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ADVANCING FLOOD RISK SCREENING

Erik van Berchum

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Proefschrift

Ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft, op gezag van
de Rector Magnificus prof. dr. ir. T.H.J.J. van der Hagen,
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Door

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"I believe one of the greatest human failings is to prefer to be right than to be effective."

Stephen Fry

Summary

Many coastal cities are facing a rapidly growing risk of flooding. Flood hazards like coastal storm surge and extreme rainfall are increasing in intensity and – due to urbanization, sea level rise and subsidence – more people and investments are exposed to the threat of flooding than ever before. This problem will increase further in the coming decades, especially given that considerable growth is expected in some of the world's most vulnerable cities and regions. This rapid growth leaves the challenging task to find effective and sustainable strategies that reduce the flood risks to an acceptable level.

The size and layout of coastal cities often demand a coordinated strategy, that combines various flood risk reduction measures. A crucial part of the planning and early design process is identifying effective flood risk management strategies. The many measures that can be considered and the limited availability of data and resources characterized this early phase. Designers and engineers in flood risk management currently have only few tools specifically developed for these early stages in the design. In common practice, this often leads to either considering only a few intervention options using detailed simulation models or flood risk analysis based on conceptual optimization tools, which lack specific local inputs. In the early phase of planning and design, there is a need to compare a great number of measures and strategies, without needing unpractical amounts of time, data, and resources. This dissertation introduces flood risk screening as a form of analysis that aims to fill this gap.

This research aims to identify the needs and challenges of this early planning and design phase, and to develop and implement a model framework to support decision making in this stage. At the centre of the study is the development and application of the Flood Risk Reduction Evaluation and Screening, FLORES, model. This dissertation includes two real-life case studies used to develop the FLORES model. Also, it presents two applications of flood risk screening using the FLORES model, namely flood risk analysis based on low-resolution data, and flood risk analysis under deep uncertainty.

In this study, a framework is developed to schematize and analyse a flood-prone city in a manner that is both generally applicable and quick to implement. A useful model for flood risk screening should be able to (1) quickly transfer to other cities because of a generic setup and schematization, (2) simulate the impact of both structural and non-structural flood risk reduction measures, (3) compare strategies based on multiple performance metrics, (4) simulate the effects of multiple, compounded effects of flood hazards, (5) simulate based on limited data, and finally (6) explicitly design for uncertainty.

FLORES is developed based on these characteristics. FLORES is a rapid flood simulation model using relatively simple hydraulic formulas to reduce computational

load. Due to the its short computation time, it is possible to evaluate many different strategies for different storms and future scenarios on a single computer. Also, the model has a generic setup, which is easily adapted to other regions. FLORES was initially developed to model the effects of coastal storm surge and was later expanded to include pluvial flooding and their compounded effects. FLORES schematizes a coastal city as a collection of drainage basins, which are defined as areas where all water flows towards the same point. The flood simulation runs hydrological water balance equations for each basin for each time step throughout the simulated storm. It combines the resulting water levels with additional information to calculate the economic damage and the number of people affected.

We implemented the FLORES model in two case studies. In the first case study: the Houston-Galveston Bay Area, USA, the modelling mainly focussed on coastal storm surge. It showed that the flood risk reducing capabilities of the chosen strategy mainly depend on the choice of coastal protection on the islands. Especially the effectiveness of Nature-based Solutions in Galveston Bay heavily relied on the placement and elevation of coastal structures. For Beira, Mozambique, the model was expanded to include pluvial flooding. Here, coastal structures are combined with other measures to account for pluvial flooding, such as drainage, retention, and early-warning systems. The use of flood risk screening provided insight into the effectiveness of individual measures, and their combinations into strategies, and prioritizes strategies based on predetermined goals. For Beira, this gave insights into the effectiveness and necessity of both the coastal structures and the inland measures, like an expansion of the drainage system. For the short term, and future scenarios with little predicted climate change, strategies that focused on limiting the threat of extreme rainfall were highly prioritized, as this was the main contributor to the current flood risk. However, on a longer scale, and for futures with more extreme hazards due to climate change, the loads on the coastal system rise significantly. In these scenarios, the effect of coastal storm surge on the flood risk is much more profound, making coastal protection more critical. In both cities (Houston and Beira), these insights can be used to support decision-makers in finding the most effective strategy. Moreover, they also lead to a better understanding of the local flood risk.

