifies which parameters need to be monitored (signposts) and at what values decisions need to be made on what solution to implement (triggers). There should be a lead time incorporated into the triggers, because time is needed to implement the solution before the tipping point is reached. And contingency actions can be specified, these include capitalising actions, defensive actions, corrective actions and reassessment (Kwakkel et al., 2010). Trigger values should also be made for the re-evaluation of the plan itself, these should incorporate a significant lead time before values of the uncertainties are reached that have not been considered in the current plan.

STEP 7 & 8. MONITORING AND IMPLEMENTATION

The final step consists of executing the monitoring plan. The situation should be monitored until trigger values are reached. When this happens work should be started to implement the corresponding action. While the monitoring is ongoing, further research can be done into the actions that correspond with the most likely futures as determined from the monitoring.

When the implementation of an action starts, a new phase in the design process begins, in which the measures are worked out more in detail. After the action has been implemented the process goes back to the monitoring step until new actions are required.

The monitoring plan can be adjusted as required, when deficiencies in the monitoring plan are detected during the monitoring phase or if unexpected side effects of flood risk reduction measures that need to be monitored are encountered.

Eventually, the plan will have to be re-evaluated, for this a trigger value was set in the monitoring plan but it can also be due to unexpected developments that threaten the policy goals, the approach then goes back to step 1.

3.3. Reflection on approach

This section reviews possible limitations of the newly developed approach. These limitations will be further reviews in section 4.7 after the completion of the case study.

Combining the DAPP approach with an evaluation over a large ensemble of possible futures will make the approach computationally expensive, especially as wider ranges of future conditions are used to ensure taking into account all the possible futures. The uncertainty subspace should be evaluated over the most important external factors. This means that the number of model evaluations is dependent on the power n, where n is the number of main external factors, on the number of grid points used over the axes. As more external factors are incorporated, the number of evaluations (grid points) also becomes dependent on a higher order. When more main external factors are selected, the number of axes increases also. A four-dimensional (or more) situation would be difficult to visualise with the pathways image. Furthermore, as more situations are analysed, the pathways can become problematic visually. With so many grid points and paths leading between them, the picture can become very densely packed and obscure. It is expected that this could be resolved by showing this in an interactive way in 3D software.

Determining the correct trigger values might be difficult, because it is unknown at what rate the signpost values will increase. Triggers have to be determined so that there is enough lead time in order to have the necessary measures ready in time, but because of the uncertain rate of increase the required value is difficult to ascertain. Depending on the situation, this can be an important problem. A possible approach, trigger-probability mapping, is described in Raso, Kwakkel and Timmermans (2019), in it the probability of implementation an action too early and too late is compared in order to come to a trigger value with the lowest probability of regret.

A further difficulty with the unknown increase rate of the signposts might be that it should be estimated before implementing an action, as it affects the lifetime of an action. If an action is taken based on a trigger value but only a few years later another trigger value is reached, it would have been better to implement the second action right away. This is difficult to fully resolve. But it is expected that if the situation is monitored according to the established monitoring plan and short-term estimates are made for the coming years these will be reasonably accurate and will thus not lead to severe problems in most cases. This approach does reduce uncertainty, but it cannot be removed.

4. CASE STUDY: BEIRA, MOZAMBIQUE

The case study treated in this chapter is on the city of Beira, Mozambique. The city of Beira faces a hydraulically complex problem with limited financial means under deep uncertainty. It is hydraulically complex because of the local topography, wide range of possible solutions, limited financial means, uncertainty about its future environment and a lack of (reliable) data.

It is expected that an adaptive approach will provide a valuable contribution to finding a solution to the problems Beira faces. Longer term planning will allow the city to reserve areas which are required for flood risk reduction measures, allow the city to reserve money for the necessary investments and prevent the city from implementing measures that will have negative consequences in the future.

The case study is examined stepwise with the flood risk adaptation pathways approach. Each section represents a step as described in chapter 3, step 7 and 8 are the implementation of the plan and thus cannot be treated. After the case study has been performed, the approach is reflected upon in section 4.7.

4.1. Current and future situation

Beira is a city with 500.000 inhabitants, the second largest city in Mozambique. It lies at the mouth of the river Pungwe on the Indian ocean. The city was founded, in 1890, by the Portuguese on top of a sand dune and was originally meant for a maximum of 30.000 inhabitants. Since then, the city has developed into lower lying areas which nowadays suffers severe flooding problems. The cities problems are the following: Firstly, flooding due to rainfall occurs regularly especially in the lower lying areas, secondly tropical storms cause flooding from the sea and lastly the coast is eroding due to natural and human causes, which makes the city more prone to flooding from the sea.

The city was struck by a powerful cyclone this year which caused widespread damage. The cyclone struck the city at neap tide which prevented even worse. It is clear however, that the city has a major problem with coastal and stormwater flooding.

Compound flooding effect is able to cause significant problems for Beira. When high sea water levels coincide with large amounts of precipitation, the rainwater will not be able to run off to sea, because the drainage system relies on gravity. The flooding problem Beira faces needs to be managed for the city to be able to develop further, however the city only has limited financial means to accomplish this.

A masterplan has been created for the city for 2030 which aims to bring economic development to the city and resolve its flooding problems. The economic development drive consists of making use of the cities location and port to create welfare, and to create better housing for the inhabitants (Deltares & Witteveen en Bos, 2013). New coastal protection and drainage measures are incorporated to resolve current flooding problems and to prepare the city for climate change (Deltares & Witteveen en Bos, 2013).

Section 4.1.1 collects available data which is required to run the model and section 4.1.2 investigates the possible future conditions. The data in section 4.1.1 has been taken from van Berchum et al. (2019) as this report had already collected the relevant data. Section 4.1.2 makes future predictions based on the IPCC report (Christensen et al., 2013; Church et al., 2013) for rainfall intensity increase and sea level rise and economic and population growth predictions based on economic reports (African Development Bank Group, 2018; World Bank, 2017) and the Beira masterplan (Deltares & Witteveen en Bos, 2013).

4.1.1. AVAILABLE DATA

This chapter describes the data and scenarios which were used as input for the FLORES model. First, the hydraulic boundary conditions are described and secondly the regional information is discussed. Lastly, the scenarios for development and hydraulic boundary conditions are given. Additional information can be found in Appendix A.

Hydraulic boundary conditions

This section describes the required hydraulic information to run FLORES. The sources used in this study are shown in Table 4-1. Wind and surge data is used to create storm events and rain data for rain events, which are then used as the hydraulic boundary conditions to calculate flooding in FLORES. A correlation between the storm and rain events is then required to calculate risks. See Appendix B.1 for further information.

Table 4-1: Hydraulic boundary conditions input.

REQUIRED INPUT	SOURCE	REFERENCE	DATA TYPE
SURGE DATA	GAR15 storm surge	(Cardona et al., 2014)	Global open data
RAIN DATA	Adaption to climate change Feasibility study	(CES & Lackner, 2013)	Local data
WIND DATA	GAR15 cyclonic wind	(Cardona et al., 2014)	Global open data
CORRELATION (WIND AND RAIN)	ERA-Interim	(Dee et al., 2011)	Global open data

GIS information

The Beira region was mapped with a GIS, the input for this computation is given in Table 4-2. The regional information from the GIS provides the model with land height, see Figure 4-1, land use and population living in each area. Furthermore, a flood-damage function and flood reduction measures were defined in FLORES.

Table 4-2: Region information data input.

REQUIRED INPUT	SOURCE	REFERENCE	DATA TYPE [RESOLUTION]	COORDINATE REFERENCE SYSTEM (CRS)
ELEVATION	LiDAR Digital elevation model (DEM)	(Geoscience Australia, 2013)	Local data [2m]	EPSG:32736
EXPOSURE - STRUCTURAL	ADFR (R5) – Building exposure	(Eguchi et al., 2016)	High-level [450m]	EPSG:32736
EXPOSURE - POPULATION	ADFR (R5) – population exposure	(Eguchi et al., 2016)	High level [450m]	EPSG:32736
DAMAGE CURVES	Global flood depth-damage functions	(Huizinga, de Moel, & Szewczyk, 2017)	Global open data [-]	-
FLOOD RISK REDUCTION MEASURES	Risk-based screening tool for fast flood risk assessment in developing countries	(van Berchum, 2018)	Local/ global open data	-

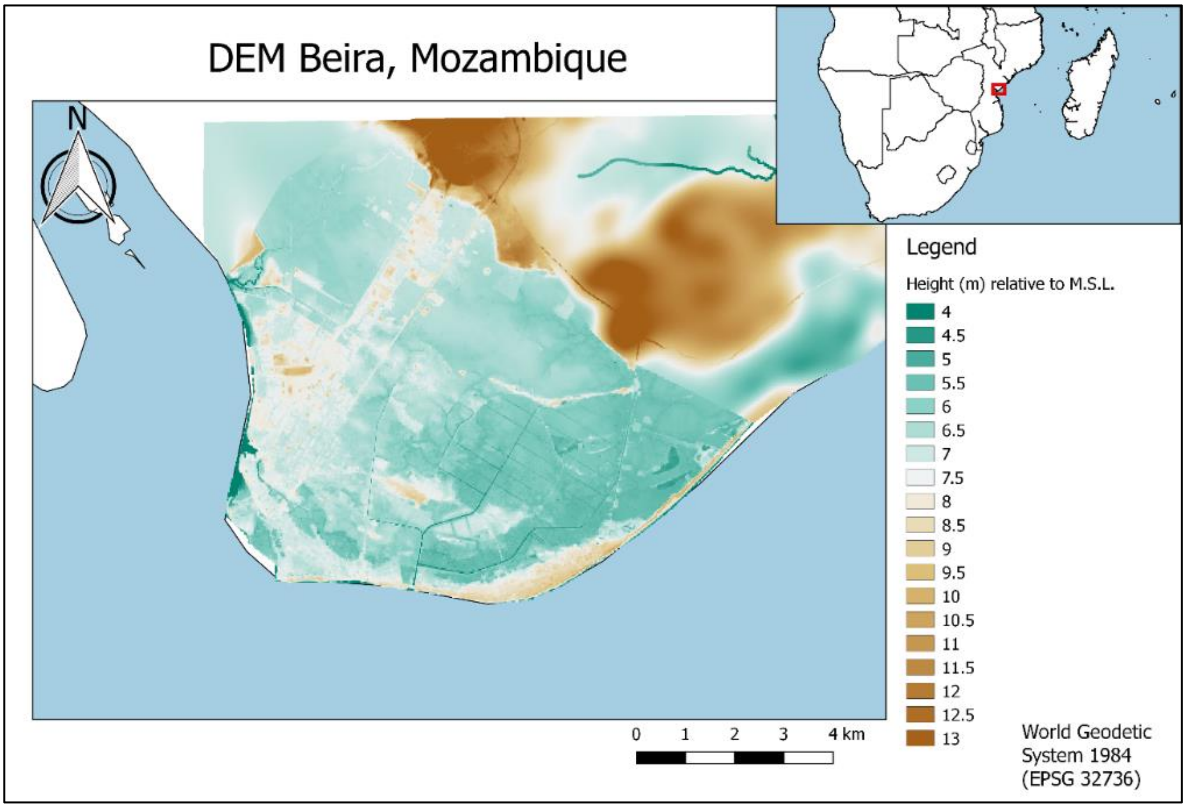


Figure 4-1: Digital Elevation Map of Beira.

4.1.2. POSSIBLE FUTURES

In this section the possible futures which serve as input into FLORES are analysed. The ranges of possible increase in rainfall intensity, sea level rise and development are estimated based on the available sources.

Climate

The climate estimates are based on chapter 13 and 14 of the fifth assessment report of the IPCC (Christensen et al., 2013; Church et al., 2013). There is significant uncertainty about the climate change predictions. Beira lies in an especially uncertain zone, in between an area with rainfall increase and rainfall decrease. That the sea level will rise is quite certain for Beira, the extend however is highly dependent on which climate scenario is used (Church et al., 2013). The change in storm intensity and frequency of occurrence is difficult to predict because of insufficient data for the South-Indian Basin, thus only global predictions can be made.

Rainfall

The precipitation forecasts for the long term for Beira are still highly uncertain. Most climate models predict that the majority of Eastern Africa will receive a significant increase in monsoon rainfall, while most of Southern Africa will receive less precipitation throughout the year (Christensen et al., 2013). Beira is located on a transition area, between these two regions and thus it is difficult to predict with certainty what will happen here. Furthermore it is expected that the rainy season will become shorter, with less rainfall earlier on, but more intense rainfall periods later on in the rainy season (Christensen et al., 2013).

To accommodate all possible futures a range of rainfall intensity increases will be investigated, between +0% and +80%. Rainfall intensity is the most important parameter of the rainfall as short and intense periods of rainfall create the most drainage problems. The return period of the rainfall events will remain the same. The range is based on the October to march estimates (the rainy season falls within this period) of the RCP2.6 and RCP8.5 IPCC scenarios for the Eastern Africa region. The possible decrease in rainfall is not incorporated into the analysis as this is less important for the flood risk reduction measures, and because under that scenario intensity is also expected to increase.

Sea level rise

Sea level rise is expected to be somewhere between +0.35m and +0.65m in 2100 relative to 2020 in the region around Beira (Church et al., 2013). Tropical storms are also expected to increase in severity (Christensen et al., 2013), to simplify the situation this is included as an extra increase in sea level rise. The range of relative sea level rise is estimated to be between +0m and +0.8m as opposed to the current situation (van Berchum et al., 2019). This is expected to give a good overview of most of the possible futures.

Development

The development factor consists of population growth and economic development. There is spatial variety in the population growth so that districts with space for expansion have higher growth rates. The distribution of the population growth is further described in Appendix B.3.

Low population growth is estimated as a yearly 2.25% increase and a high population growth at 4.25% (Deltares & Witteveen en Bos, 2013). Low economic growth is estimated to be 3.7% yearly (African Development Bank Group, 2018; World Bank, 2017), while high economic growth is estimated as 5% yearly.

The low increase rates will be taken as a 100-year annuity, to come to the range of possible futures that will be investigated. Taking the low increase rate does not mean that high increase futures are neglected. Fixing the rate at these low levels for 100 years leads to high increases, as normally the increase rate would most likely decrease over time. This leads to an economic value increase range between +0% and +3800% and a population increase range between +0% and 925%.

4.2. Analyse the problem

As mentioned in section 3.2, the policymaker needs to determine the goal of the flood risk management process. Together with the policymaker an optimisation problem can then be decided upon.

For this case study we will assume the goal of the policymaker is to arrive at an economic optimum. The optimisation problem is defined as a three-pronged optimisation problem, consisting of a simple cost optimisation based on Vrijling et al. (1995) and an exploratory modelling approach to reduce the affected population and to improve the flexibility of the plan so that the plan is robust under different futures.

The economic optimum is found by striving for the lowest yearly total costs as is possible, see Figure 2-1. The total costs are the yearly expected flood damage combined with the yearly costs of the flood risk reduction measures, see equation 1. The yearly costs of the flood reduction measures are reached by dividing the costs of construction by their approximated lifespan, see equation 2.

$$Yearly\ total\ costs\ (\$) = \frac{Yearly\ expected\ flood\ damage\ (\$)}{Yearly\ costs\ flood\ risk\ reduction\ measures\ (\$)} \qquad \text{(Eq.1)}$$

$$Yearly\ costs\ flood\ risk\ reduction\ measures\ (\$/Yr.) = \frac{Construction\ costs\ measures\ (\$)}{Lifetime\ measures\ (Yr.)} \qquad \text{(Eq. 2)}$$

The policy goal and the optimisation problem, as used in this case study, are thought to be sufficient, since this case study is only used as a proof of concept. In real world applications any optimisation problem and policy goal can be used. This has been reflected upon later in the discussion.

Seven runs were performed in order to search through the uncertainty region, Figure 4-2. Three runs with each only one increasing uncertainty. Three runs with two of the uncertainties increasing and lastly one run with all the uncertainties increasing.

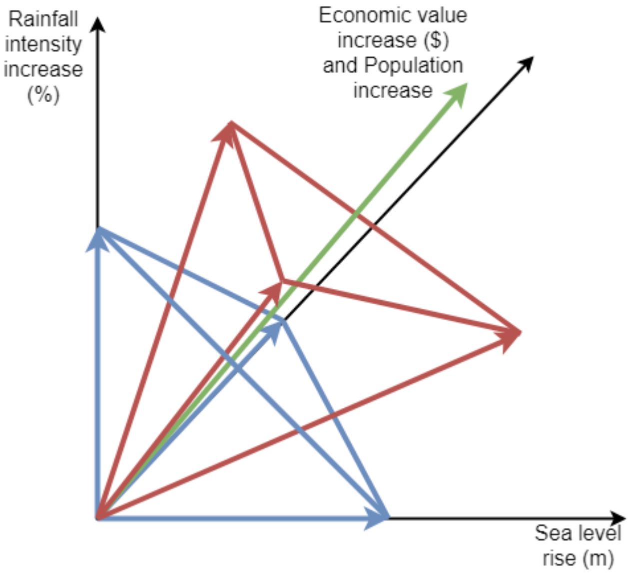


Figure 4-2: Model runs, blue arrows: single uncertainty, red arrows: two uncertainties, green arrow: three uncertainties.

Figure 4-3 shows the risk levels over the runs if no solutions are implemented. It clearly shows that the risk (economic risk) and affected population especially increase due to economic development and population growth. When growth and development is included, sea level rise and rainfall intensity increase the risk and affected population significantly. An initial analysis shows that, under all the circumstances shown in Figure 4-3, the total costs will be lower if flood risk reduction measures are implemented. This is shown in further detail in Figure 4-8 and in Appendix C.

In order to reach an economic optimum, the extend of the problem is defined as the gap between the predicted yearly expected damage without any measures implemented (base risk) and the lowest possible total costs with (or without) implemented solutions. The pathways will be created in such a way as to minimise the difference between total costs and lowest possible total costs, while taking the affected population and flexibility into account. The affected population will be minimised for the cost-effective measures and the flexibility will be ensured by creating a concatenation of actions, which allows easy switching between them.

Table 4-3: Conditions corresponding to the steps in the runs, relative to current situation. The development axis is given in steps, where the development steps correspond to an economic growth percentage and population growth percentage.

Step	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
R.I. increase (%)	+10	+20	+30	+40	+50	+60	+70	+80
S.L.R. (m)	+0.1	+0.2	+0.3	+0.4	+0.5	+0.6	+0.7	+0.8
Development step (-)	10	20	30	40	50	60	70	80
Economic growth (%)	+44	+107	+197	+328	+515	+785	+1172	+1729
Population growth (%)	+25	+56	+95	+144	+204	+280	+375	+493

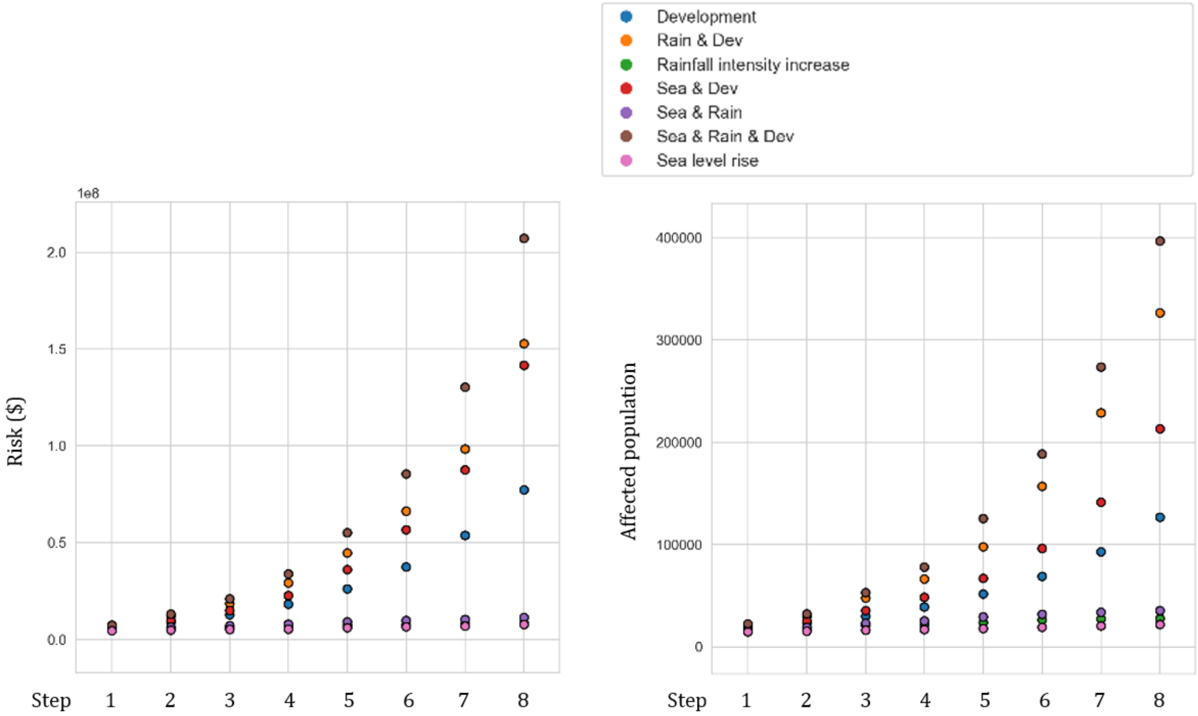


Figure 4-3: Base risk levels in the different model runs, Table 4-3 shows the conditions corresponding to the steps.