Two newly introduced applications, related to low-resolution data and flood risk analysis under deep uncertainty, focus on recent developments in Digital Elevation Models, or DEMs, and robust decision making. DEMs are spatial representations of the local elevation and are crucial input for any flood risk analysis. Several (near-) global, free DEMs have been developed based on satellite measurements in recent years. Although still lacking the level of detail required for conventional flood simulation software, they could provide a cost-effective alternative in the conceptual design phase in combination with a flood risk screening model, such as FLORES. In this study, Beira's analysis – based initially on high-resolution LiDAR data – was repeated with three free global DEMs (SRTM, ALOS World 3D, and TanDEM-X WorldDEM). The comparison showed that only the TanDEM-X WorldDEM (90m), with the highest vertical resolution of the three global DEMs, was sufficiently accurate. Analysis based on the WorldDEM

dataset resulted in noticeable differences in flood extent but led to similar results in prioritizing strategies and effectiveness of risk reduction measures.
The second new application focussed on flood risk analysis under deep uncertainty and the potential of flood risk screening models in robust flood risk management planning. The Beira case study was complemented with investment timing and structural lifetime and introduced flood risk screening to develop a dynamically robust flood risk management plan. Robustness zones, graphical representations of the range of exogenous parameters like sea-level rise, storm intensity, and urban development, for which flood risk measures are effective, have been developed Using feature scoring and robustness zones, it provided support to develop a dynamically robust flood risk management plan for Beira that that is applicable and sustainable under changing future conditions.

Flood risk screening, and the models such as FLORES that facilitate it, can provide model-based support in the planning and early design stages of flood risk management, where fast and easy flood risk assessment deliver valuable insights. Large uncertainties and an almost endless range of options characterize these early design stages. As flood risk management is becoming more complex and integrated, so do the challenges faced by the experts and decision-makers. Advances such as the continuing development of flood risk screening tools are necessary to ensure the efficiency and effectiveness of flood risk management planning.

Samenvatting

Een groot aantal kuststeden staan onder de druk van een groeiend overstromingsrisico. De dreiging van het water, bijvoorbeeld in de vorm van stormvloed of extreme regenval, neemt toe in intensiteit en daarnaast – vanwege verstedelijking, zeespiegelstijging en zakking van de ondergrond – wonen meer mensen op een kwetsbare locatie dan ooit tevoren. De verwachting is dat in de komende decennia dit probleem alleen maar verder toeneemt, met name omdat de grootste groei wordt verwacht in de meest kwetsbare steden en regio's in de wereld. Dit leidt tot de opdracht om een effectieve en duurzame strategie te vinden om het overstromingsrisico te verlagen tot een acceptabel niveau.
De grootte en complexiteit van deze steden vraagt veelal om een gecoördineerde strategie, bestaande uit een combinatie van overstromingsrisico-verlagende maatregelen. Een cruciaal onderdeel van het vroeg planning- en ontwerpproces is de identificatie van effectieve overstromingsrisicomanagement strategieën. Deze vroege fase is gekarakteriseerd door de vele mogelijke maatregelen en het gebrek aan data en middelen. Op het moment hebben ontwerpers en ingenieurs in overstromingsrisicomanagement maar weinig ondersteunende hulpmiddelen voorhanden, specifiek voor deze eerste conceptuele fases. Dit leidt er vaak toe dat er maar een paar strategieën worden vergeleken met gebruik van gedetailleerde simulatiemodellen of dat het risico wordt geanalyseerd gebaseerd op conceptuele modellen die niet gebaseerd zijn op specifieke lokale data. In de vroege fases van planning en ontwerp is er een behoefte om veel verschillende strategieën te kunnen vergelijken, zonder hier onpraktische hoeveelheden tijd, data, en middelen aan te moeten besteden. Dit proefschrift introduceert overstromingsrisico-screening als een form van analyse die aan deze behoefte probeert te voldoen.