4.3. Flood risk reduction measures

Table 4-4, shows the flood risk reduction measures which were implemented in FLORES to manage the flood risk. Figure 4-4, shows a map of Beira and where the measures are located. Most of the measures that are investigated come from Van Berchum et al. (2019). The larger drainage and retention measures have been added for this study. The flood proving measures are a new addition to the FLORES model, created for this case study. The measures are explained in this section and more information on how the measures are included in the model can be found in Van Berchum et al. (2019).

Structural measures

These measures are designed to reduce flood risk originating from coastal flooding. The coastline is divided into two coastal sections; an eastern and western section. Three options are available to reduce the coastal flood risk; sand supplements, heightening dunes and constructing a floodwall.

Drainage measures

The drainage measures aim to reduce flood risk originating from pluvial flooding. There is a second phase drainage measure, which comprises of further rehabilitating the remaining parts of the old drainage system. A micro drainage system, with small gullies is proposed to increase the drainage capacity of areas where the water otherwise stagnates. A more expensive surface water drainage system and an extra-large version are also included in the analysis.

Retention measures

Retention measures store the rainwater to prevent flooding. This is especially useful when the drainage capacity of the used system is insufficient to drain all the rainwater to sea in a timely matter. An important factor here, is that the current drainage system drains under gravity so that when high sea levels coincide with heavy rainfall the water will not be able to drain off to sea. In these situations, retention measures will be indispensable. Two locations for retention measures are chosen, which are shown in Figure 4-4.

Emergency measures

Emergency measures aim to protect people from a flooding event by evacuating prior to the flood event. Timely evacuation can only be realised with early warning systems and when good evacuation routes are available. These are both emergency measures which are taken into account in the case study.

Flood proving measures

Flood proving measures aim to prevent damage by reducing the number of vulnerable elements or the vulnerability of these elements in flood prone areas. Two options have been selected for use in the case study. The first is strengthening houses, which consists of small low costs adjustments to individual houses which will make them less prone to flooding. Examples would be to install the electrical elements at a certain height from the floor or to elevate the base of houses slightly. The other option is to prevent settlement in flood prone areas. This can be done through the means available to the policymaker. For example, certain objects can be placed to make it impossible to build houses there, but a functioning land registry would be another option. Costs of prevention of settlement has been based on World Bank (2010) and the improvement of the houses is based on Deltares and Witteveen + Bos (2013) and Wissing (2015).

Table 4-4: Flood risk reduction measures, (van Berchum, 2018)**. L: Length, V: Volume. Source:** (Arcadis, 1999; CES & Lackner, 2013; Deltares et al., 2015; Deltares & Witteveen en Bos, 2013; van Berchum et al., 2019; Wissing, 2015; World Bank, 2010)

NAME	LOCATION (BASIN ID)	TYPE	DIMENSIONS	CONSTANT COSTS ($)	VARIABLE COSTS ($)
Heighten dunes	East (28,27,22,21)	Structural	L:9500 m	3 Million/km	1.5 Million/km/m
Sand supplements			L:9500 m	2 Million/km	0.5 Million/km/m
Heighten dunes	West (33,43)	Structural	L:4800 m	4 Million/km	1.5 Million/km/m
Floodwall			L:4800 m	5 Million/km	1 Million/km/m
Second phase drainage	(41,26,37,28,22, 20)	Drainage		12 Million	
Micro drainage	(1,2,3,5,8,9,12, 13,14,15,22,23, 24,25,27,28,35, 37,40,41,43)	Drainage		8 Million	
Surface water drainage system				40 Million	
Surface water drainage system XL				80 Million	
Retention	East (28,22)	Retention	V:1.5*10^6 m^3	5 Million	
Retention large			V:3.0*10^6 m^3	10 Million	
Retention extra large			V:6.0*10^6 m^3	20 Million	
Retention	Chota (41)	Retention	V:1.0*10^6 m^3	2 Million	
Retention large			V:2.0*10^6 m^3	4 Million	
Retention extra large			V:4.0*10^6 m^3	10 Million	
Improve evacuation	(12,13,14,15,16, 23,26,27,28,36, 38,40,41,42)	Emergency		1.5 Million	
Early warning system	(23,26,28,31,32, 33,34,36,38,39, 40,41,42,43)	Emergency		0.4 Million	
Strengthening houses	(23,26,27,40,41)	Flood proving		1 Million	
Prevent settlement vulnerable areas				4 Million	

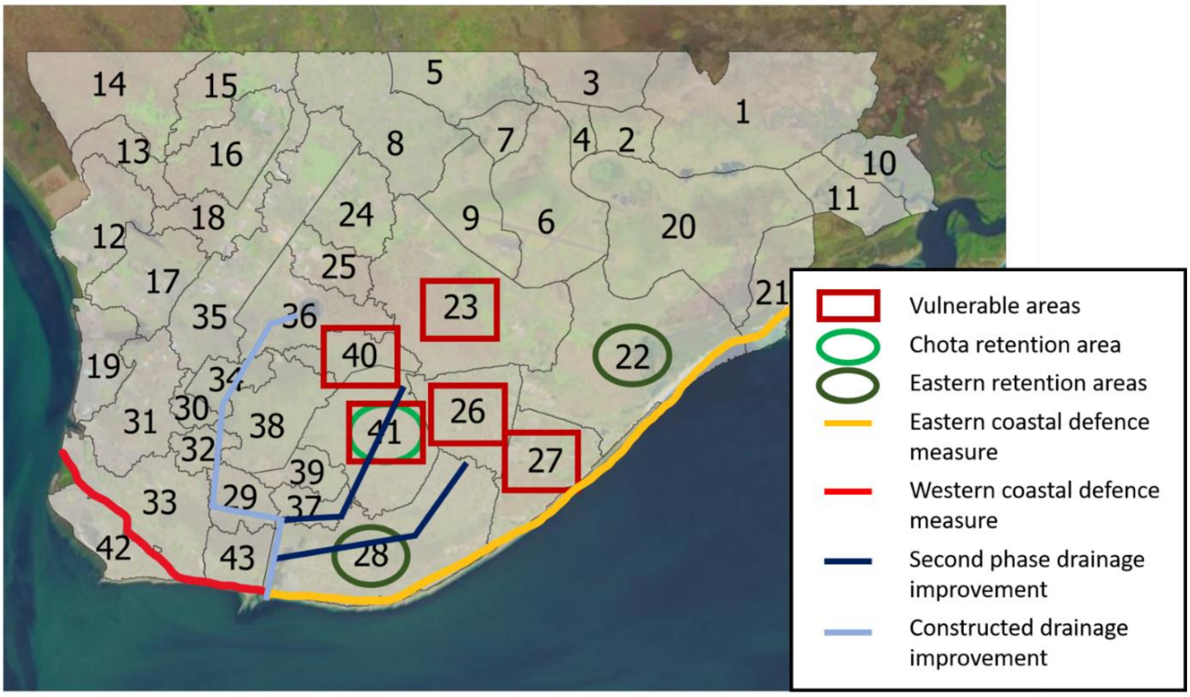


Figure 4-4: Map of Beira, showing the locations of flood risk reduction measures. The area is split into 43 basins for FLORES.

4.4. Testing flood risk reduction measures

In this section, the flood risk reduction measures have been tested and assessed on their effectiveness in terms of the determined optimisation problem. A single model run was used for an initial evaluation of the measures, this tested them on several conditions within the determined uncertainty intervals. An inland coastal defence measure was removed on this basis, because it barely had any effect, and several new retention and drainage measures were added (by going back to step three). After this the model was run for the seven different combinations of uncertainties, Figure 4-2. This method was selected to search through the uncertainty region while limiting the amount of computation time that is needed. Using the exploratory modelling workbench, each model run explored 50 different strategies over 8 steps with 24 risk events. Thus, the base model is run 9600 times for every model run and a total of 67,200 runs. With an average run duration of 1 minute, this already led to a significant computation time. A full factorial subspace division would for example be an excellent way to test the solutions over the full range of possible futures. However, this would lead to 614,400 runs. Since this is a proof of concept, it was not deemed time effective to do this. It should also be noted that this leads to a very long run time under any circumstance. Especially when one considers, that the 50 different strategies were not chosen as an optimum amount, but rather in order to limit the required computation time. More different strategies would be better, but for this case study it was deemed an acceptable trade-off to reduce the computation time.

The model results were in turn visualised and analysed using tools in the exploratory modelling workbench. The results of the seven runs can be found in appendix C. In this chapter, only parts of the model outcomes are shown, and the focus lies on the results of the analysis tools used and final outcomes. In the next section the results of a feature scoring analysis and PRIM analysis are shown. These were used to determine measures of interest, which were then further analysed by directly looking at model outcomes. This resulted in the creation of the effectiveness regions which are given in section 4.4.3.

4.4.1. FEATURE SCORING

A feature scoring analysis was used to determine which measures had a significant effect on the risk reduction, the reduction of the number of affected people, and the construction costs. This analysis was done for the current situation, for an increased rainfall intensity, sea level rise and development.

Current situation

Figure 4-5 shows the results of the FS analysis in the current situation. Figure 4-5a, shows the influence of the measures on the risk reduction. It shows that the retention measures, and especially the eastern retention option, are effective in reducing the risk. The western coastal defence measure also is a strong influence on the risk reduction. Prevention of settlement in the vulnerable areas is a further strong influence. Lastly, the second phase drainage option also performs rather well. The remaining options do reduce the risk but not as strongly as the ones mentioned.

Figure 4-5b, shows that for reducing the affected population three measures are by far the most important. The two emergency measures are not surprisingly the two most important factors. After these the remaining important factor is the western coastal defence structure. For the risk reduction many other flood risk reduction measures are also important, but for the affected people it is only the western coastal defence structure. This implies that the flooding from rain is damaging to the elements in the flood zone, but that this flooding from rain is often not deep enough to threaten people.

Figure 4-5c, shows the influence of the measures on the construction costs. This is of course an indirect representation of Table 4-4, but it is interesting to look at it in combination with Figure 4-5a,b. It shows that the extra-large storm drainage system and the eastern coastal defence measure are expensive measures, which have, at least in the current situation, far higher influence on construction costs than on risk reduction.

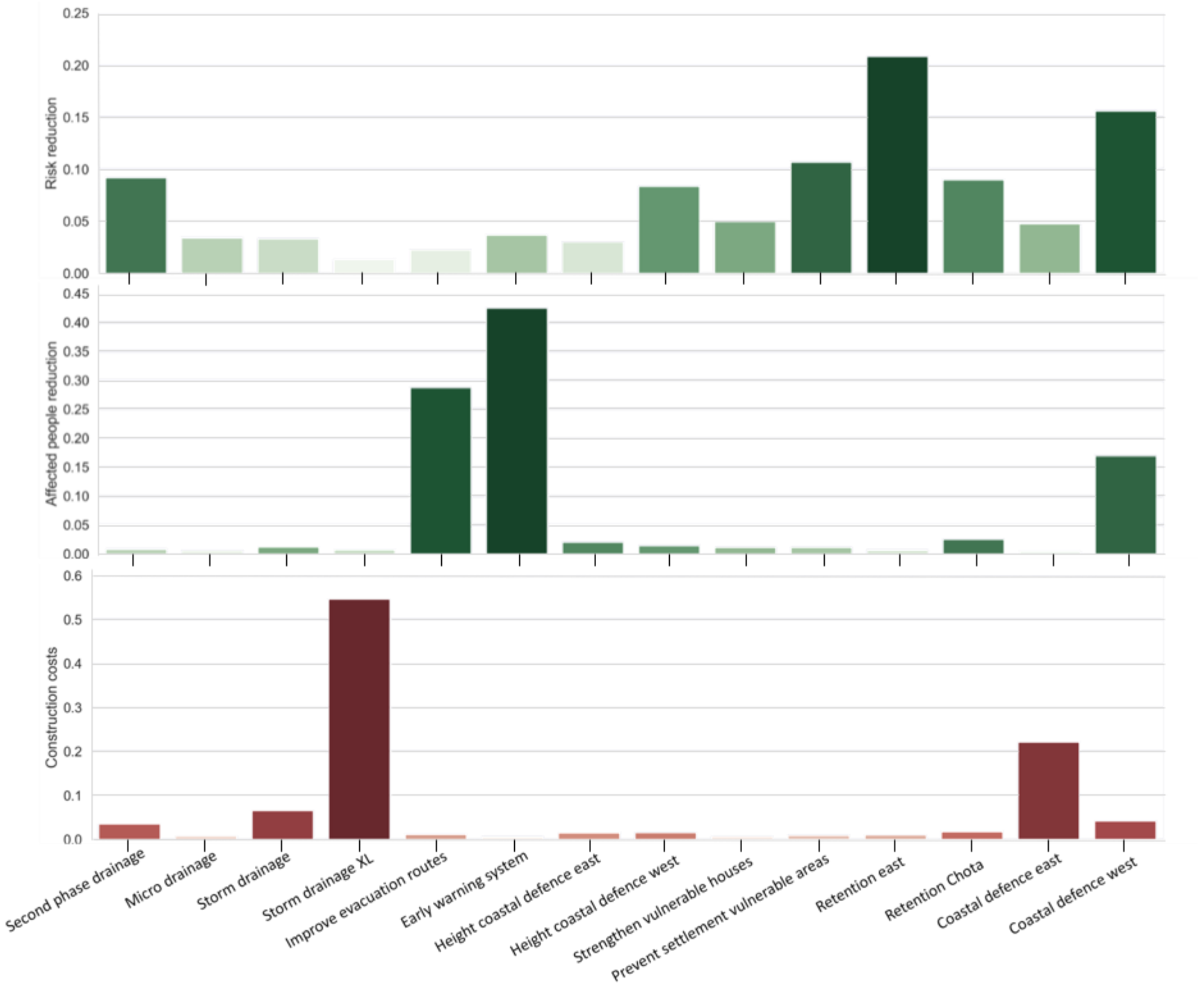


Figure 4-5: Feature scoring results for the current conditions.

Risk reduction under increasing rainfall intensity

Figure 4-6a shows which measures have the biggest influence on risk reduction when there is increasing rainfall intensity. Preventing settlement in the selected vulnerable areas has the biggest influence on the risk reduction. This indicates that the areas were rightly selected as flood prone due to rainfall events. Preventing people from settling here would mean the city has to invest less to provide enough drainage capacity for this area. It also means an area is available for the retention areas. The two retention areas are the next two most important measures according to the feature scoring. That the retention areas are more important than the drainage can mean two things. Either there is so much rainfall in a short amount of time that creating enough capacity cannot be created. Or compound flooding effects are important, even in a situation where only the rainfall intensity increases. The cities drainage system relies on gravity to drain, no pumping capacity is available to take over when the sea water level is too high.

The effect of all the drainage measures combined is also significant. The score of individual drainage measures is affected by the other drainage measures. The way these drainage measures have been implemented in the model, leads to the score of one drainage measure reducing the score of another. This is taken into the account in the analysis.

Risk reduction under sea level rise

Figure 4-6b shows that the biggest influence on the risk reduction under sea level rise is the construction of the coastal defence measure along the western section. This section protects somewhat higher lying land, but it is also the most developed part of the city. Apparently, this is endangered by the sea level rise and thus needs additional protection.

Besides this the retention measures are still valid options, because the base rain situation is severe enough to justify these measures. The prevention of settlement in vulnerable areas is also still of significant influence on the risk reduction.

A significant finding is the lack of real importance of the eastern coastal defence section. This is probably because the eastern stretch of coast is already quite well protected by naturally occurring dunes, see Figure 4-1.

Risk reduction under economic development and population growth

The situation under economic development and population growth, see Figure 4-6c, is as can be expected, less clear-cut than under rainfall intensity increase and sea level rise. The eastern retention measure becomes a less important influence on the risk reduction, and most other measures become slightly more important. The western coastal defence section and the prevention of settlement have the most significant increase in their importance for risk reduction. That the prevention of settlement becomes more important is not surprising, because the vulnerable low-lying areas that it targets are otherwise expected to have significant growth in human settlement.

Reduction in affected people

For the reduction factor of the number of affected people, Figure 4-7, the two evacuation measures are the most important. These measures are essential under all the different external factors. Under an increasing sea level, Figure 4-7b, the western coastal defence structure becomes a significant factor as well. This again indicates that flooding from the sea has a stronger impact on affected people. Based on the results of this feature scoring analysis, it thus appears that improving the evacuation measures will produce good results under any scenario.

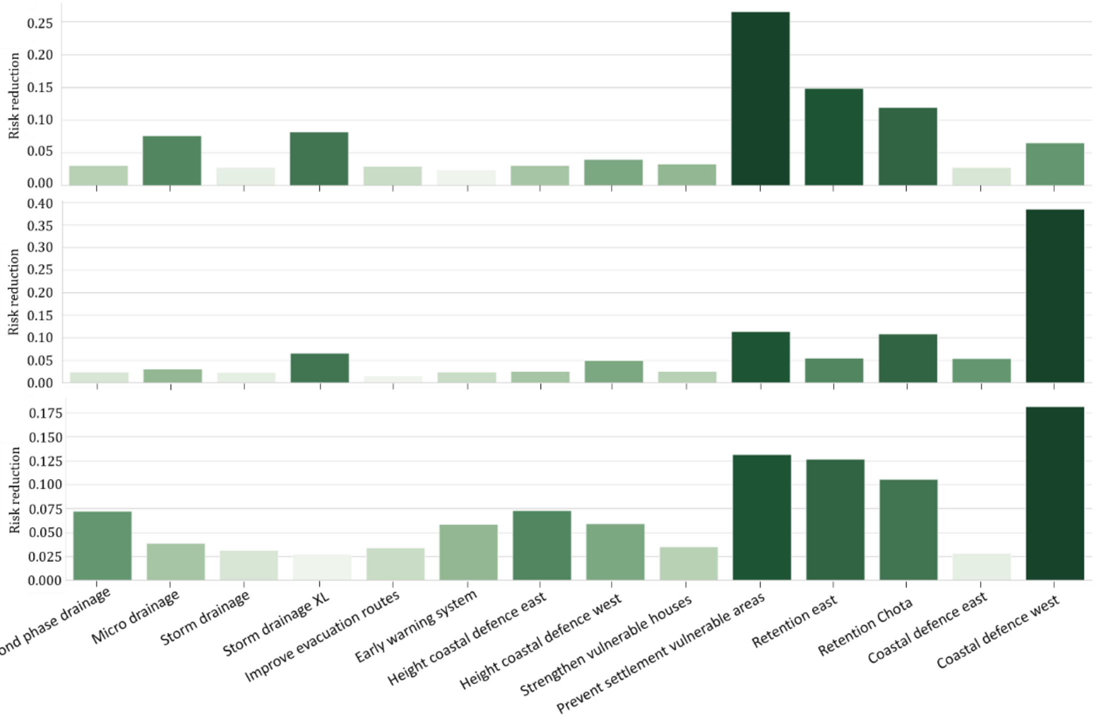


Figure 4-6: Feature scoring results for risk reduction, top (a): Rainfall intensity increase, middle (b): Sea level rise, bottom (c): Development.

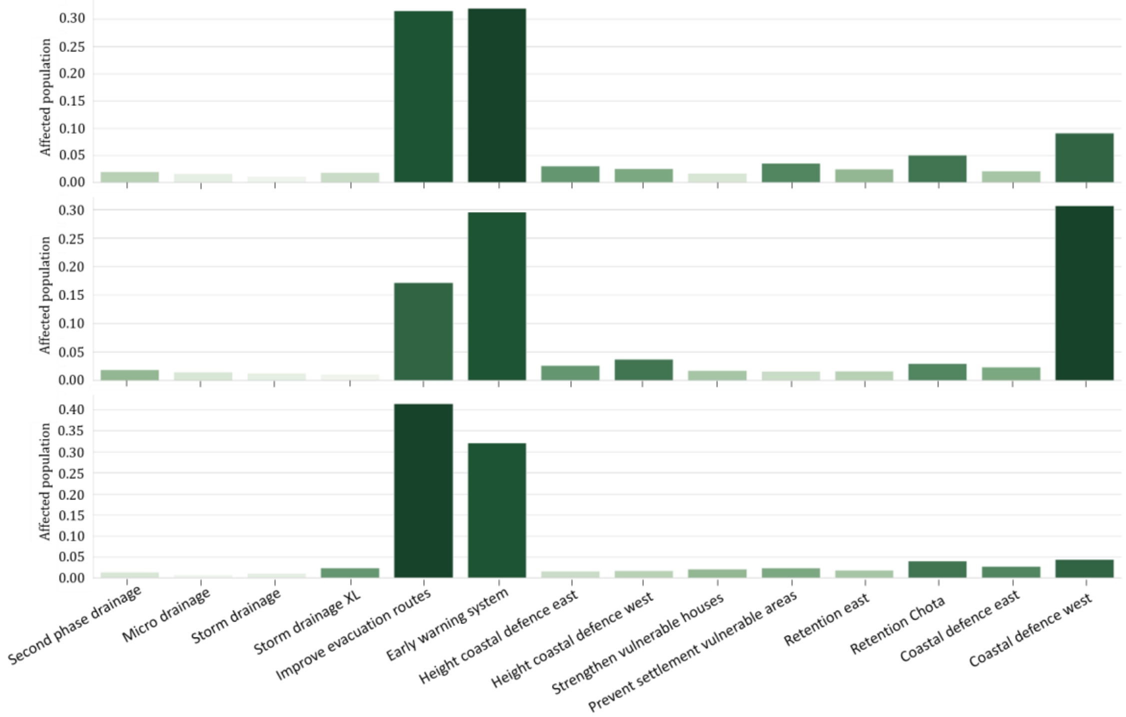


Figure 4-7: Feature scoring results for reduction in affected population, top (a): Rainfall intensity increase, middle (b): Sea level rise, bottom (c): Development.

4.4.2. PRIM ANALYSIS

A PRIM analysis was performed, see Appendix C, to find the most important measures for reaching a certain threshold performance with a risk reduction, affected people reduction and construction costs. The results of this PRIM analysis are shown in Table 4-5, these point us in the right direction in terms of desirable measures for section 4.4.3.

Table 4-5: Results of the different PRIM analyses.

CONDITIONS	PREFERENCE	SELECTED MEASURE
CURRENT SITUATION	1	Chota retention
	2	Western coastal defence measure
	3	Do not heighten western dunes
	4	East retention
	5	Prevent settlement vulnerable areas
	6	Early warning system
	7	Improve evacuation routes
INCREASING RAINFALL INTENSITY	1	Chota retention
	2	Prevent settlement vulnerable areas
	3	Strengthening houses
	4	East retention
SEA LEVEL RISE	1	Chota retention
	2	East retention
	3	Western coastal defence measure
	4	Sand suppletion east
DEVELOPMENT	1	Western coastal defence measure
	2	Second phase drainage
	3	East retention

4.4.3. EFFECTIVENESS REGIONS

As stated in section 4.2, the main focus in this case study is to reach an economic optimum. To be able to analyse which runs perform well and which measures are responsible for promising results, the number of runs to be analysed is reduced by selecting the best performing ones first. Thus, the nine solutions with the lowest total costs are selected. The lowest costs are checked over all points of the model runs. Selecting the best option at multiple points gives the best solution at any level of increase of the external factors. This ensures that at all points the lowest total costs options are selected. After optimising for the lowest total costs, the affected population is optimised for.

The total cost is the yearly total cost, which is the addition of the yearly expected damage (the risk from FLORES) and the yearly costs of a measure. Since no maintenance costs are implemented in the model, the yearly costs of a measure are the costs of implementing it divided by an expected lifetime. In this case study the lifetime is estimated to be 40 years for the flood risk reduction measures.

The nine most cost-effective options are compared on the basis of their total costs, remaining risk, affected population and construction costs. Through this analysis combined with the results from the FS and PRIM analysis the individual measures are selected which are effective in the selected options.

Current situation

Figure 4-8 shows that in the current situation, doing nothing is economically less attractive than implementing certain measures. The nine most cost-effective options are shown in Table 4-7 and are compared with their scores in Figure C-9. Table 4-6, shows the measures that have been selected for the effectiveness regions in the current situation.

Table 4-6: Measures for the effectiveness regions in the current situation. Yes or none, means that the measure is in the transition between effective and ineffective.

TYPE	SELECTION
SECOND PHASE DRAINAGE	Yes or none
MICRO DRAINAGE	Yes or none
SURFACE WATER DRAINAGE	None
SURFACE WATER DRAINAGE XL	None
IMPROVE EVACUATION	Yes
EARLY WARNING	Yes
STRENGTHENING HOUSES	None
PREVENTING SETTLEMENT	Yes
RETENTION EAST	XL to none
RETENTION CHOTA	Normal to large
COAST EAST	None
COAST WEST	None or heighten dunes
HEIGHT COAST MEASURE EAST	-
HEIGHT COAST MEASURE WEST	9m when applicable

Effectiveness regions

Figure 4-9 to Figure 4-12 show the effectiveness regions over the different model runs. These results are based on appendix C. When measures occur often in the nine most cost-effective solutions, with a preference for the best performing options (in terms of total costs and affected population), these are selected for the effectiveness regions. The regions show under what conditions which measures are possible candidates for the actions that will form parts of the pathways, the caption of Figure 4-9 gives a further explanation of the figure.

Table 4-7: Nine most cost-effective options in the current situation.

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast measure east	Height coast measure west	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
CS1	None	None	None	None	Yes	Yes	-	11.5	Yes	Yes	East XL	Chota large	None	Heighten dunes
CS2	Yes	None	None	None	None	None	-	-	None	Yes	None	Chota	None	None
CS3	None	None	Yes	None	Yes	Yes	-	10.7	None	Yes	East large	Chota large	None	Floodwall
CS4	None	Yes	Yes	None	Yes	None	-	11.3	Yes	Yes	East large	Chota large	None	Floodwall
CS5	None	None	None	None	None	None	-	9.0	None	Yes	East XL	Chota large	None	Heighten dunes
CS6	None	Yes	Yes	None	Yes	None	-	-	None	None	East XL	Chota XL	None	None
CS7	None	None	None	None	None	None	9.8	-	None	None	East	Chota	Sand suppletion	None
CS8	Yes	Yes	None	None	Yes	Yes	11.0	-	Yes	Yes	East large	None	Sand suppletion	None
CS9	Yes	None	None	None	None	None	-	9.2	None	Yes	East large	Chota XL	None	Floodwall

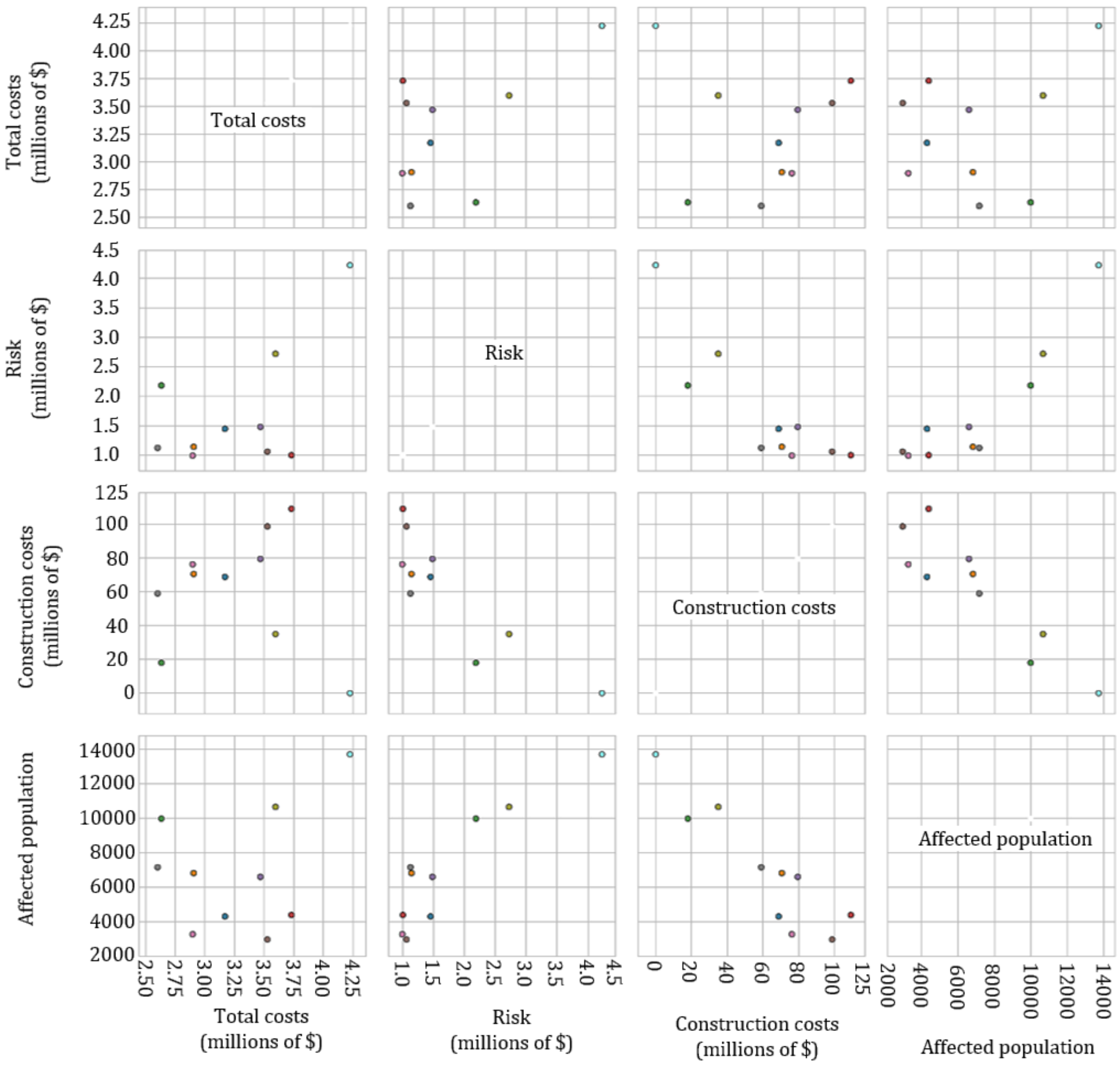


Figure 4-8: Nine most cost-effective options and do-nothing option (cyan) in the current situation. It shows that the selected options are all more cost-effective, have lower risk and lower affected population than the do-nothing option.

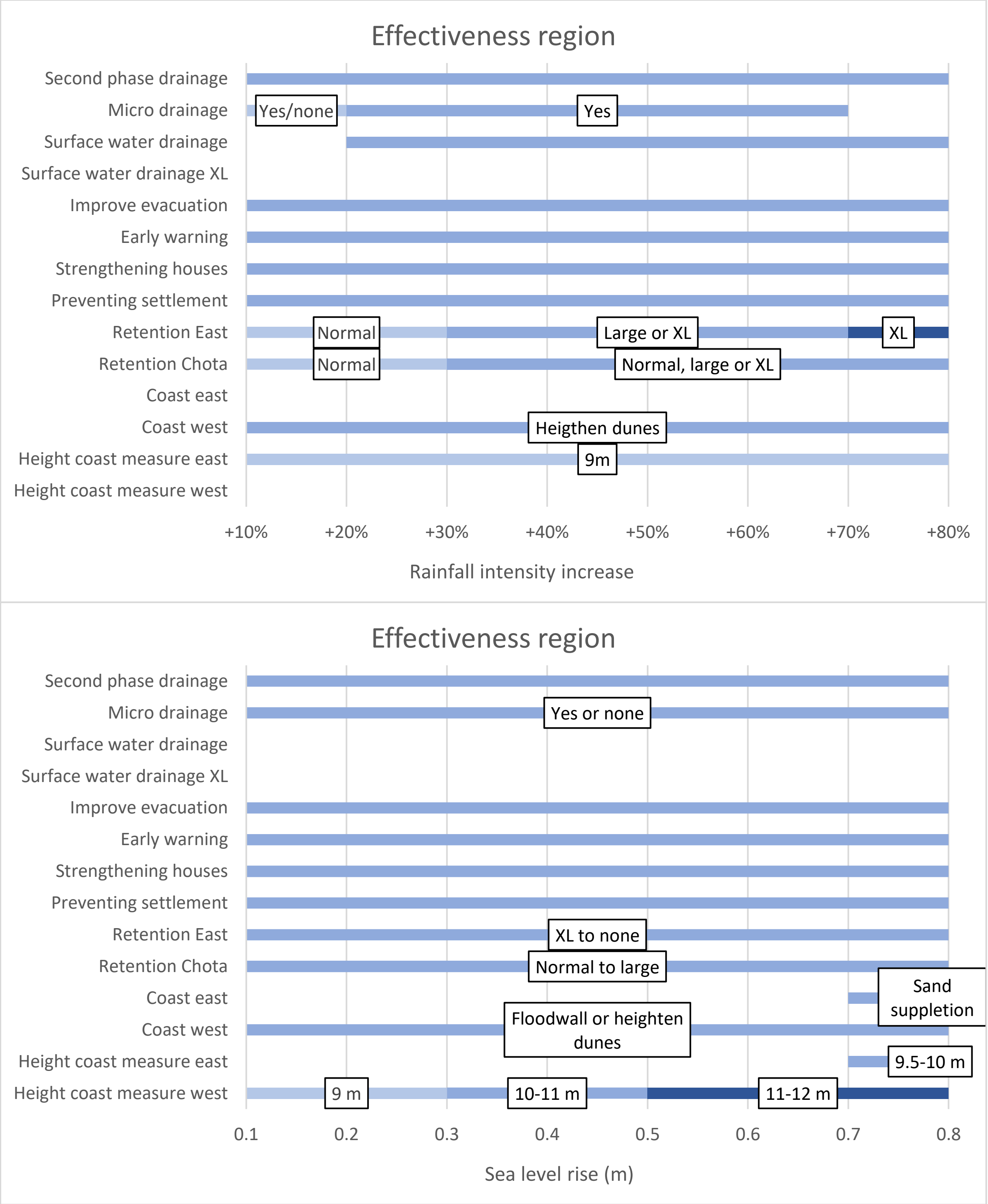


Figure 4-9: 1D effectiveness region, top: Rainfall intensity increase, bottom: Sea level rise (2018 base values). The rainfall intensity increase picture is used a frame of reference to explain the figure: The relevant information to take away from the figure is under what condition which measure is an option to be part of the actions for the pathways. Three of the flood risk reduction measures are used to explain: The second phase drainage is cost-effective in the current situation and will remain this for all increases of rainfall intensity, it will not be sufficient to reach policy goals on its own but it can make a valuable contribution. The surface water drainage system only becomes cost-effective from a +20% rainfall intensity increase. The XL drainage system does not become cost-effective for rainfall intensity increase alone, in other figures (Figure 4-10 for example) it does become cost-effective. Yes or none, means that the measure is in the transition between effective and ineffective.

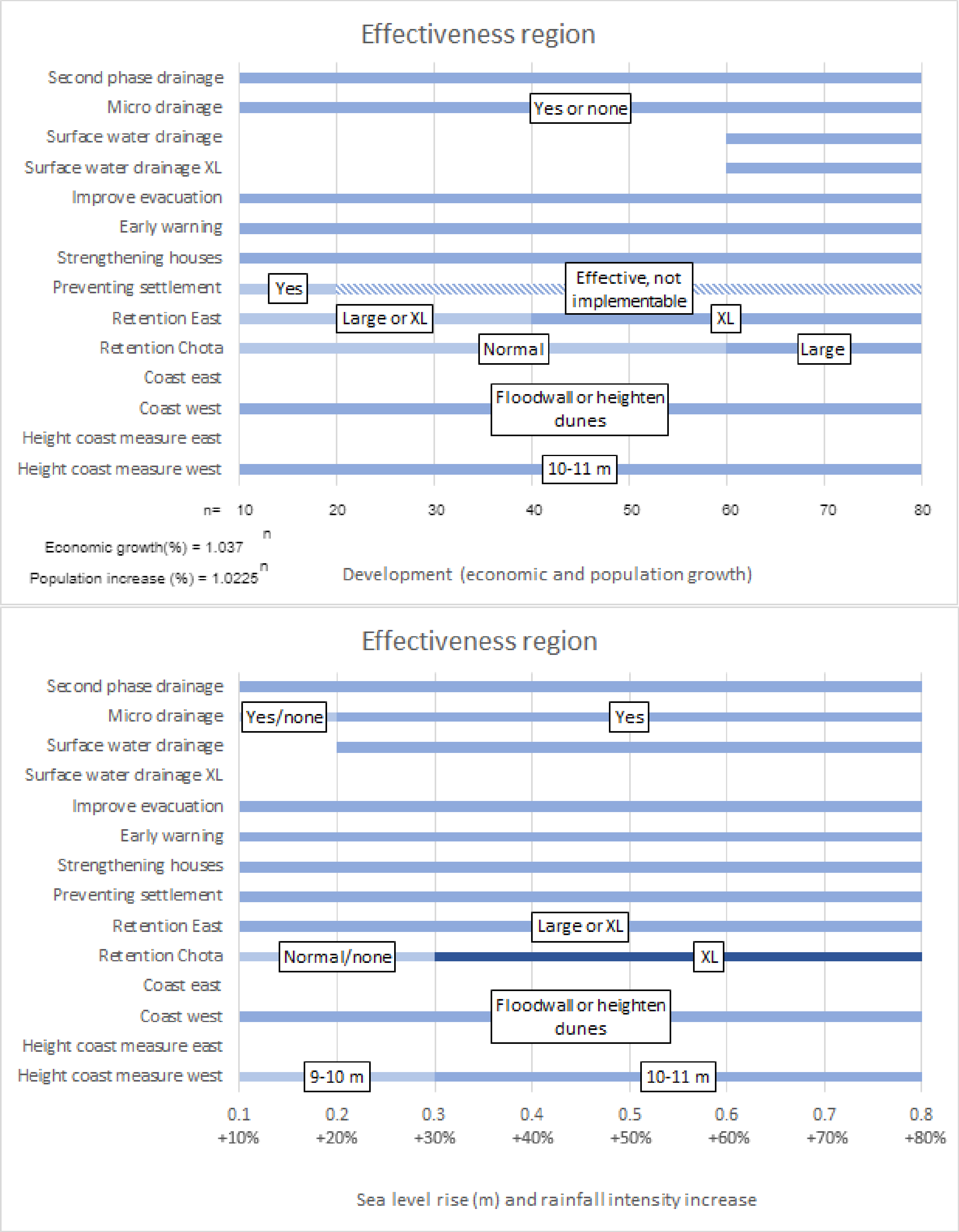


Figure 4-10: 1D effectiveness region, top: Development, bottom: Sea level rise and rainfall intensity increase (2018 base values).

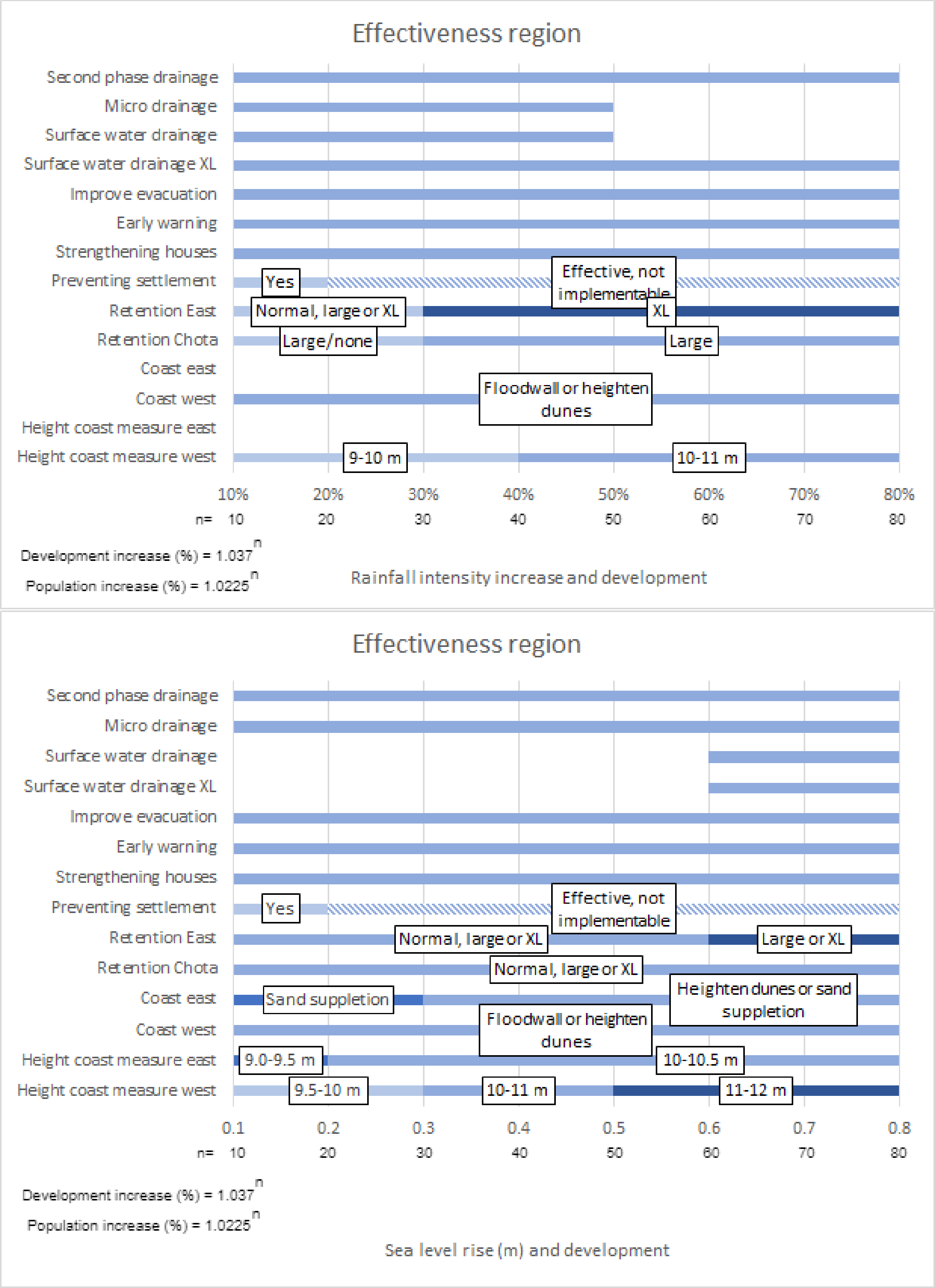


Figure 4-11: 1D effectiveness region, top: Rainfall intensity increase and development, bottom: Sea level rise and development (2018 base values).