Deze studie richt zich op het identificeren van de benodigdheden en uitdagingen van deze vroege planning- en ontwerpfase, en het ontwikkelen en toepassen van een model kader dat het maken van beslissingen in deze fase kan ondersteunen. In het hart van de studie staat de ontwikkeling en toepassing van een dergelijk model: het Flood Risk Reduction Evaluation and Screening, of FLORES model. Dit proefschrift omvat onder andere twee voorbeeldstudies die zijn gebruikt voor de ontwikkeling van het FLORES model. Daarnaast introduceert het twee toepassingen van overstromingsrisico-screening, namelijk overstromingsrisico-analyse op basis van beperkte data en robuust ontwerpen. Het gebruik van een overstromingsrisico-screening model maakt deze toepassingen eenvoudiger in overstromingsrisico-management.
In deze studie is eerst een kader ontwikkeld om een kwetsbare stad te analyseren en schematiseren op een manier die zowel breed toepasbaar als makkelijk toe te passen

is. Hiervoor zijn een aantal kenmerken geïdentificeerd: Een overstromingsrisico-screening model moet (1) snel op een andere stad toepasbaar zijn dankzij een generieke opzet en schematisering, (2) de impact van zowel constructieve als niet-constructieve maatregelen kunnen simuleren, (3) strategieën kunnen vergelijken gebaseerd op meerdere resultaten, (4) het effect van meerdere, tegelijk werkende overstromingstypes kunnen simuleren, (5) simuleren op basis van gebrekkige data, en (6) expliciet kunnen ontwerpen voor onzekerheid door middel van verkennend modelleren ('exploratory modelling').

Het FLORES model is gebaseerd op deze kenmerken. Het model draait om een snel overstromingssimulatiemodel dat gebruik maakt van relatief simpele formules, welke vele male worden herhaald voor verschillende stormen, overstromingsrisico-strategieën, en toekomstscenario's. Vanwege de erg korte simulatietijd is het mogelijk om naar veel verschillende strategieën te kijken, terwijl het model nog steeds eenvoudig op een enkele computer kan draaien. Ook heeft het model een generieke opzet, welke makkelijk aan te passen is naar andere regio's. Hierbij was het eerst ontwikkeld voor het modelleren van de effecten van stormvloed op een kuststad, maar is het later uitgebreid voor het modelleren van overstroming door regenval en het samenwerkende effect tussen de twee. Deze snelle simulatie mogelijk vanwege de manier waarop de stad, de overstroming en de maatregelen zijn geschematiseerd. In het FLORES model is de stad geschematiseerd als een collectie van drainage bassins, die zijn gedefinieerd als delen van de stad waar al het water naar hetzelfde punt stroomt. De simulatie berekent de waterbalans voor ieder van deze bassins voor iedere tijdsstap gedurende een storm. De resulterende waterniveaus in ieder bassin worden vervolgens gebruikt om de economische schade en het aantal getroffen mensen te berekenen. Het FLORES model is toegepast in twee casussen. In de eerste casus: de Houston-Galveston Bay Area in de VS richtte het model zich vooral op stormvloed. Het liet zien dat het invloed van de gekozen strategie op het overstromingsrisico voornamelijk afhangt van de soort kustverdediging op de eilanden. Vooral de effectiviteit van natuurlijk oplossingen ('Nature-based Solutions') in Galveston Bay was sterk afhankelijk van de plaatsing en hoogte van kustverdedigingswerken.

In Beira, Mozambique, was het model uitgebreid met extreme regenval. Hier werden kustverdedigingswerken gecombineerd en vergeleken met andere maatregelen die zich vooral op regenval richten, zoals drainage, opslag, en waarschuwingssystemen. Het gebruik van de overstromingsrisico screening gaf inzicht in de effectiviteit van individuele maatregelen en hun samenwerking als onderdeel van strategieën, en prioriteert strategieën gebaseerd op vastgestelde doelen. Voor Beira gaf dit meer inzicht in de effectiviteit en de noodzaak van zowel de kustverdediging en de binnenlandse maatregelen, zoals het uitbreiden van het drainagesysteem. Voor de korte termijn - en voor toekomsten waarbij weinig klimaatverandering wordt verwacht – werden strategieën die zich vooral richtten op de regenval sterk geprioriteerd, aangezien dit de grootste aanjager is van het huidige overstromingsrisico. Echter, op een langere termijn – en voor toekomstscenario's met sterkere zeespiegelstijging en regenval – stegen de belastingen op het kustsysteem snel en is het effect van stormvloed op het overstromingsrisico veel duidelijker aanwezig, wat kustverdediging belangrijker maakt. In beide steden (Houston en Beira) kunnen deze inzichten worden gebruikt om beslissingen te ondersteunen omtrent het vinden van de meeste efficiënte strategie. Daarnaast leiden ze tot een beter begrip van het lokale overstromingsrisico en hoe dit beïnvloed wordt door maatregelen en scenario's.

Het eerste van de twee geïntroduceerde toepassingen richt zich op digitale hoogtemodellen. Deze zijn cruciale input voor elke vorm van overstromingsrisico-analyse. Recentelijk zijn meerdere (bijna)-wereldwijde, gratis digitale hoogtemodellen ontwikkeld op basis van satellietdata. Ondanks dat deze qua detailniveau nog niet precies genoeg zijn voor meer gebruikelijke simulatiesoftware, kunnen het een kosteneffectieve alternatieven zijn in de conceptuele fase, in combinatie met een screening model zoals FLORES. Dit proefschrift beschrijft de analyse van Beira – die oorspronkelijk is uitgevoerd gebaseerd op hoge-resolute LiDAR data – met drie gratis, wereldwijde hoogtemodellen (SRTM, ALOS World 3D, en TanDEM-X WorldDEM). De vergelijking laat zien dat alleen de TanDEM-X WorldDEM (90m) geschikt was, aangezien het de beste verticale resolutie had van de drie onderzochte hoogtemodellen. Vergelijking tussen de WorldDEM dataset en de LiDAR dataset laat merkbare verschillen zien qua overstromingsgebied, maar leidde uiteindelijk tot vergelijkbare resultaten in termen van effectiviteit van maatregelen en het prioriteren van strategieën.
De tweede nieuwe toepassing richt zich op het plannen van robuust overstromings-risicomanagement strategieën, en de potentie die screeningsmodellen daarin kunnen hebben. Het is aangetoond hoe overstromingsrisico-screening kan worden gebruikt om een dynamisch robuust overstromingsrisico-managementplan te ontwikkelen. In dit proefschrift is de Beira casus uitgebreid om de timing van investeringen en de levensduur van constructies mee te kunnen nemen. Hiernaast zijn ook robuustheidszones ontwikkeld voor individuele maatregelen. Dit zijn grafische weergaves van het bereik in omstandigheden – gekenmerkt door zeespiegelstijging, storm intensiteit en stedelijke ontwikkeling – waarvoor een maatregel nog effectief en geschikt is. Door middel van meerdere analyses, zoals feature scoring en robuustheidszones, is het mogelijk om de ontwikkeling van een dynamisch robuust overstromingsrisico-managementplan voor Beira te ondersteunen dat toepasbaar en houdbaar is onder veranderende toekomstige omstandigheden.

Overstromingsrisico-screening, en de modellen zoals FLORES die het mogelijk maken, heeft de potentie om vroege planning en ontwerpfases te ondersteunen, op een moment in het ontwerp waar snelle en eenvoudige overstromingsrisicoanalyse tot veel nuttige inzichten kan leiden. Deze eerste fases van het ontwerp zijn vaak gekenmerkt door grote onzekerheden, veel verschillende uitgangspunten, en een bijna oneindige hoeveelheid opties. Op een moment waar overstromingsrisicomanagement steeds complexer en meer integraal wordt, geldt dit ook voor de uitdagingen voor de overstromingsrisico-experts en ontwerpers. Vooruitgang, zoals de voortdurende ontwikkeling van screening modellen, zijn noodzakelijk om de efficiëntie en effectiviteit te blijven bieden die van ons verwacht wordt.