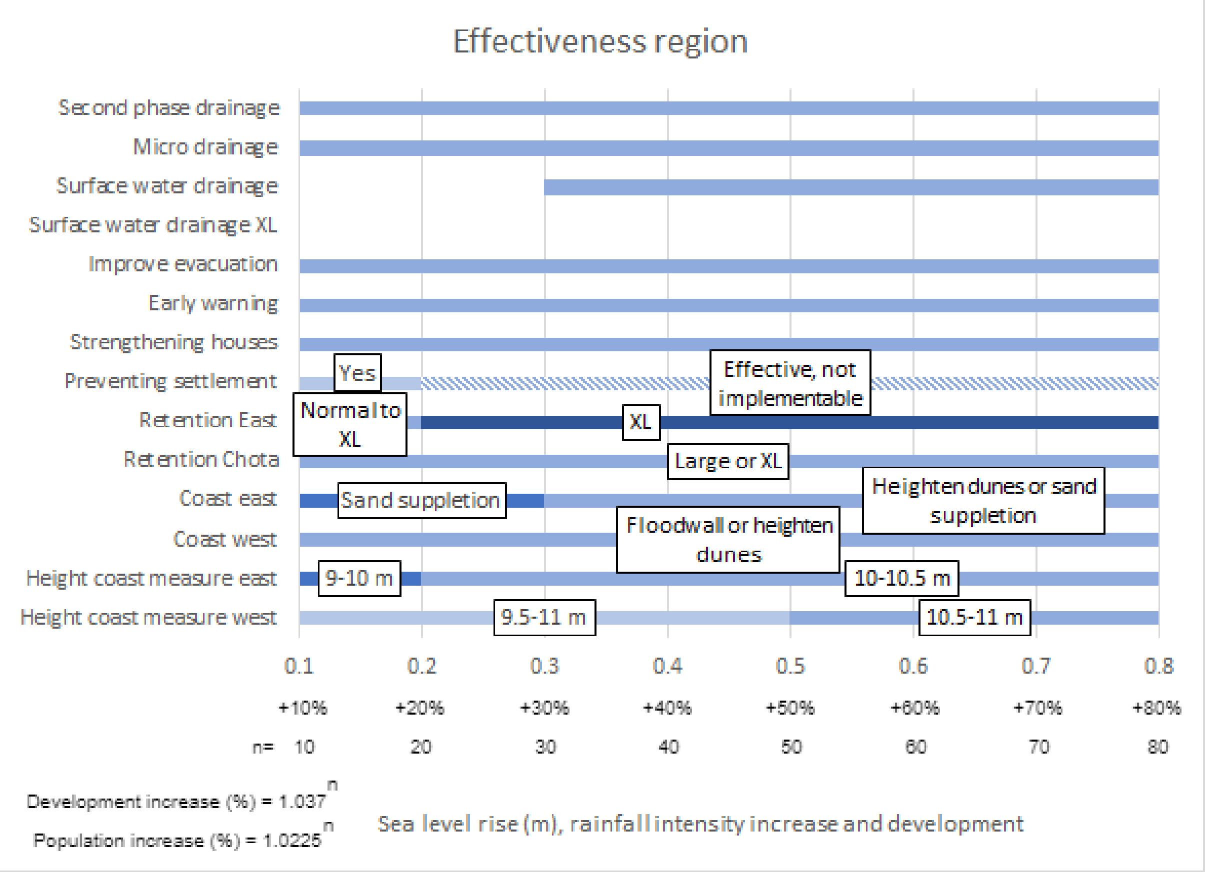


Figure 4-12: 1D effectiveness region for sea level rise, rainfall intensity increase and development (2018 base values).

4.5. Creating flood risk adaptation pathways

In this section pathways will be created based on the results of the analyses in section 4.4 and the results from the model runs which are given in appendix C.

4.5.1. SELECTED ACTIONS

In this section the most promising options are selected in order to create pathways with them in the next section. Options are primarily selected on their cost-effectiveness and secondarily on construction costs, risk reduction and on the reduction of the number of affected people.

Current situation

Two combination of solutions performed especially strong and are selected as possible starting points.

Low cost, cost-effective option

Option CS2 is low cost and cost-effective. The resulting risk is still relatively high compared to other options, but because of the limited investment costs it is a viable option. The reduction in affected population is poor however, but this option will be altered by including both emergency measures to address this.

Medium cost, cost-effective option with high risk reduction

Option CS5 is more expensive than option CS2 but has a higher risk reduction. It has comparable cost-effectiveness to option CS2. This option has a medium reduction in affected people, it will also be altered to include both emergency measures.

Table 4-8: Options for current situation (height in metres).

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast	Height coast	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
CS2	Yes	None	None	None	None	None	-	-	None	Yes	None	Chota	None	None
CS5	None	None	None	None	None	None	-	9.0	None	Yes	East XL	Chota large	None	Heighten dunes

Run 1: Rainfall intensity increase

Figure D-1, shows that the option 'Do nothing' has higher total costs under all levels of rainfall intensity. This thus means that solutions should be implemented, because doing nothing is economically less attractive than implementing the selected solutions. The nine options that were selected based on the total costs are shown in Figure D-1. From these, five solutions were selected to use as actions for the pathways shown in Table 4-9.

Early lowest cost option

Option R1 is the cheapest option to implement, it has reasonable risk reduction and reduction in the number of affected people. It is not the most advantageous solution economically and all of the other selected nine options score better in risk reduction.

Early economically most advantageous option

Option R8, has the lowest total costs until 30% rainfall intensity increase. Its risk reduction is average compared with the other selected options. The reduction in the number of affected people is comparatively high.

Mid-increase economically advantageous options

Option R2 is one of the most economically advantageous options, in the range from 30% RI increase to 70% increase. It has a good reduction in the number of affected people and lies in the medium cost range.

Mid-high increase economically most advantageous option

Option R5 scores well in terms of total costs over the whole range of RI, but especially on the mid to late range of RI. In terms of affected population it scores poorly, thus this option should be altered slightly to achieve more optimal results on this aspect.

Highest risk and affected population reduction option

Option R4, has the highest risk reduction and reduction in the affected population of the selected options. It is however also the most expensive of these options. It is one of the more economically advantageous options from +30% RI onwards.

Table 4-9: Selected options under rainfall intensity increase (height in metres).

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast	Height coast measure west	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
R1	Yes	None	None	None	Yes	Yes	-	-	Yes	None	East	None	None	None
R2	Yes	Yes	None	None	Yes	Yes	-	8.5	Yes	Yes	East large	Chota XL	None	Floodwall
R4	Yes	None	None	None	Yes	Yes	9.6	12.0	Yes	Yes	East XL	Chota	Sand suppletion	Floodwall
R5	None	None	Yes	None	None	Yes	-	-	None	Yes	East XL	Chota	None	None
R8	Yes	None	None	None	Yes	Yes	-	8.6	None	Yes	East	Chota	None	Heighten dunes

Run 2: Sea level rise

Figure D-2, shows the most cost-effective solutions under SLR and the do-nothing option. It shows that doing nothing is less cost-effective than taking measures to reduce flood risk. The selected options are shown in Table 4-10.

Low to mid-range SLR low cost option

Option S7 is a low-cost option with reasonable risk reduction. Under low to mid-range SLR, it is the most cost-effective option. In terms of affected population it also scores strongly compared to most other options.

Robust option

S1 (R2), has been selected here because it was also present under increasing rainfall. Under the SLR it is thus still one of the nine most cost-effective solutions, in comparison with the other nine it has medium cost-effectiveness, risk reduction and construction costs. In terms of the number of affected people it scores quite strongly.

Mid-range SLR option

Option S9 is the most cost-effective under a mid-range SLR. It has medium construction costs and risk reduction compared to the other SLR options. The reduction in affected people is poor, but adding emergency measures would resolve this problem, thus it is selected as a possible option.

High SLR or high-risk reduction option

Option S6 (R4) is the most cost-effective option at high SLR. It has the highest risk reduction and reduction in the number of affected people of all the options under all amounts of SLR. A further benefit is that it also scores as the most cost-effective high rainfall increase option. It is however, one of the more expensive options of the nine most cost-effective options under SLR.

No prevention of settlement option

Option S8 is the most cost-effective solution without preventing settlement. If a solution is preferred without that measure it is thus possible, but it will be less effective. The option also has poor reduction in the number of affected people, but this is also because of the lack of emergency measures. These could still be added in the event that this option would be used.

Table 4-10: Selected options under sea level rise (height in metres).

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast	Height coast measure west	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
S1	Yes	Yes	None	None	Yes	Yes	-	8.5	Yes	Yes	East large	Chota XL	None	Floodwall
S6	Yes	None	None	None	Yes	Yes	9.6	12	Yes	Yes	East XL	Chota	Sand suppletion	Floodwall
S7	Yes	None	None	None	Yes	Yes	-	8.6	None	Yes	East	Chota	None	Heighten dunes
S8	None	Yes	None	None	None	None	9.8	11.4	None	None	East large	Chota XL	Sand suppletion	Floodwall
S9	Yes	Yes	None	None	None	None	-	10.9	Yes	Yes	East	Chota large	None	Floodwall

Run 3: Development

Figure D-3 shows the results of run 3, this run only has an increase in development. This situation is linked to the current situation, as the hydraulic boundary conditions do not change in this run, only the damage resulting from it. This results in options with mixed flood coastal and rainfall flood risk measures, which become increasingly expensive as more effective measures are needed to reduce the flood risk because of the increased vulnerability of the area. The selected options are shown in Table 4-11.

Low cost, cost-effective low-medium development option

D9, is a low-cost option which is cost-effective for low to medium development. It does have one of the lowest risk reductions of the nine options, but it does have the best reduction in affected people. It lacks the prevention of settlement, which would prevent that measure to be used at a later date when the development has increased.

High development cost-effective option

Option D1 is the most cost-effective option in a situation with high development. It is the most expensive option to construct but has good risk reduction. It has a reasonable reduction in the number of affected people, which would increase to a good reduction if complemented with the improved evacuation option.

High development medium cost option

Option D8 is slightly less expensive than D1, but also has less risk reduction. It is less cost-effective than D1 but could be a good option if the money is not available to construct D1.

Table 4-11: Selected options under development (height in metres).

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast measure east	Height coast measure west	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
D1	Yes	None	None	Yes	None	Yes	-	10.6	Yes	Yes	East XL	Chota large	None	Heighten dunes
D8	None	None	Yes	None	Yes	Yes	11.0	10.9	Yes	Yes	East XL	None	Sand suppletion	Floodwall
D9	Yes	None	None	None	Yes	Yes	-	11.2	Yes	None	East XL	Chota	None	Heighten dunes

Run 4: Sea level rise and rainfall intensity increase

Figure D-4, shows the results of run 4, this run has SLR and RI increase. This run and run 7 have the heaviest boundary conditions imposed on the system. The options selected for the further use in the pathways are shown in Table 4-12.

Low cost, low increase option

SR3 is a low-cost early option, it is cost-effective only under the first step of this run. It therefore is not a full solution of the problem, but more a steppingstone to something more permanent.

Low cost, medium risk reduction option

SR5 is also a low-cost option, but almost twice as expensive as SR3. It does however have a much better risk reduction and is thus a solution that can stay in place for a longer time. It remains reasonably cost-effective until the higher increases in RI and SLR. The reduction in affected population is poor and would need to be complemented by the emergency measures in order to become more effective in that regard.

Medium cost, cost-effective option

SR8 is a cost-effective option under most of the situations in this run, especially under medium SLR and RI increase. It has high risk reduction, high reduction in affected population and medium construction costs.

High increase, high cost, high risk reduction option

Option SR4, is a cost-effective option under the higher increases of RI and SLR. It has one of the highest risk reductions, and it has a good reduction in the number of affected people but is also one of the most expensive options in this run.

Table 4-12: Selected options under sea level rise and rainfall intensity increase (height in metres).

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast	Height coast measure west	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
SR3	Yes	None	None	None	None	Yes	-	-	None	None	East XL	Chota	None	None
SR5	None	Yes	None	None	None	None	-	9.7	None	Yes	East large	None	None	Heighten dunes
SR8	Yes	None	None	None	None	Yes	-	11.9	Yes	Yes	East large	Chota XL	None	Floodwall
SR4	Yes	Yes	Yes	None	None	Yes	-	-	Yes	Yes	East XL	Chota XL	None	None

Run 5: Rainfall intensity increase and development

Figure D-5 shows the results of run 5, a combination of rainfall intensity increase and development. It is clear from the results that measures must be taken to come closer to the economically optimal situation.

Low cost low increase option

RD5 is, compared to the other cost-effective measures in this run, a low-cost option. It is cost-effective for the first stages of the external factors in this run. Its risk reduction and reduction in the number of affected people is average in comparison to the other options.

Cost-effective option 1

Option RD2 is a cost-effective option over most of the levels of increase in this run. Only early on RD5 performs better. It has a good risk reduction and medium reduction in affected people. With the addition of the early warning system this option will perform well on all of the performance measures.

Cost-effective option 2

RD7 is very similar to RD2 in terms of performance and selected measures. It is slightly less expensive, but also has less reduction in risk and affected population.

Table 4-13: Selected options under rainfall intensity increase and development (height in metres).

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast	Height coast measure west	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
RD5	Yes	Yes	Yes	None	Yes	None	-	9.8	None	Yes	East XL	None	None	Floodwall
RD2	Yes	None	None	Yes	None	Yes	-	10.6	Yes	Yes	East XL	Chota large	None	Heighten dunes
RD7	Yes	None	None	Yes	None	Yes	-	9.3	None	Yes	East XL	Chota large	None	Floodwall

Run 6: Sea level rise and development

Figure D-6, shows the results of a run with SLR and development.

The options that have been selected below, do not score very well in terms of affected population. But as already has been mentioned earlier, in such cases we add both emergency warning systems. It was determined in the FS that these are by far the most important for the reduction in affected people, so this is expected to yield good results.

Low increase low cost option 1

SD7 is slightly cheaper than SD9 and its measures have more focus on rainfall flooding than on coastal flooding. It is slightly more cost-effective in the lower ranges of SLR and development, but it will fit less well in a pathway which deals with more SLR.

Low increase low cost option 2

SD9 is the most cost-effective option after SD7 in the lower ranges of SLR and development. Its measures are more focused on coastal flooding, and thus would fit better in a pathway dealing with SLR.

High increase, most cost-effective option

SD6, is the most cost-effective option in the higher increases of SLR and development. It has the highest risk reduction of all the options and is the most expensive of the selected options.

High increase option

SD4 has a slightly lower cost-effectiveness as SD6 but is slightly cheaper to implement. It also has slightly worse risk reduction, which also leads to the conclusion that the coastal measures in this option are higher than necessary.

Table 4-14: Selected options under sea level rise and development (height in metres).

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast measure east	Height coast measure west	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
SD7	Yes	Yes	None	None	Yes	None	9.3	9.5	Yes	None	East XL	Chota XL	Sand suppletion	Floodwall
SD9	Yes	Yes	None	None	None	Yes	10.3	10.8	Yes	Yes	East	Chota XL	Sand suppletion	Heighten dunes
SD6	Yes	Yes	Yes	None	None	Yes	10.3	11.0	Yes	Yes	East XL	Chota large	Heighten dunes	Floodwall
SD4	Yes	None	None	Yes	None	None	11.0	11.8	Yes	Yes	East large	Chota	Sand suppletion	Floodwall

Run 7: Sea level rise, rainfall intensity increase and development

Figure D-7 shows the results of the run with SLR, increasing RI and development. This run has the most severe external factors of all runs, and is the most extreme case analysed. The same actions have been selected as in run 6.

This is probably because of the following factors: Development is a driving factor for the implementation of measures, as the vulnerability of the area increases enormously which leads to many implemented measures for high development regardless of the hydraulic boundary conditions. Furthermore, rainfall flooding is already a severe problem in the current situation and thus measures have to be taken to reduce it even if it does not increase further. Coastal flooding is much less severe in the current situation and only becomes a bigger issue as the SLR becomes higher.

Table 4-15: Selected options under sea level rise, rainfall intensity increase and development (height in metres).

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast measure east	Height coast measure west	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
SRD6	Yes	Yes	Yes	None	None	Yes	10.3	11.0	Yes	Yes	East XL	Chota large	Heighten dunes	Floodwall
SRD7	Yes	Yes	None	None	Yes	None	9.3	9.5	Yes	None	East XL	Chota XL	Sand suppletion	Floodwall
SRD9	Yes	Yes	None	None	None	Yes	10.3	10.8	Yes	Yes	East	Chota XL	Sand suppletion	Heighten dunes

4.5.2. FLOOD RISK ADAPTATION PATHWAYS

The selected options from the previous section have been reworked into actions in this section, the results are shown at the top of Figure 4-13. Attention has been paid to creating logical sequences between the actions and thus reworking them in order to get this. Furthermore, emergency measures have been implemented in all actions because the reduction in affected people is large compared to the costs involved of implementing these measures. Preventing settlement has also been added to all actions, this is because all actions without these measures implemented are less cost-effective than the ones with this measure. Because this measure should be taken early on in order to be implementable, this measure is implemented right away.

The pathways are shown in Figure 4-13, it shows the pathways over the external uncertainties. Thirteen actions form a set of pathways through different external conditions. The origin of the graph is the current situation, in which action 1 should be implemented. Then depending on which external factors increase other actions should be implemented. For example if the development increases action 7 should be implemented and if it increases even further action 8. And a second example, if at first development increases (to n=50) such that action 7 is implemented and then the rainfall intensity increases with +30% action 9 is implemented. In this way the picture shows what measures are required when conditions change.

More pathways are certainly possible and many more combinations can be made on the basis of policymaker and stakeholder preferences. Different pathways based on different trade-offs between total costs, risk reduction, affected people and construction costs were not made, because overall it was possible to optimise on all aspects. The decision to select both emergency measures in all pathways is one example. The costs are not great enough to justify not implementing them, thus a pathway/action without them would be less valuable. The creation of pathways with different trade-offs would however, still be possible, but the result would become quite complicated because the number of different actions would rapidly increase. For the purpose of this case study, this is not required.

Legend	Second phase drainage	Micro drainage	Surface water drainage	Surface water drainage XL	Improve evacuation	Early warning	Height coast measure east	Height coast measure west	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
A1	Yes	None	None	None	Yes	Yes	-	-	None	Yes	None	Chota	None	None
A2	Yes	None	None	None	Yes	Yes	-	8.5	None	Yes	East	Chota	None	Heighten dunes
A3	Yes	None	None	None	Yes	Yes	-	8.5	Yes	Yes	East XL	Chota	None	Heighten dunes
A4	Yes	None	None	None	Yes	Yes	-	11	Yes	Yes	East	Chota	None	Heighten dunes
A5	Yes	None	None	None	Yes	Yes	9.5	11	Yes	Yes	East XL	Chota	Sand supplection	Heighten dunes
A6	Yes	None	None	None	Yes	Yes	-	11	Yes	Yes	East XL	Chota large	None	Floodwall/ Heighten dunes
A7	Yes	None	None	None	Yes	Yes	-	10.5	Yes	Yes	East XL	Chota	None	Heighten dunes
A8	Yes	None	None	Yes	Yes	Yes	-	10.5	Yes	Yes	East XL	Chota large	None	Heighten dunes
A9	Yes	Yes	None	None	Yes	Yes	-	10.5	Yes	Yes	East XL	Chota large	None	Heighten dunes
A10	Yes	Yes	None	Yes	Yes	Yes	-	10.5	Yes	Yes	East XL	Chota large	None	Heighten dunes
A11	Yes	Yes	None	None	Yes	Yes	9.5	10.5	Yes	Yes	East XL	Chota large	Sand supplection	Heighten dunes
A12	Yes	Yes	Yes	None	Yes	Yes	10.5	11	Yes	Yes	East XL	Chota large	Heighten dunes	Heighten dunes

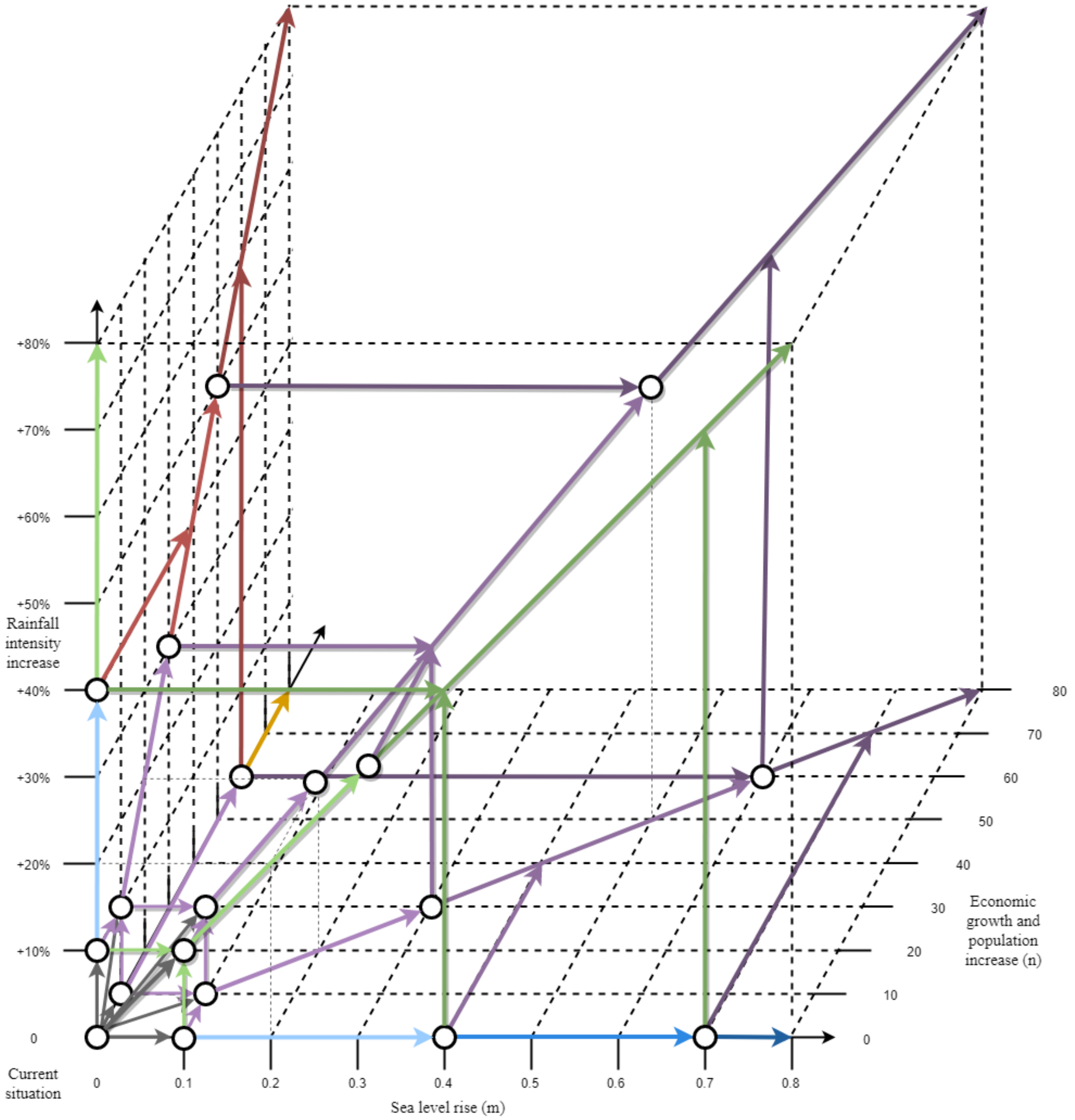


Figure 4-13: Resulting pathways, they show what action should be taken under which combination of external factors. The origin of the graph is the current situation, from which point on the external factors can increase. This increase is uncertain and it is thus unknown at what point in the graph the situation will end up. The pathways show what happens under the different possible futures. There are more possible combinations of external factors in between the pathways, in between the pathways there are connection pathway arrows to show the transition between pathways. Action description is given in legend above, with height in meters.

4.6. Creation monitoring plan (initial analysis only)

In this section the monitoring plan is treated. The signposts are defined and how these can be monitored is explained. Some requirements for the trigger values are given, but these are not treated in detail as this would require a whole new analysis on possible rates of increase. Furthermore, when new actions are taken slightly too late it is not a significant problem in the current case study, because it only means that the situation deviates from the optimum situation. While contingency actions are shortly mentioned and examples are given, it is not done in more detail as creating contingency actions would require an additional analysis with more information on the local situation. Five signposts have been determined in order to be able to monitor the situation.

The first signpost detects sea level rise. Measuring equipment can be used to measure the sea level at a location of the coast of Beira. The tides can then be subtracted from the data, after which an average sea level can be detected. After which a database of yearly average sea level can be made to detect sea level rise. Certain levels of sea level rise can then be set as trigger values to start an intervention. A trigger value can then be set early enough to incorporate lead time required for the construction of the measures and incorporate extra lead time to allow time for late detection, since the extend of sea level rise will only be known after it has happened. Measuring the sea level would also provide local information on storm events, instead of the currently used regional data, and thus improve the available data for calculating flood risks.

The second and third signposts detect the change in rainfall intensity. Per rainfall event, the amount of rainfall in mm can be measured along with the duration of the event. This is already done currently, with two precipitation measurement stations in Beira. This can then be used to measure the rainfall intensity of the event. After which the rainfall intensity can be averaged over the rainy season. This allows the creation of a database with yearly averages and extreme values to detect the rainfall intensity increase trend and the increase of intensity and frequency of the extremes. Certain levels of rainfall intensity increase can then be set as trigger values, with the same lead time considerations as for the sea level rise.

Most cities keep track of their population growth and economic growth. In Beira, the number of inhabitants is counted every decade, which is a sufficient frequency, however, it was not reliable enough to be used for this study. Economic data from local sources was not available to this study. Lacking local alternatives World Bank and African Development Bank documents were used for the number of inhabitants and economic value, and their growth. When the number of inhabitants and economic value are being kept track of locally, these can be used as the fourth and fifth signposts to detect when interventions are required. During testing of the measures and actions, population growth and economic growth were coupled, but in reality these will not be coupled. Triggers can be defined for both population growth and economic growth separately, based on the preferences of the decision maker and the lead time requirements.

An example of a necessary contingency action would be an action to keep the areas required for retention available for implementation. This means keeping these areas clear of activities that would block the construction of retention areas, most notably this will mean battling irregular settlement. Examples of a possible action would be the creation of a park, or the construction of easily replaced structures such as a parking lot.

4.7. Reflection on the flood risk adaptation pathways approach

This section reviews the benefits and limitations that arose from applying the newly developed approach to the case study.

Benefits

The flood risk adaptation pathways image, while initially difficult to interpret, becomes a clear visual way of representing the needs in terms of flood risk reduction measures over different futures. When policymakers see the pathways picture, it provides them with the scope of the challenge presented by future conditions and what actions, combinations of measures, are important. This was observed in a short workshop at the 2019 Africa Works conference in Rotterdam, where the flood risk adaptation pathways were presented to policymakers. After an initial challenging explanation, the audience mentioned that the FLORAP image clearly showed them what requirements, in terms of measures, different futures posed. This would need further interaction with policymakers to investigate more thoroughly, as this is only one experience, for this purpose it would be useful to organise new workshops to discuss the results with more policymakers (and possibly other stakeholders).

The flood risk adaptation pathways image shows that under possible future conditions certain measures can be indispensable, thus locating possible lock-ins and other path dependency problems. In this case study it was found that the prevention of informal settlement was required in areas which are vulnerable to flooding, for having more optimal pathways for the higher increases in rainfall intensity, sea level rise, economic growth and population growth. Prevention of settlement was only deemed possible under low levels of population growth, because at higher levels these areas would have already been occupied by new inhabitants. We have thus identified an important lock-in in this case study, because when the area is filled with inhabitants the policymakers have no other choice than to implement far more expensive actions consisting of expensive drainage and coastal defence measures.

In the case study we could create a stepwise integration of the actions. Optimising the pathways for flexibility resulted in a plan that mostly consisted of non-hard structures. For example, floodwalls were disfavoured because it would be more difficult to adjust their height as requirements changed. For the coastal protection sand-based solutions were used, which follow a stepwise increase in height from the early actions to the later actions. This flexibility reduces costs when new actions have to be implemented.

Furthermore, this sequence of actions, means that more expensive options can be taken later while the early actions consist of less expensive solutions. This is especially useful in this case study, as the city of Beira has very limited financial means. As the economic growth of the city continues, the city will have more financial capacity at a later point in time to construct the more expensive measures, in an earlier stage it is made sure the flood risks are kept at an acceptable level through the use of lower cost options. In the created flood risk adaptation pathways plan, the early actions consist of low-cost measures while the later actions consist of much more expensive actions.

Limitations

The used exploratory modelling approach had some drawbacks in the case study: Analysing the case study was time consuming and complex because of the many different situations to analyse. This is further increased when, as intended, multiple pathways are created with different optimisation preferences. The problem could be resolved by using a direct search model. This has some other drawbacks however, with most notably an increased computation time and the risk of creating a black box. Creating a black box, would mean that the selection process of the measures, and the way the trade-offs are made, is no longer transparent. This makes it more difficult to involve stakeholders into the process, as making transparent choices and co-operating with stakeholders is important to involve them, which will create resistance to the process (De Bruijn & Ten Heuvelhof, 2008; De Bruijn et al., 2010).

Section 3.3 already mentioned that the approach might become computationally expensive when employed to a case study. While performing the case study this was indeed a problem. Fewer, than optimal, possible futures and fewer strategies per future were investigated in order to reduce the computation time. As more complex cases are investigated this will become even more problematic. If a full factorial subspace division would have been used, with a more optimal number of strategies (~100), the number of model runs would have been 1,230,000. One FLORES model run approximately takes 1 minute on one computer core (although it is expected this will be reduced as the model is further developed), this would mean one core would have to run for 853 hours. As more cores are available, for example through high performance computing setups, more will obviously be possible.

Section 3.3 also noted that it would be difficult to determine trigger values which would incorporate enough lead time in order for measures to be constructed in time. For cases like the used case study however, it is not very problematic, because of the used policy goal. If measures are completed a few years too late in the case study, it only means that for a few years the economic optimum was not achieved. There is no major shift in risk if measures are finished too late because the adaptation tipping points are primarily based on economic optimal performance, not on safety requirements. This limitation is the result of removing the time estimate from the scenarios.

Lastly, it can be quite difficult to interpret the pathways image, which is the main result of the approach. Policymakers need to be able to interpret the pathways, for this the pathways need to be clearly explained first. This is closely linked to the first benefit described at the beginning of this section, which mentioned that if they are understood they can be very helpful for policymakers. It was mentioned there already that a workshop could be organised, which is also able to help in this respect, as it can provide valuable experience on how policymakers interpret the image and how it can be best explained to them.

5. DISCUSSION

This chapter discusses factors possibly having an influence on the result of the study. Overall these factors have been deemed as acceptable, but they should be taken into account when considering the results of the study.

The uncertainty sampling was changed to reduce the required computation time. A full factorial subspace division would have been preferred, but it would have created computation times that were too large in the context of this study. The researcher of this research beliefs that it was possible to test the new approach in this simplified way, but in a real case a full factorial subspace division should be used to increase the amount of combinations that the measures are tested on.

In the case study, a simplified optimisation problem was used. The primary goal was to create an economic optimum, dealing with flood risk and construction costs, after which the goal was to reduce the affected population and to ensure flexibility of the plan. One of the goals of DAPP is to create multiple pathways with different objectives to create a plan that satisfies the needs of policymakers and stakeholders. This is also part of the newly created approach, but because of the extensive analysis which was already required for one optimisation objective it was decided to simplify it for the case study. This was deemed acceptable, because the current case study is a proof of concept and not an advice to policymakers. Creating the additional pathways should not result in any problems not already encountered in the case study, it will only take more time to perform and it will be more computationally expensive.

The cost aspect in the case study was treated in a simplified manner. Maintenance costs have not been treated and extra costs from phasing the implementation of measures have not been accounted for. Lastly, a 40-year lifetime was estimated for the flood risk reduction measures. This was done because there is no estimate of the duration that an action will be used, before another has to be used. A longer lifetime would favour more expensive actions while a shorter one would favour less expensive ones, because the yearly costs were estimated by dividing the construction costs by the lifetime. Again, the simplification of the case study is justified by it being a proof of concept. In a real advice situation, a more exhaustive cost estimation can be performed.

In the case study economic growth was combined with population growth into one external factor called development. This was done in order to prevent the creation of a situation with four main external factors. Four separate main external factors would have required more model runs and would have complicated the creation of the effectiveness regions and the pathways. It is a drawback of the approach that it becomes complicated when there are situations where many external factors are important.

Only 50 strategies were tested per run. This is not enough to test all different possible strategies, but because of this the results were treated with the necessary caution and options were adapted where necessary. Furthermore, because no dedicated computer was available the model runs separated in sets of two (except for one, because there were 7 runs). This means that in those combinations of runs the same strategies were analysed, and in the others slightly different strategies. The result of these drawbacks is a suboptimal analysis, because not all combinations of measures have been tested. This was known beforehand and was deemed not to be a problem for testing the approach.

Currently, the FLORES model has only been partially validated for the Beira case due to limited availability of data and the model is still under development (van Berchum et al., 2019). This can have an influence on which measures were selected in the case study, this is however not of importance for the conclusions on the approach itself.

6. CONCLUSION

This study created a new approach for dealing with long term deep uncertainty in flood risk management; Flood Risk Adaptation Pathways (FLORAP). The approach aims to strengthen the flood risk management (FRM) approach to dealing with long-term deep uncertainty, by combining it with robust decision making approaches. This section concludes on the research questions that guided this study.

Firstly, a literature study was performed on the FRM approach to clearly document its limitations. In the FRM approach, scenario creation and analysis is the main way of dealing with long-term (deep) uncertainty. These scenarios can be qualitative storylines describing possible future worlds, which influences the external factors of importance in a certain way. The scenarios can also be quantitative, in which case numerical estimates are made for the future situation. These are often based on regression techniques and datasets on the factors with measurement data over many years. The problem with qualitative scenario use is that these scenarios are subjective and often very limited in number. Under deep uncertainty, the solutions can never be fully tested by such a limited set of scenarios and this leaves open a lot of uncertainty for the possible conditions under which the solutions were not tested. Quantitative scenarios are based on regression techniques and rely on the availability of accurate and long datasets. If long-term datasets are not available, it is often not possible to perform such regression techniques. Furthermore, regression techniques cannot take changes in a trend into account, which means there is a risk of under- or overestimating values.

With the limitations identified, the literature study then moved on to robust decision making approaches to find suitable additions for the FRM approach. Robust decision making approaches use robustness and flexibility as part of their optimisation goal to ensure that the set of actions functions satisfactorily over a large range of possible scenarios. This way, the importance of not knowing the future is decreased, as the solution is expected to function regardless. Robustness ensures that the selected measures have adequate performance over the range of possible futures they have been subjected to. Flexibility is built into a solution, allowing changes to be made as it becomes necessary because of changing conditions. Robust decision making approaches often use a large ensemble or continuous space of possible future situations. The possible scenarios are not given a probability and are all seen as equally likely in the analysis. If the range of possible futures that is analysed is sufficiently large, this ensures that the solutions are robust and or flexible under (almost) all possible futures, which should thus mean the policy objectives are reached under (almost) all possible scenarios.

Robust decision making approaches can thus be useful for FRM to reduce the negative effects of different than designed for conditions. This can be done with the incorporation of the robustness and flexibility performance measures and by designing over a larger ensemble of possible scenarios. Based on the literature study, it is thought, that the explicit incorporation of many different possible futures and their structured analysis can strengthen the FRM approach in the conceptual design phase.

Based on the results of the literature study, this study created the flood risk adaptation pathways approach, the results of which consists of three main parts; the effectiveness regions, the pathways and a monitoring plan. In order to use the approach, the FLORES model was adapted to be able to test actions over increasing external factors. The effectiveness regions are the result of testing the individual flood risk reduction measures. The effectiveness regions depict under what combination of external factors which solution is an effective option. They provide an overview of what solutions can be used under different futures and it provides the basis on which the pathways can be built. The FLORAP pathways are the main result of the approach. They show the actions that can be taken under different external factors and the sequence in which they can be taken. The actions have been optimised to fit together in the pathways approach, so that later actions can build on earlier actions. This is what makes the plan flexible and, combined with the large range of possible external factors over which it has been realised, is what aims to improve the performance under long-term (deep) uncertainty. Finally, a monitoring plan is needed to use the created pathways, which monitors the external factors, so that when the trigger values are reached, the required actions can be implemented.

The approach to create the FLORAP plan, mentioned above, is an iterative set of eight steps: It starts with analysing the situation, after which it determines the extent of the problem. These first two steps are comparable to the risk analysis and risk assessment from FRM. Thirdly, it determines possible flood risk reduction measures to reduce the problem, after which it tests the effectiveness of the measures. Based on these results the fifth step is to create the FLORAP plan, consisting of the flood risk adaptation pathways and image, after which it makes the monitoring plan. After this the situation can be monitored (step 7) and when required actions can be implemented (step 8). Steps 3 to 8 replace the risk reduction step of the FRM approach. The first seven steps of the approach are used in the conceptual design phase and should be used in combination with a flood risk screening model, step 8 is its continuation into the next design phases.

The approach was applied to a case study on Beira, Mozambique, to test its limitations. The main limitation appears to be that the approach is computationally expensive. This was the case for the case study, which had to be simplified for the approach to work. The exploratory modelling approach to testing the solutions, part of step 4 and 5, became time consuming and complex, because of the large number of possible futures and strategies that all had to be analysed. The more main external factors are included into the analysis (the case study only had three), the more computationally expensive and time consuming it will become. Furthermore, having more than three main external factors also creates problems with the representation of the pathways image. As more situations are analysed the pathways image can become obscured because of the large number of pathways. The FLORAP image can be difficult to interpret for users who are not familiar with it, and care should be given to clearly explain it to policymakers to enable them to use it. Lastly, because the rate of increase of the external factors is unknown, it is difficult to establish correct trigger values for the signposts. This is a problem because a lead time for construction needs to be incorporated in these trigger values to make sure measures are finished on time. It also creates a problem for the lifetime of actions, as the lifetime depends on the rate of increase of the external factors. This leads to difficulties for investment decisions; when should an action be taken and when would it be more advantageous to select a more advanced action instead? This is a drawback of the FLORAP approach, which was created by removing the timeline from the possible futures.

The benefits of the approach were also tested in the case study. The main benefit of this approach is the ability to anticipate for all possible futures, which is realised by investigating a large range of possible futures with the flood risk screening model and then using a DAPP like approach to create a flexible set of actions. This creates a plan which is robust to changing circumstances. The FLORAP image can then show policymakers what measures would be required under certain conditions and thus allows to plan for the measures ahead of time. This makes it possible to keep the measures implementable and plan for the necessary investments. The sequential coherence between actions is improved, which makes implementation of the successor action cheaper. Furthermore, it allows the policymaker to focus on the selected measures at the time that these are required, which means remaining measures can be investigated in more detail. The effectiveness regions show visually when measures are effective and when they are not. This provides the information for the FLORAP image, but can also be used by policymakers (and stakeholders) to discuss on the tested measures. Such a broad overview of the effectiveness of measures under different conditions is valuable in complex case studies where many possible options are discussed. Finally, the plan leaves room for pathways with different optimisation preferences to allow for further investigation of the possibilities and to allow for different preferences of policymakers and stakeholders.

Overall, the approach can help in the early design phases of long-term flood risk management processes. It would for example be a valid option, when creating a masterplan for the flood defences of a city. Care should be taken to ensure that the approach remains clear and that the computation time remains manageable. If this can be ensured, it provides a solid approach for dealing with long-term uncertainty while maintaining the core FRM approach. If properly introduced, the FLORAP image lets policymakers see in one view which measures are needed under the corresponding futures, providing a powerful tool to communicate the required measures arising from an FRM approach in complex situations.

7. RECOMMENDATIONS

Additional research is required into determining trigger values of the signposts. This is not unique to the newly developed approach, but is something that has not been fully worked out in the adaptive approaches. However, in the FLORAP approach the problem has been exacerbated by removing the time estimate. Estimating the appropriate value in order to have enough lead time to complete measures before they are required is difficult, especially without the timeline.

During the execution of the case study it was found that adaptation tipping points can be rather difficult to establish as definitively as the definition suggests. An adaptation tipping point is defined as a point where the magnitude of change due to changing conditions is such that the current action will no longer be able to meet the objectives, meaning a new action is required. However, the question arises if an objective is always so clearly definable and set in stone to be able to state this. For example, should a whole new action be implemented when the objective is only barely missed? Because in the case study a cost optimisation was the main objective, it would not have made sense to implement a new action when the new action would only be slightly more optimal, since this means taking unnecessary risk for only a marginal improvement. The certainty which the adaptation tipping points seem to imply can be rather misleading, at least depending on the performance objectives. Further research into how these should be established in an actual real-life application could provide interesting discussion points and new insights. In the current research, the adaptation tipping points were approached less stringently.

The visualisation of the pathways approach on the 3D external factors axis, can become obscured quickly. The amount of information in these graphs can become too much, especially as more possible futures and optimisation preferences are investigated. It is, however, believed that this approach can be a very powerful way of communicating the required actions under different futures. More research into how this can be represented in a clear way would be very helpful. Graphical designers or software engineers might be able to create an interactive 3D picture, which would allow users to focus the information and thus make it more comprehensible.

Lastly, repeating the case study for different situations with different focusses and optimisation objectives would be required to mature the approach and make sure it is widely applicable. Especially, the testing of the FLORAP image and the effectiveness regions in different case studies, to determine their added value in different situations, would be interesting. A further example would be the creation of pareto optimal pathways using the current approach, which could be an interesting addition that was not performed in the current study because of time constraints. Finally, testing the approach with the use of a direct search engine to partially replace the exploratory modelling approach in the FLORAP approach would be a valuable addition to the approach. The direct search method would help in applying the model under complex circumstances, as it was found that the approach can get very labour intensive and complex to analyse.

8. REFERENCES

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APPENDIX

A. ADITIONAL INFORMATION FLORES

This appendix describes the functioning and data requirements for FLORES and the adaptations made to FLORES by this researcher. First the changes that had to be made for Van Berchum et al. (2019) are described after which changes that were made for this study specifically are given.

Functioning of FLORES

The functioning of FLORES is shown in Figure A-1, its setup is based on the XLRM framework shown in Figure A-2.

First, it generates a flood reduction strategy by choosing combinations of the possible measures (policy levers). Then the selected flood risk reduction strategy is subjected to the hydraulic boundary conditions for different flood events, which consist of the combination of rainfall events and storm events with different return periods. This calculates probabilities of failure of the measures and expected flood levels per flood event. This is followed by a calculation of the impact, by using the flood levels and the demographic information. This leads to the creation of a risk profile over the different storm events. Which is then used to calculate the reduction in risk and affected population and the construction costs (performance metrics). The data for that strategy under one scenario is stored and then the process is repeated for a number of scenarios (external factors) and a large number of strategies. The required data input for FLORES is shown in Table A-1.