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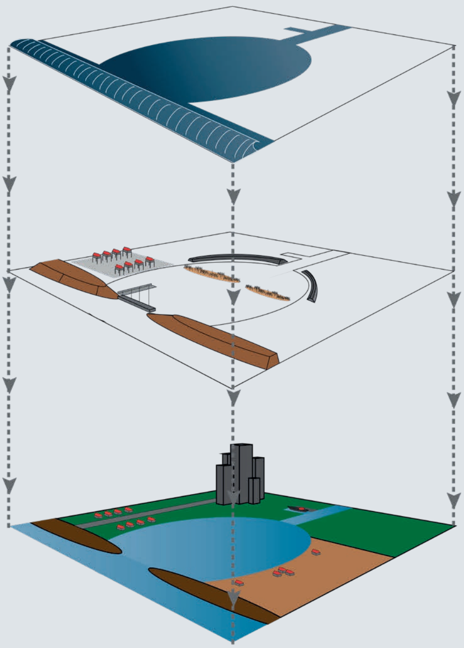


Chapter 1

Introduction

1.1 Background

In many places around the world, human activity has developed in areas vulnerable to flooding. Among natural hazards, floods are the most recurring, posing major threats to socioeconomic development and the safety of inhabitants (Fraser et al., 2016). Analysis, assessment and mitigation of floods is the field of flood risk management. To better understand the framework of flood risk management and what tools managers have at their disposal, we will take a closer look at flood risk itself.

There are several ways to define flood risk. This is the result of the wide variety of fields that touch on the problem of flooding, each requiring a different focus and different terms to make it fit within the existing vocabulary. Even so, all have found some general terms describing the interaction between a natural phenomenon (often called the flood hazard) and receptors (exposed property or people), connected through a pathway that might include other land or flood protection, and which may lead to consequences (e.g. damage, loss of life) (Samuels et al., 2009, Sayers et al., 2013). One form – mostly used in engineering – defines flood risk as the combination of the probability and the possible impact. For economic damage, this is often simplified to flood risk being the multiplication of probability x damage. For non-economic impact (e.g., loss of life, societal risk), this definition can be used as well, although in a slightly different setup. This idea of defining risk in terms of probability and consequence is very well-suited for developed areas, protected by flood defences, as it puts the main focus on the engineers ability to lower the probability of flooding, grouping all other options to alter flood risk under 'consequence' (Klijn et al., 2015). Important to note here is that the word 'multiplication' doesn't just mean that the flood risk is calculated by calculating the probability of a flood event and multiplying it with an estimate of its consequences, but rather the combination of these two terms across all possible events, as one event can never be representative for the whole situation (Kaplan and Garrick, 1981).

In a more extensive form, flood risk is a function of three factors: hazard, exposure, and vulnerability. Here, hazard is defined as the likelihood of a potentially destructive event, exposure as the assets – economic and human – that can be affected by the event, and vulnerability as the likelihood that, and to which extent, the assets will be damaged. This definition is popular with a wider variety of fields, also including other types of disaster risk management, because it enables us to easier describe measures that involve spatial planning, behavioural adjustments, or emergency measures. The interaction between the terms can easiest be visualized when we look at a single event. Here, a combination of a flood hazard, exposed value, and vulnerability to the flood hazard can lead to damage, which is called the flood impact. However, like

previous example, this single event is not representative for all situations, because it could be an extreme case. Therefore, the best way to manage the flood protection is to look at all possible events, taking into account the probability of occurrence of each of them. This package of all events and their underlying combination of hazard, exposure, and vulnerability, is called the flood risk (Simpson et al., 2014).
In the face of the current developments, where both human presence in flood-prone areas and the occurrence of extreme weather events are rapidly increasing, it may come as no surprise that the expected annual damage by flooding is increasing as well (Doocy et al., 2013, Mechler and Bouwer, 2015). This complicates the efforts of many large cities worldwide to manage the risk of flooding effectively.