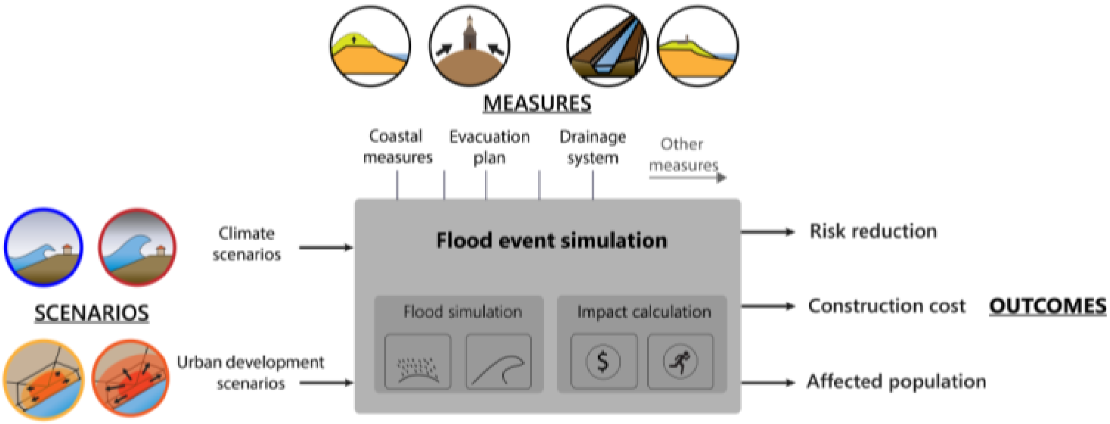

Figure A-1: Functioning of FLORES, compare to Figure A-2.

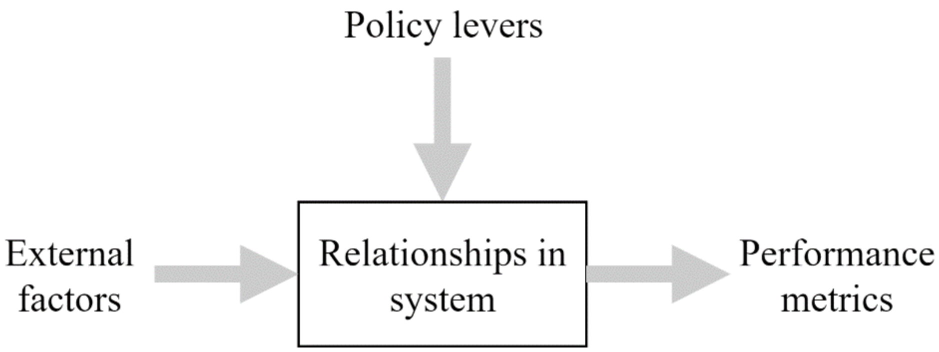

Figure A-2: XLRM framework (Kwakkel, 2017).

Table A-1: Required input FLORES (van Berchum et al., 2019).

LAYER	REQUIRED INPUT	DESCRIPTION
REGION LAYOUT	Elevation	Absolute height of the area above a specific datum
	Land cover	Type and/or value of land (e.g. residential/ business/other purposes)
	Vulnerability	Scale of potential impact (e.g. Number of inhabitants, land value)
	Damage curves	Relation between inundation level and percentage of value damaged
	Development	Population growth, urban development
FLOOD RISK REDUCTION STRATEGY	Structural measures	Types of measures, construction costs, location, efficiency
	Non-structural measures	Type of measures, implementation cost, expected impact
HYDRAULIC BOUNDARY CONDITIONS	Surge data	Time series of water levels during a storm for different return periods
	Rain data	Time series of rain intensity for different return periods
	Wind data	Main wind direction and wind speed during different storms
	Future changes	Change in hazard intensity

FLORES adaptations and changes made for Van Berchum et al. (2019)

Van Berchum et al. (2019) adapted the FLORES model to the city of Beira, Mozambique. The researcher of this research prepared the geographical information, which is input for the model, in a GIS and worked on improving the computation time of the model. This section describes the processes involved in doing so.

The DEM (Digital Elevation Map) that was provided for the model contained a number of flaws that had to be addressed before it could be used for the simulation runs. Several areas with faulty data had to be removed from the DEM because of their impact on the drainage results. The removed areas were all small enough to allow for interpolation in order to fill the created gaps.

The DEM was also filtered to remove local irregularities and to remove houses as this would lead to wrong flood depths. A measurement error in the DEM had been previously discovered, and this was adjusted to create a DEM with the corrects heights relative to M.S.L.

Part of a drainage system that had been constructed in the previous year was not present on the DEM. This was adjusted in the GIS to be able to calculate drainage directions for the model.

Basins were delineated and inter-basin drainage directions and capacities were calculated, which are required for the flood simulation. This was done by calculating the drainage directions of the DEM in GIS and on the basis of this drainage basins were delineated. Together with the drainage directions, the inter-basin drainage direction and capacities were calculated.

The DEM was divided into height contours, and these also divided per basin. This allows the model to calculate flooding per height contour per basin. The demographic information was then divided per contour and basin to provide the model with the information about the vulnerability of the area.

The FLORES model had previously relied on a single core processor from the EMA-workbench. The model was altered at certain points to allow for a multi-core processor to be used. This reduces the computation time significantly depending on the number of cores that are available for the computation.

Adaptation for current study

Specifically, for this study the model was adapted to allow for changing external factors in a single run. This allows for more in-depth research into the influence of the changing external factors on the required solutions and was required for the creation of pathways.

The model was adapted to introduce a new class of flood reduction measures, named flood proving measures. These flood proving measures aim at reducing damage through the reduction in vulnerability of the area. The required input for the flood proving measures is a factor for reducing the damage, a factor for reducing the affected population and a fixed cost.

Finally, a calculation of the total yearly costs was added to the model, this is a combination of the construction costs divided through the corresponding lifetime and the yearly expected damage (yearly risk).

B. INPUT DATA

This appendix further elaborates the data used for running FLORES.

B.1. Hydraulic boundary conditions

The hydraulic boundary conditions used in FLORES are shown in Table B-1 and Table B-2.

Table B-1: Storm data used as input for FLORES (Cardona et al., 2014).

RETURN PERIOD STORM	MAXIMUM SURGE (M)	WIND VELOCITY (M/S)	WAVE HEIGHT (M)	STORM DURATION (HRS)	NORMAL TIDAL AMPLITUDE (M)
0	0	0	0	24	3.4
2	0.18	20	4.5	24	3.4
5	0.32	22	5	24	3.4
10	0.49	25	6.2	24	3.4
50	1.57	30	6.8	24	3.4
100	2.24	35	7.8	24	3.4

Table B-2: Rain data used as input for FLORES (CES & Lackner, 2013).

RETURN PERIOD RAIN	RAIN INTENSITY (MM/HR)	RAINFALL DURATION (HRS)
0	0	24
2	7	24
5	9	24
10	11	24
50	14	24
100	16	24

Correlation

The correlation is used to create the risk based on the flood events over which the FLORES model is evaluated. ERA-Interim data (Dee et al., 2011) was used to calculate the correlation between rainfall and storm events. The correlation was calculated and analysed; the resulting correlation turned out to be approximately zero.

B.2. Limitations GIS information

A number of issues limitations regarding the GIS information is discussed here:

- The DEM had a few local errors, manually introduced by a previous editor. These areas were removed and interpolated, so locally some data has been lost. Because the affected area was relatively limited, the data loss is not expected to be a problem.
- The height of the DEM is affected by the houses in the city. When damage calculations are performed based on inundation damage curves this should be realised and if the influence on the outcome is deemed to be significant, it must be factored in. Because a complete list of houses was not available, due to the difference in sample year, this could not be filtered out. It means that the height data becomes less reliable for the damage calculation, it is not expected to be a problem for the flooding simulation.
- The census data regarding population and houses is from the year 2007. This data is thus already quite old, and as such a factor will have to be introduced to account for the population growth. This can have severe influence on the model results if not handled correctly, especially since the population growth has occurred irregularly over space. Extra care must be taken in resolving this issue, which will be done during model optimisation.

- Because of memory constraints in the GRASS tool in QGIS, the basins that have been derived have a horizontal resolution of ten by ten. This is however not expected to have a significant effect on the model outcome.
- Within a basin, areas with the same height have been joined together to create one elevation contour. These areas within the basin aren't necessarily connected in reality, this is a simplification in the model to retain a manageable number of subareas for the model to perform calculations on.

B.3. Development scenarios

Population growth is determined by multiplying the growth factor times the total population. It is then spatially distributed, based on the available free space and proximity to the city.

The basins with the highest expected population growth are shown in Figure B-1. People are expected to settle there because these areas are still relatively close to roads and the city and because there is room for unregulated development in these areas. Furthermore, slums will often appear in geographically hazardous locations (United Nations Conference on Housing and Sustainable Urban Development, 2015). These considerations lead to expected growth unregulated housing in these areas. This leads to more people at risk of flooding as these areas are also mostly low lying and thus more prone to flooding.

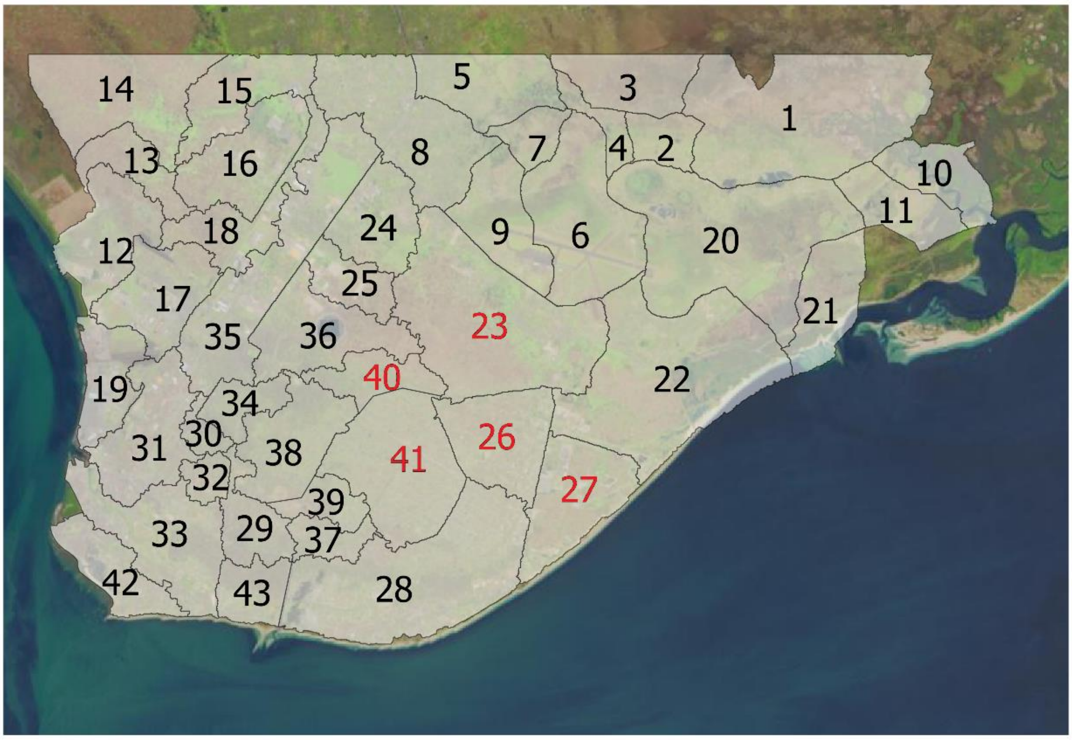

Figure B-1: Areas with high population growth in red for a low economic development scenario.

C. PATIENT RULE INDUCTION METHOD

This appendix describes the functioning of the PRIM algorithm (Friedman & Fisher, 1999) in the first section. In the second section, the PRIM analysis, from which the results in section 4.4.2 are presented, is performed.

C.1. Description PRIM algorithm

The PRIM algorithm limits the design space, by selecting regions of the model input space, where a large concentration of model outcomes satisfies a certain set of thresholds (Friedman & Fisher, 1999). The algorithm aims to limit the design space, while limiting the loss of outcomes of interest (van Berchum et al., 2019). The process is visualised in Figure C-1,b, where the design space is made smaller to select a region with as many outcomes of interest (blue dots) as possible, while removing as many of the other outcomes (green dots) as possible. This process is repeated until, the density (fraction of outcomes that are of interest in the selected box) is as high as possible, while the coverage (fraction of outcomes of interest that are within the selected box) remains above a set threshold, this is shown in Figure C-1,a. The restricted dimensions are then saved as the relevant factors for meeting the threshold values, these are shown in Figure C-2.

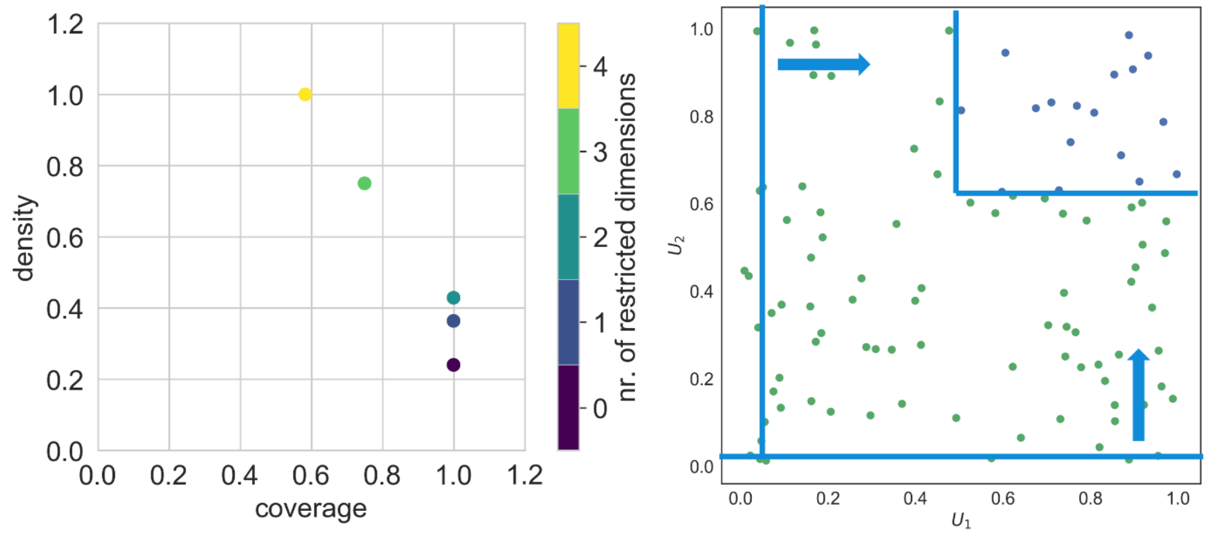

Figure C-1: PRIM analysis functioning, a: Dots represent the number of times the PRIM box selection is repeated. The number of restricted dimensions is the number of model inputs that are selected as important for reaching the threshold values. b: Shows the selection of the design space, in order to find the design space which maximises the fraction of outcomes that are of interest, while limiting the outcomes of interest that are not in the selected design space. Source (b): (Kwakkel, 2018)

C.2. PRIM analysis

The PRIM analysis is performed for the main scenarios, in order to find which flood risk reduction measures are likely options under each scenario.

Current situation

The current situation is analysed by performing multiple PRIM analyses with different threshold values. First high values are given for risk reduction and reduction in affected people. The second PRIM analysis focusses on reducing the number of affected people. The third aims to present a solution with low costs and good reduction values.

High risk reduction

Figure 4-2, shows the measures the PRIM found with the threshold values from Table C-1. The result has a density of 1, which means that all realisations which have these measures implemented meet the threshold values. The coverage is 0.636, so approximately two thirds of the realisations that meet the threshold are represented by these solutions.

The results suggest that retention areas are important parts of any solution. All options for retention are represented, so it seems it is mostly a question of which size retention area is required. Preventing settlement in the vulnerable areas is also part of the PRIM results. Both results correspond with the feature scoring results.

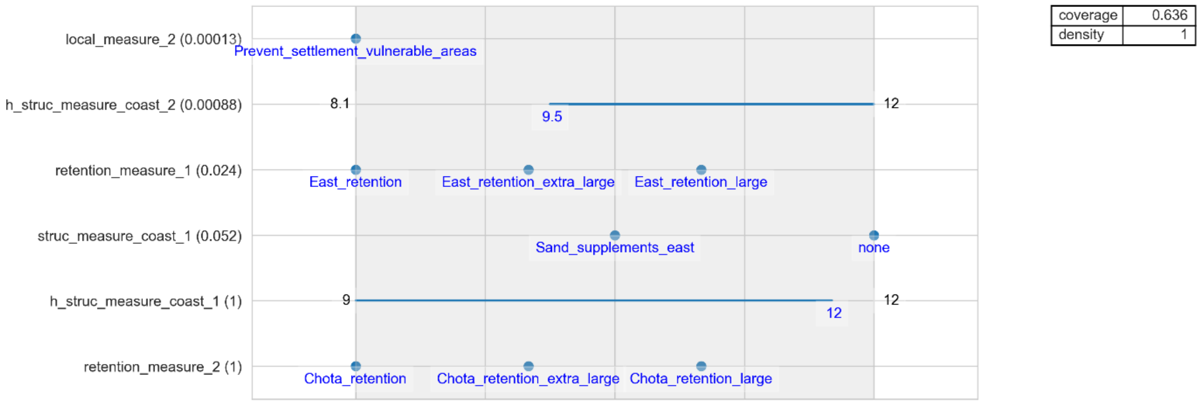

Figure C-2: PRIM analysis results, based on 44 cases of interest, threshold values shown in Table C-1.

Table C-1: Threshold values used for PRIM analysis.

Outcome	Threshold value
Risk reduction fraction	>0.7
Affected population reduction fraction	>0.6
Construction costs	<225 million dollar

Affected people reduction

For reducing the number of affected people, we see that constructing the western coastal defence measure is a good option, Figure C-3. This has a high qp-factor and is thus considered to be statistically significant. The other options come with much lower statistical significance but nonetheless give us an indication. Both emergency measures are selected, which matches with the outcomes of the FS. The Chota retention is also listed as a factor, which was not really picked up in the FS.

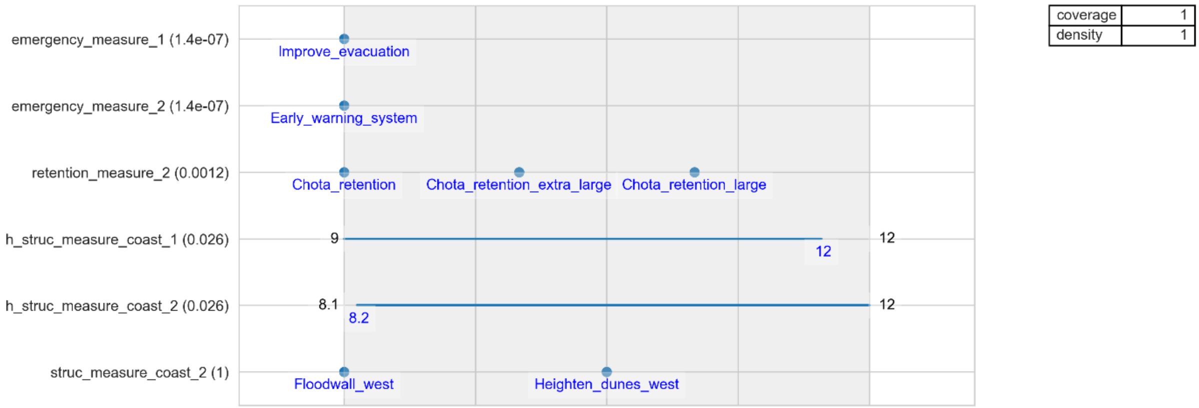

Figure C-3: : PRIM analysis results, based on 21 cases of interest, threshold values shown in Table C-2.

Table C-2: Threshold values used for PRIM analysis.

Outcome	Threshold value
Risk reduction fraction	>0.1
Affected population reduction fraction	>0.75
Construction costs	<300 million dollar

Cost-effective reduction

Figure C-4, shows that for a cost-effective solution the extra-large drainage system must not be included in the current situation. It gives an indication albeit with a low qp-factor that the eastern retention measure should either be large or extra-large. The settlement prevention measure is again indicated, just like both emergency measures (low qp-factor).

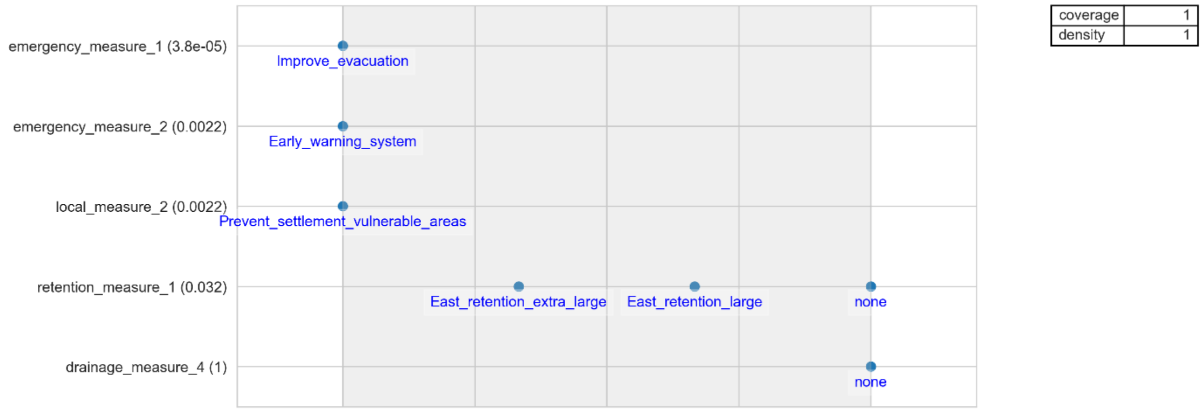

Figure C-4: PRIM analysis results, based on 50 cases of interest, threshold values shown in Table C-3.

Table C-3: Threshold values used for PRIM analysis.

Outcome	Threshold value
Risk reduction fraction	>0.6
Affected population reduction fraction	>0.6
Construction costs	<100 million dollar

Measures under increasing rainfall intensity

Figure C-5, shows the outcomes of a PRIM analysis with the thresholds displayed in Table C-4. For this PRIM run the reduction fractions are kept quite low at 0.5 and 0.6, but only nine of the 50 cases remain as cases of interest. It has a coverage of 0.667 which means that approximately two thirds of the cases of interest are represented by these outcomes. The density of 1 shows that all the results with these measures selected satisfy the imposed thresholds.

This thus means that two thirds of the solutions that satisfy the threshold has either the large or the extra-large eastern retention area and the normal, large or extra-large retention in Chota. The retention areas were already selected under the base situation and are still effective in the increased rainfall scenario.

The two flood proving measures, the strengthening of vulnerable houses and the prevention of settlement in vulnerable areas are both selected. The prevention of settlement was also selected in the base situation.

The drainage measures are not shown in the PRIM results except for the second phase drainage which did not rate very high in the FS either. This will further be analysed in section 4.4.3. It is expected at least some of the drainage measures will be required to create the actions.

In order to create significant reduction in the risks, it thus appears necessary to use a large combination of different measures.

Figure C-5: PRIM analysis results, based on 9 cases of interest, threshold values shown in Table C-4.

Table C-4: Threshold values used for PRIM analysis.

Outcome	Threshold value
Risk reduction fraction	>0.6
Affected population reduction fraction	>0.5
Construction costs	<225 million dollar

Cost-effective risk reduction under rainfall intensity increase

The Chota retention option is again selected by the PRIM analysis. This is thus a strong indication that these should be implemented, including when costs are a factor. Preventing settlement is also selected, so based on all the previous results it is likely to be an important part of any solution.

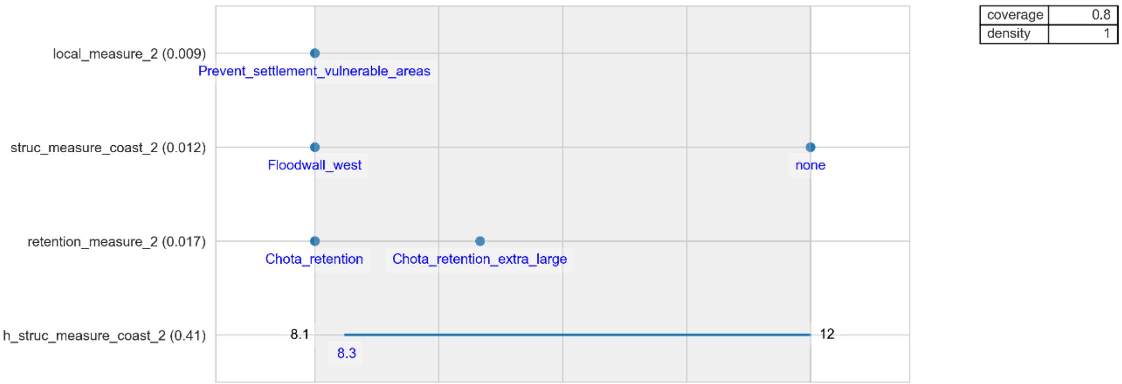

Figure C-6: PRIM analysis results, based on 5 cases of interest, threshold values shown in Table C-5.

Table C-5: Threshold values used for PRIM analysis.

Outcome	Threshold value
Risk reduction fraction	>0.55
Affected population reduction fraction	>0.5
Construction costs	<150 million dollar

Measures under sea level rise

Figure C-7, shows the measures that the PRIM analysis selected for the threshold values as shown in Table C-6. The coverage of 0.444 means that less than half the solutions that meet the threshold are represented by these measures. The density of 1 means that all the runs with these measures do meet the threshold. This thus means that this set of solutions does meet the set goals, but that they are not the only set of solutions that do this.

Figure C-8, shows the result of a PRIM analysis with a different set of thresholds. The coverage becomes slightly higher and the density remains at 1.

Based on both PRIM results it seems that the eastern structural measure should be implemented. Either a floodwall should be constructed, or the dunes should be heightened. The PRIM also gives a minimum for this height; somewhere around 8.7 meters.

Fewer rain flood risk reduction measures have been selected indicating the increased importance of the threat from sea flooding, which is a logical result of the increased sea level.

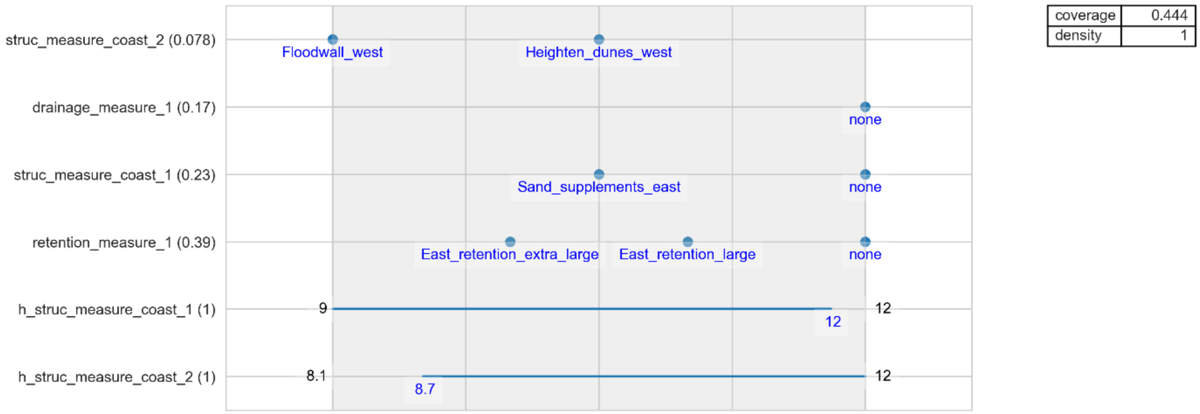

Figure C-7: PRIM analysis results, based on 18 cases of interest, threshold values shown in Table C-6.

Table C-6: Threshold values used for PRIM analysis.

Outcome	Threshold value
Risk reduction fraction	>0.7
Affected population reduction fraction	>0.6
Construction costs	<225 million dollar

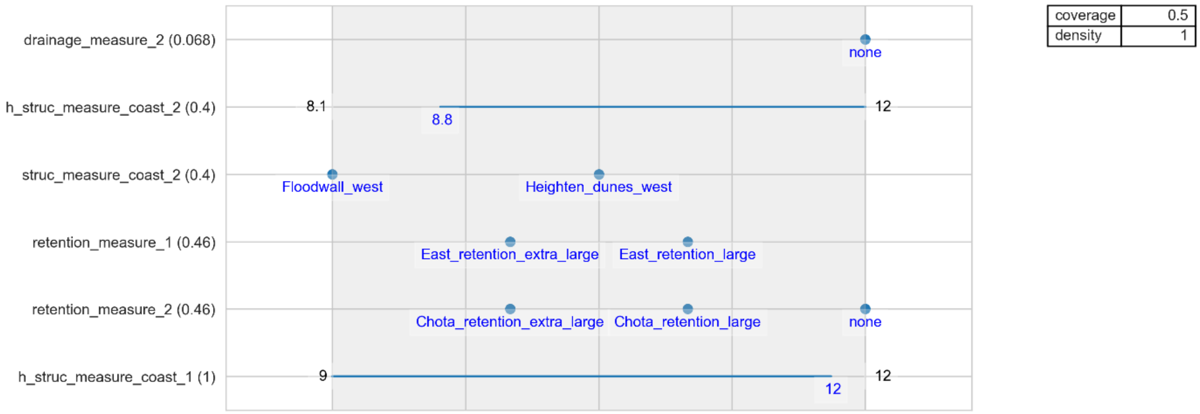

Figure C-8: PRIM analysis results, based on 10 cases of interest, threshold values shown in Table C-7.

Table C-7: Threshold values used for PRIM analysis.

Outcome	Threshold value
Risk reduction fraction	>0.8
Affected population reduction fraction	>0.7
Construction costs	<225 million dollar

Measures under development

Figure C-9, shows the selected measures under development. It has a low coverage, but it does show us which measures function well. Just like in the FS, the western coastal defence measure, the second phase drainage and the eastern retention perform well. Other options that performed well in the FS are not shown, but with the low coverage in mind this does not carry much weight.

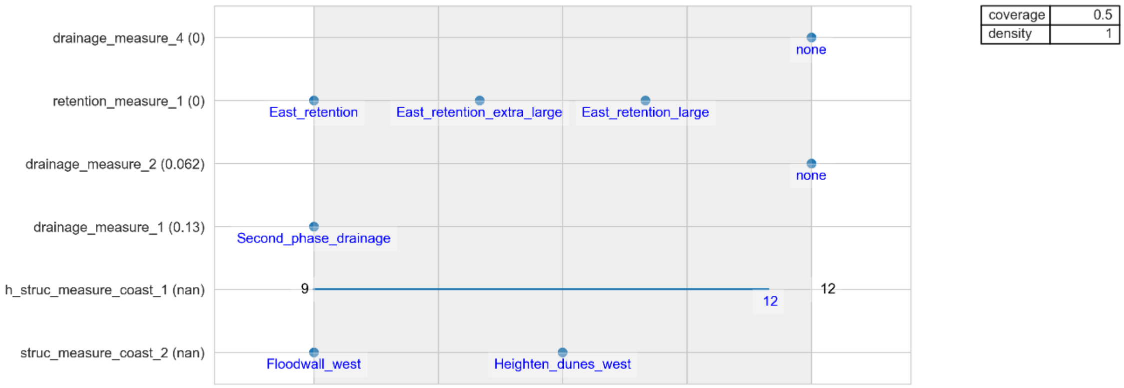

Figure C-9: PRIM analysis results, based on 8 cases of interest, threshold values shown in Table C-8.

Table C-8: Threshold values used for PRIM analysis.

Outcome	Threshold value
Risk reduction fraction	>0.7
Affected population reduction fraction	>0.7
Construction costs	<150 million dollar

D. RESULTS

Legend	Second phase	Micro drainage	Surface water	Surface water	Improve evacuation	Early warning	Height	Height coast	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
R1	Yes	None	None	None	Yes	Yes	-	-	Yes	None	East	None	None	None
R2	Yes	Yes	None	None	Yes	Yes	-	8.5	Yes	Yes	East large	Chota XL	None	Floodwall
R3	Yes	None	None	None	Yes	Yes	9.8	-	Yes	Yes	East	Chota large	Sand suppletion	None
R4	Yes	None	None	None	Yes	Yes	9.6	12.0	Yes	Yes	East XL	Chota	Sand suppletion	Floodwall
R5	None	None	Yes	None	None	Yes	-	-	None	Yes	East XL	Chota	None	None
R6	None	None	Yes	None	None	Yes	-	8.3	Yes	None	East XL	Chota large	None	Heighten dunes
R7	Yes	None	None	None	Yes	None	-	9.9	None	Yes	None	Chota XL	None	Heighten dunes
R8	Yes	None	None	None	Yes	Yes	-	8.6	None	Yes	East	Chota	None	Heighten dunes
R9	Yes	Yes	None	None	None	None	-	10.9	Yes	Yes	East	Chota large	None	Floodwall

Figure D-1: Nine most cost-effective solutions under rainfall intensity increase and the do-nothing option (cyan). Total costs and risk in dollars, construction costs in millions of dollars.

Legend	Second phase	Micro drainage	Surface water	Surface water	Improve evacuation	Early warning	Height coast	Height coast	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
S1	Yes	Yes	None	None	Yes	Yes	-	8.5	Yes	Yes	East large	Chota XL	None	Floodwall
S2	Yes	None	None	None	Yes	Yes	9.8	-	Yes	Yes	East	Chota large	Sand suppletion	None
S3	None	None	None	None	None	None	11.6	-	Yes	Yes	East	None	Sand suppletion	None
S4	Yes	None	None	None	Yes	None	-	11.5	Yes	Yes	None	Chota	None	Heighten dunes
S5	None	None	None	None	Yes	None	10.5	11.0	Yes	None	East XL	Chota large	Heighten dunes	Floodwall
S6	Yes	None	None	None	Yes	Yes	9.6	12.0	Yes	Yes	East XL	Chota	Sand suppletion	Floodwall
S7	Yes	None	None	None	Yes	Yes	-	8.6	None	Yes	East	Chota	None	Heighten dunes
S8	None	Yes	None	None	None	None	9.8	11.4	None	None	East large	Chota XL	Sand suppletion	Floodwall
S9	Yes	Yes	None	None	None	None	-	10.9	Yes	Yes	East	Chota large	None	Floodwall

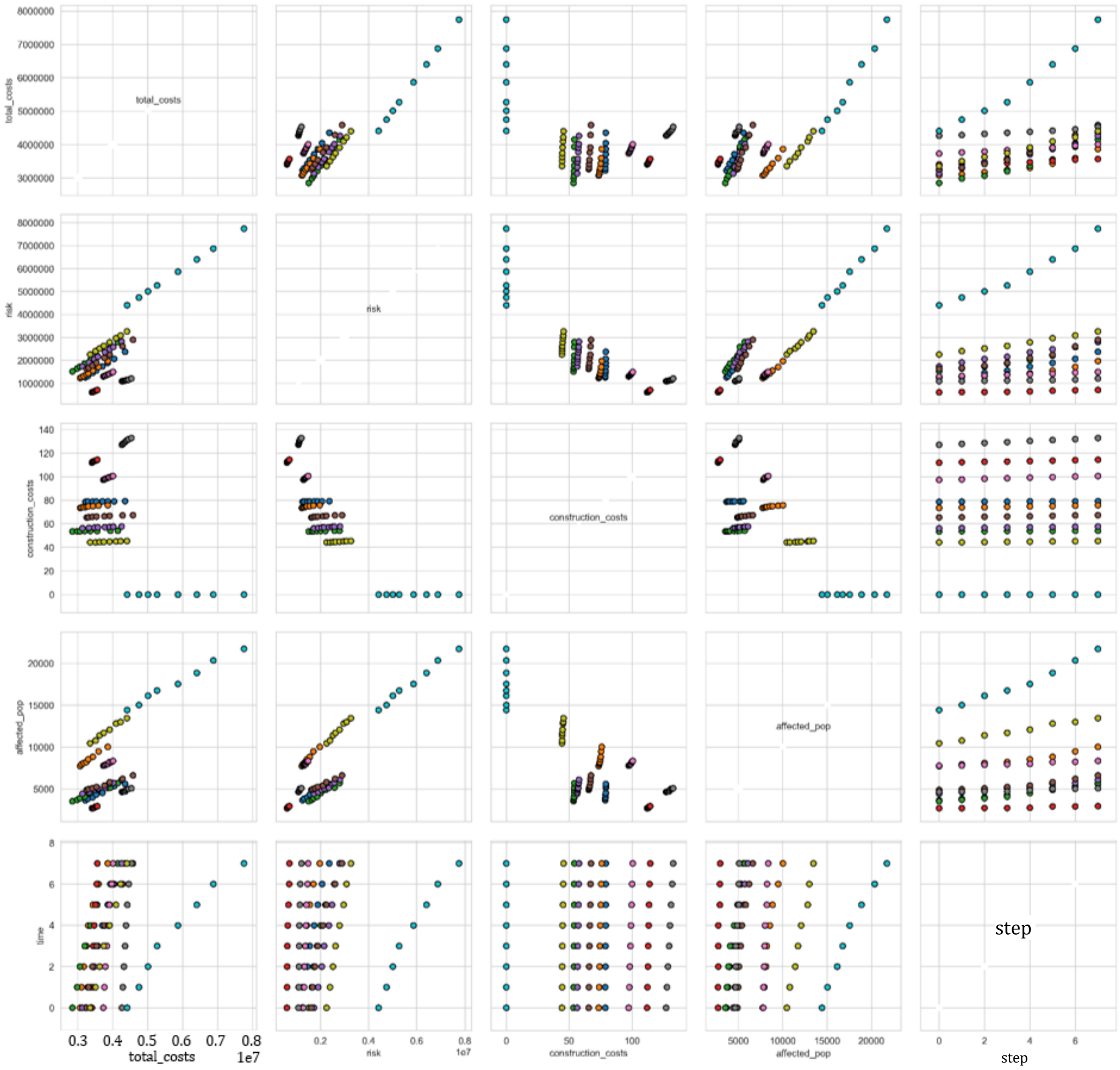

Figure D-2: Nine most cost-effective solutions under sea level rise and the do-nothing option (cyan). Total costs and risk in dollars, construction costs in millions of dollars.

Legend	Second phase	Micro drainage	Surface water	Surface water	Improve evacuation	Early warning	Height coast	Height coast	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
D1	Yes	None	None	Yes	None	Yes	-	10.6	Yes	Yes	East XL	Chota large	None	Heighten dunes
D2	Yes	Yes	None	Yes	None	Yes	11.7	11.1	Yes	None	East large	Chota large	Sand suppletion	Heighten dunes
D3	Yes	Yes	None	Yes	Yes	None	9.1	10.3	Yes	Yes	East	Chota XL	Heighten dunes	Floodwall
D4	None	None	Yes	None	None	Yes	9.3	10.4	None	Yes	East large	Chota XL	Sand suppletion	Heighten dunes
D5	Yes	Yes	Yes	None	None	None	11.0	11.0	None	Yes	None	Chota XL	Heighten dunes	Floodwall
D6	Yes	None	Yes	None	Yes	None	-	9.3	Yes	None	East large	Chota large	None	Floodwall
D7	Yes	None	None	Yes	None	Yes	-	9.3	None	Yes	East XL	Chota large	None	Floodwall
D8	None	None	Yes	None	Yes	Yes	11.0	10.9	Yes	Yes	East XL	None	Sand suppletion	Floodwall
D9	Yes	None	None	None	Yes	Yes	-	11.2	Yes	None	East XL	Chota	None	Heighten dunes

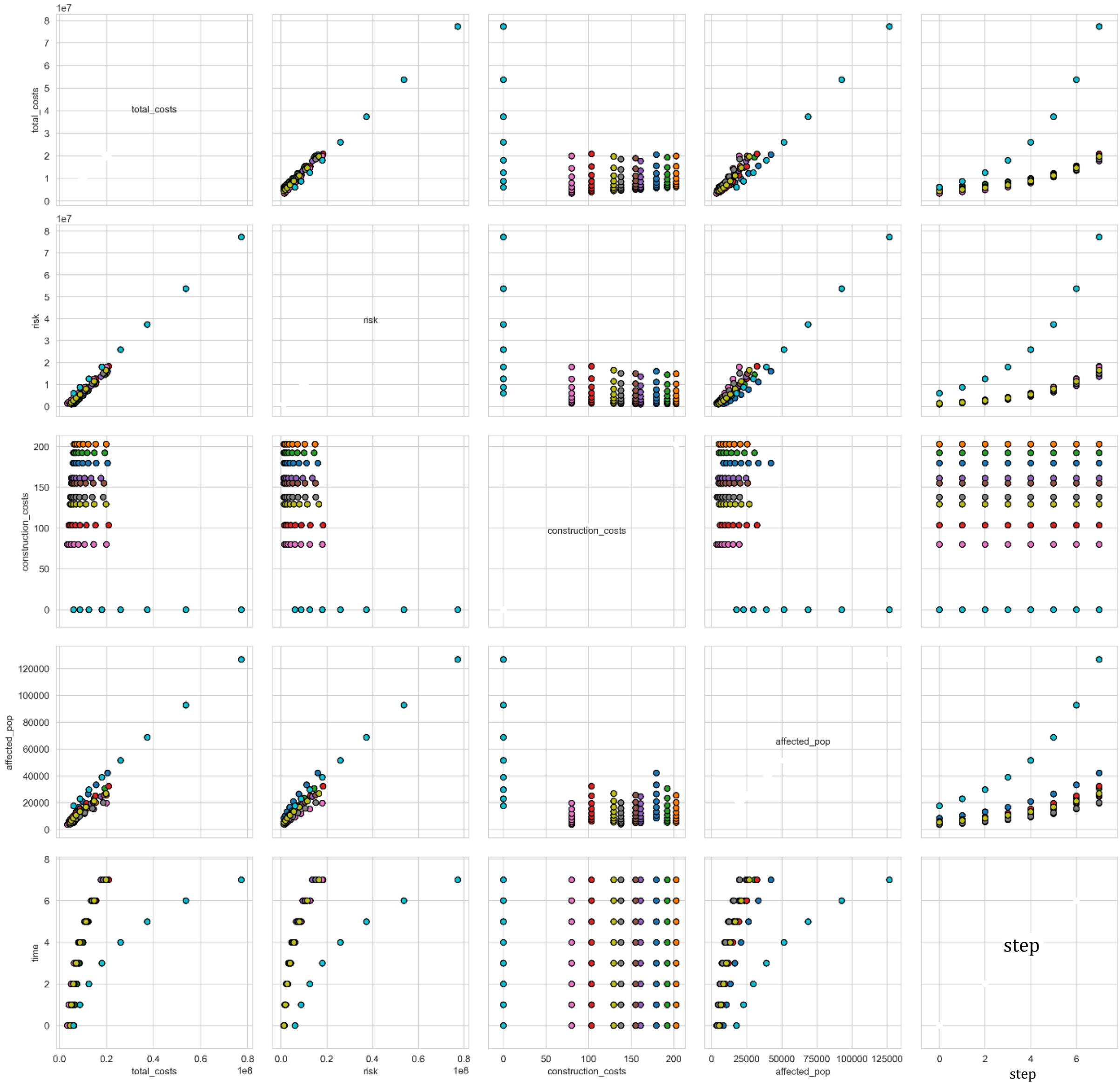

Figure D-3: Nine most cost-effective solutions under development and the do-nothing option (cyan). Total costs and risk in dollars, construction costs in millions of dollars.