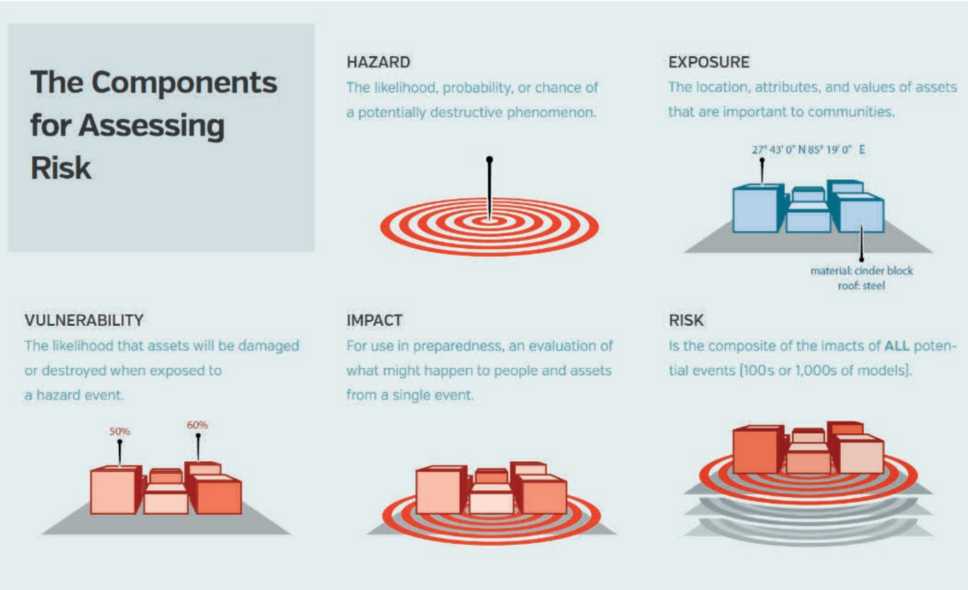


Figure 1-1: The components for assessing risk and the difference between impact and risk. Source: Crowley et al. (2014)

Flooding is usually the consequence of extreme rainfall, high river water levels, or coastal storm surges. In some cases, one event (e.g., a tropical typhoon) can cause multiple hazards. These compound flood events increase the vulnerability and complexity of the system, and have been occurring more often over the past decades (Wahl et al., 2015, Zscheischler et al., 2018). The impact of these hazards can be reduced by implementing measures, in the form of structural interventions such as levees and drainage canals or non-structural interventions such as the enhancement of evacuation routes or urban planning with flood risk in mind. Also, the city's vulnerability can be lowered through flood warning systems or floodproofing structures. Large, coastal cities often have several types of interacting infrastructures, complicating the efforts to develop an effective flood risk management plan. Because of the scale and complexity, individual measures can have negative effects on other parts or functions of the city. These require an overarching strategy, consisting of a range of different flood risk reduction measures, in order to reduce the flood risk to an acceptable level.

1.2
Designing flood risk reduction strategies under uncertainty

The process of finding the best flood risk reduction strategy usually starts off with gathering information on the situation, much of which is uncertain, for example on the flood hazards (e.g., what phenomenon is causing the flooding? what is its likelihood? How will this develop in the future?) or the local circumstances and views (What is the economic damage? Are we doing enough to limit flood risk? What types of measures are best suited for our situation?). In order to systematically deal with this uncertainty, the process of finding the optimal strategy runs through a number of increasingly detailed design loops, see Figure 1-2. Although sometimes not explicitly mentioned, this is common in almost all design practice(Voorendt, 2017). Each of these loops analyses the problems, proposes, and simulates a number of solutions, and uses the conclusions and feedback to select the most promising strategies. The overall goal here is to design the optimal strategy, which may also depend on other factors than just economic risk.
In this process, it is important to make choices at the right level, with the right level of information. Large-scale concepts can often be compared based on rough estimates and rule-of-thumb calculations. Detailed dimensioning and technical design are part of a later phase.