Legend	Second phase	Micro drainage	Surface water	Surface water	Improve evacuation	Early warning	Height coast	Height coast	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
SR1	Yes	None	None	None	Yes	None	-	9.8	Yes	None	East large	Chota	None	Heighten dunes
SR2	None	None	None	None	None	Yes	9.3	8.6	Yes	None	East XL	Chota large	Sand suppletion	Floodwall
SR3	Yes	None	None	None	None	Yes	-	-	None	None	East XL	Chota	None	None
SR4	Yes	Yes	Yes	None	None	Yes	-	-	Yes	Yes	East XL	Chota XL	None	None
SR5	None	Yes	None	None	None	None	-	9.7	None	Yes	East large	None	None	Heighten dunes
SR6	Yes	Yes	None	None	Yes	None	10.5	-	None	None	East XL	Chota XL	Sand suppletion	None
SR7	None	Yes	None	None	Yes	None	11.4	11.7	Yes	Yes	East large	Chota XL	Sand suppletion	Floodwall
SR8	Yes	None	None	None	None	Yes	-	11.9	Yes	Yes	East large	Chota XL	None	Floodwall
SR9	None	Yes	None	None	Yes	None	11.1	-	Yes	None	East XL	Chota large	Sand suppletion	None

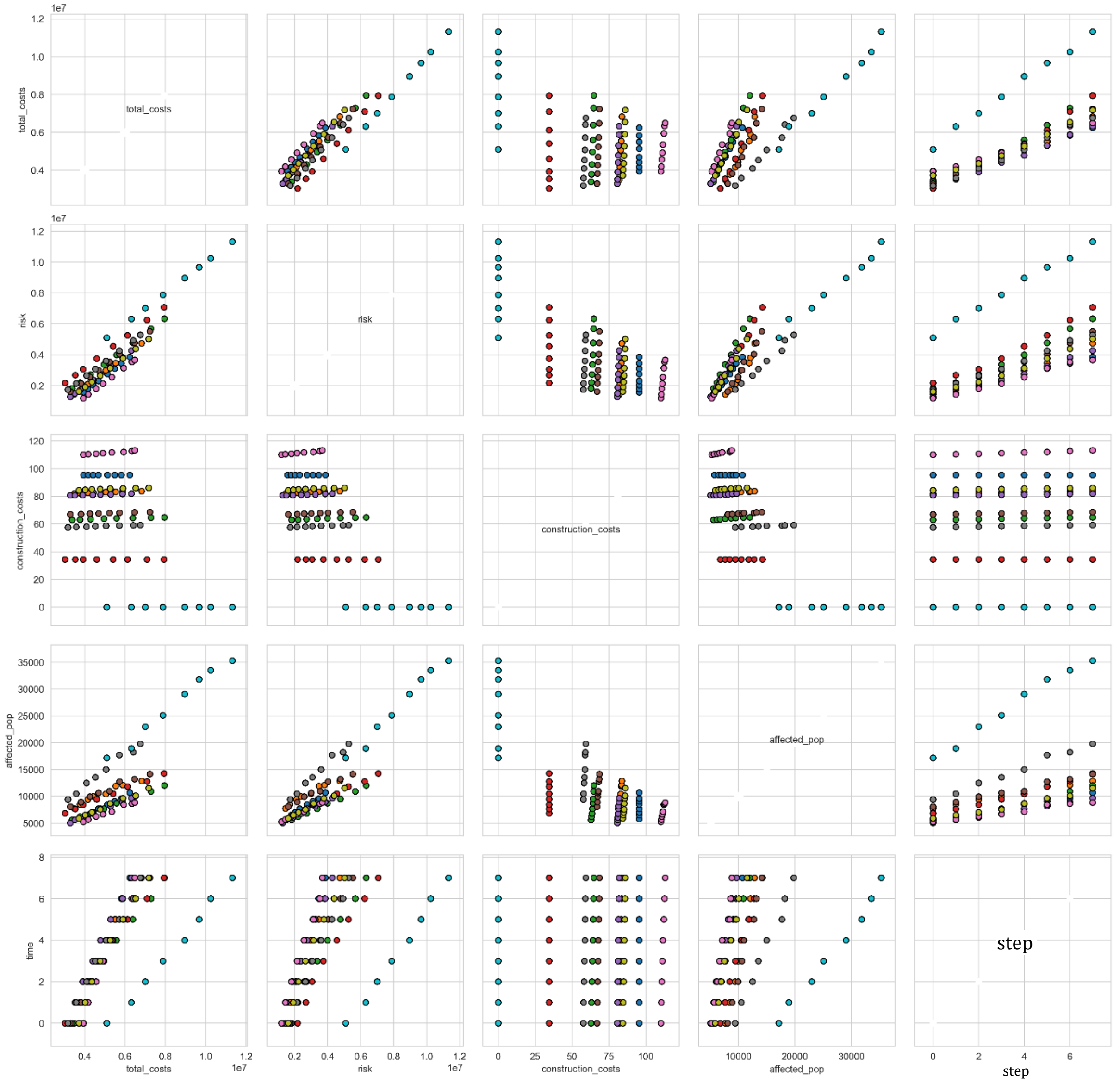

Figure D-4: Nine most cost-effective solutions under sea level rise and rainfall intensity increase, and the do-nothing option (cyan). Total costs and risk in dollars, construction costs in millions of dollars.

Legend	Second phase	Micro drainage	Surface water	Surface water	Improve evacuation	Early warning	Height coast	Height coast	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
RD1	Yes	Yes	Yes	Yes	None	None	9.9	8.6	None	Yes	East large	Chota large	Sand suppletion	Heighten dunes
RD2	Yes	None	None	Yes	None	Yes	-	10.6	Yes	Yes	East XL	Chota large	None	Heighten dunes
RD3	Yes	None	None	Yes	None	Yes	11.4	-	Yes	Yes	East	Chota XL	Sand suppletion	None
RD4	Yes	Yes	Yes	Yes	Yes	Yes	-	-	None	Yes	East XL	Chota XL	None	None
RD5	Yes	Yes	Yes	None	Yes	None	-	9.8	None	Yes	East XL	None	None	Floodwall
RD6	Yes	Yes	None	Yes	Yes	None	9.1	10.3	Yes	Yes	East	Chota XL	Heighten dunes	Floodwall
RD7	Yes	None	None	Yes	None	Yes	-	9.3	None	Yes	East XL	Chota large	None	Floodwall
RD8	None	None	None	Yes	None	None	10.6	9.1	None	Yes	East	Chota XL	Sand suppletion	Floodwall
RD9	None	None	Yes	Yes	Yes	None	-	9.5	None	Yes	East large	Chota XL	None	Floodwall

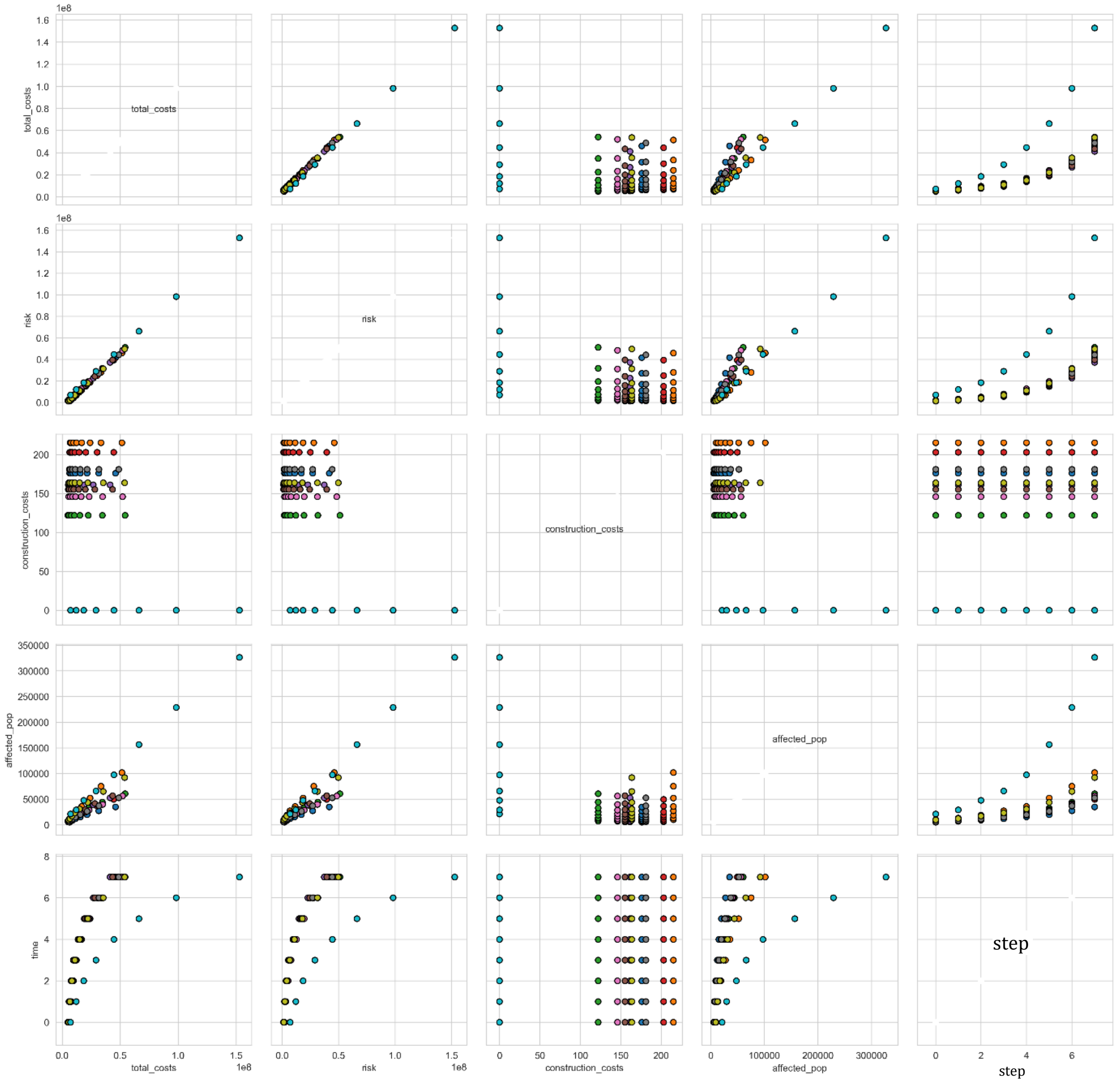

Figure D-5: Nine most cost-effective solutions under rainfall intensity increase and development, and the do-nothing option (cyan). Total costs and risk in dollars, construction costs in millions of dollars.

Legend	Second phase	Micro drainage	Surface water	Surface water	Improve evacuation	Early warning	Height coast	Height coast	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
SD1	None	None	None	None	Yes	None	11.8	8.9	None	Yes	East XL	Chota XL	Heighten dunes	Floodwall
SD2	Yes	None	Yes	Yes	Yes	None	9.8	9.7	None	Yes	East	Chota XL	Heighten dunes	Floodwall
SD3	None	Yes	None	None	Yes	Yes	11.3	10.8	None	Yes	East	Chota large	Heighten dunes	Heighten dunes
SD4	Yes	None	None	Yes	None	None	11.0	11.8	Yes	Yes	East large	Chota	Sand suppletion	Floodwall
SD5	None	None	Yes	Yes	None	Yes	11.5	10.0	Yes	None	East XL	Chota XL	Heighten dunes	Heighten dunes
SD6	Yes	Yes	Yes	None	None	Yes	10.3	11.0	Yes	Yes	East XL	Chota large	Heighten dunes	Floodwall
SD7	Yes	Yes	None	None	Yes	None	9.3	9.5	Yes	None	East XL	Chota XL	Sand suppletion	Floodwall
SD8	None	Yes	Yes	Yes	Yes	Yes	10.2	10.5	None	None	East XL	Chota	Heighten dunes	Floodwall
SD9	Yes	Yes	None	None	None	Yes	10.3	10.8	Yes	Yes	East	Chota XL	Sand suppletion	Heighten dunes

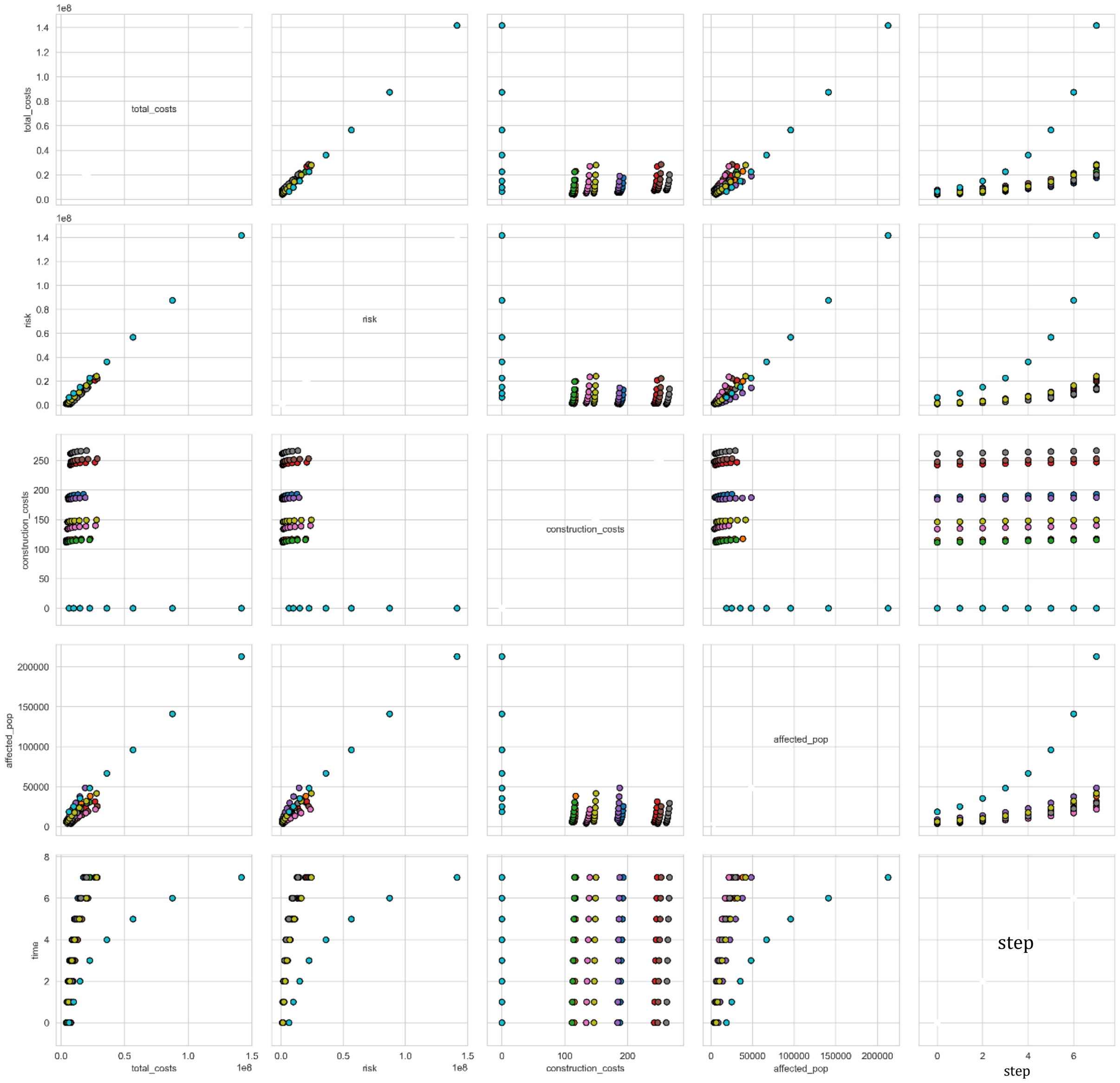

Figure D-6: Nine most cost-effective solutions under sea level rise and development, and the do-nothing option (cyan). Total costs and risk in dollars, construction costs in millions of dollars.

Legend	Second phase	Micro drainage	Surface water	Surface water	Improve evacuation	Early warning	Height coast	Height coast	Strengthening houses	Preventing settlement	Retention East	Retention Chota	Coast east	Coast west
SRD1	None	None	None	None	Yes	None	11.8	8.9	None	Yes	East XL	Chota XL	Heighten dunes	Floodwall
SRD2	Yes	None	Yes	Yes	None	None	-	8.4	None	Yes	East XL	Chota XL	None	Heighten dunes
SRD3	Yes	None	Yes	Yes	Yes	None	9.8	9.7	None	Yes	East	Chota XL	Heighten dunes	Floodwall
SRD4	Yes	None	None	Yes	None	None	11.0	11.8	Yes	Yes	East large	Chota	Sand suppletion	Floodwall
SRD5	None	None	Yes	Yes	None	Yes	11.5	10.0	Yes	None	East XL	Chota XL	Heighten dunes	Heighten dunes
SRD6	Yes	Yes	Yes	None	None	Yes	10.3	11.0	Yes	Yes	East XL	Chota large	Heighten dunes	Floodwall
SRD7	Yes	Yes	None	None	Yes	None	9.3	9.5	Yes	None	East XL	Chota XL	Sand suppletion	Floodwall
SRD8	Yes	None	Yes	Yes	None	None	-	10.6	None	None	East XL	Chota XL	None	Floodwall
SRD9	Yes	Yes	None	None	None	Yes	10.3	10.8	Yes	Yes	East	Chota XL	Sand suppletion	Heighten dunes

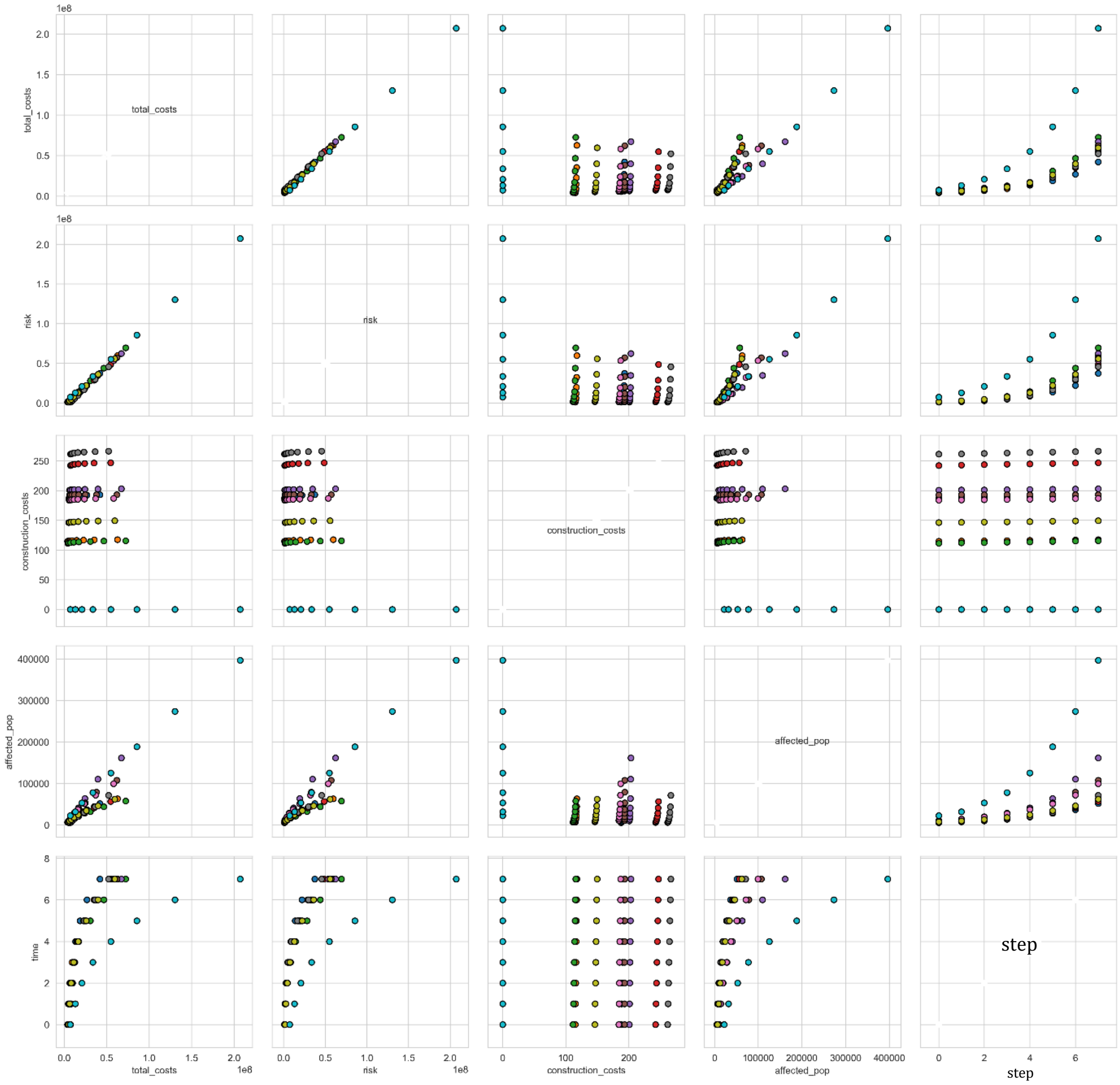

Figure D-7: Nine most cost-effective solutions under sea level rise, rainfall intensity increase and development, and the do-nothing option (cyan). Total costs and risk in dollars, construction costs in millions of dollars.