Making detailed designs at an early stage would be unnecessarily expensive and time-consuming, because this needs to be done for all proposed strategies to keep the

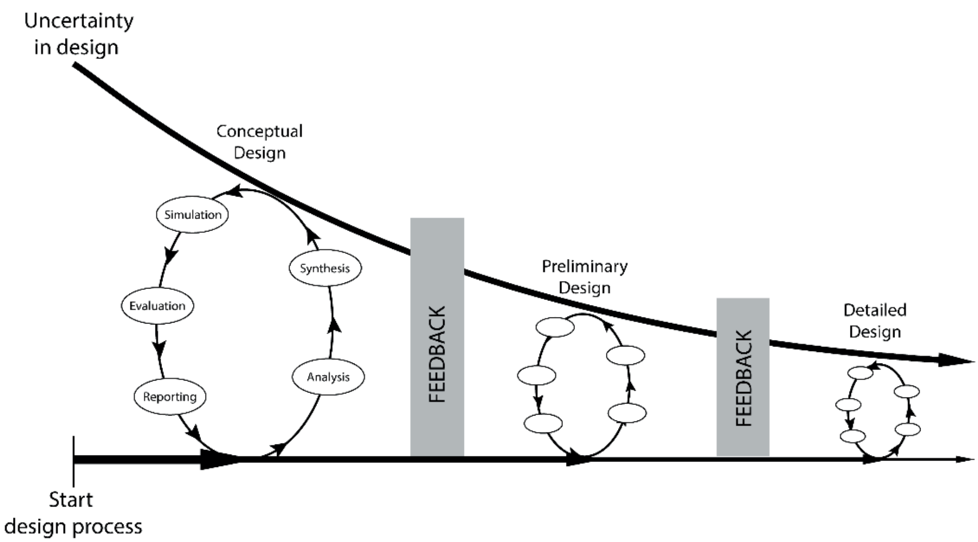


Figure 1-2: Designing with uncertainty and the role of flood risk screening

comparison unbiased. As a result, early choices, which are generally large in scale, are usually not made based on detailed information. On the other hand, detailed design choices will need much more precise data than was available in the conceptual phase. These more precise choices require models that run on more accurate data to provide better information to base these decisions on. In other words, as the level of detail goes up, so do the requirements in information (e.g., data, models) to make decisions. Looking at this design process, the conceptual phase is especially complicated, as planners have to make decisions based on limited data, knowing that large-scale decision may be hard to overturn later. This problem is extra challenging for coastal cities in developing countries. Generally speaking, these cities are less prepared, grow faster, and have less easily obtainable data to use. This leads to a more complex situation, while also time and money are more limited than in cities in developed countries.

1.3
Decision-making support tools

There is a wide variety of tools available to support decision making throughout this design process (Salman and Li, 2018). For more detailed design, computer models are frequently used (e.g., SWMM, MIKE, DELFT3D). Simulations of flood extent and damages are useful to compare flood risk reduction measures or to assess the feasibility of individual measures. Because the urban environment and the behaviour of the water are hard to simulate, most computer models focus on the later stage of design. At this point, more data is available and measures can be described in more detail. Therefore, the simulation can be run with much more accuracy. However, this high accuracy demands lots of input data and computational power. Also, these models are often not able to take non-economic consideration into account, which makes it harder to find the optimal strategy. These disadvantages make this type of computer models less suitable for use in an early design phase. The challenges here can be summarized in three parts:

- ***Evaluating many scenarios***; at the early moments of design, there are still many uncertainties and different possible choices. This complexity limits the evaluation of many different situations and scenarios, due to time constraints.
- ***Understanding the results of risk assessment;*** more than just looking for the simulation that minimizes flooding, the goal is to understand the underlying drivers and governing parameters of the flood risk. This requires sensitivity and uncertainty analysis, which puts an additional strain on computational power.
- ***Optimizing the risk management portfolio;*** finding the optimal flood risk management strategy requires evaluating many different types of measures, which also interact. Optimizing these strategies requires insight into parameters other than just the flood extent or economic damage, such as societal or environmental impact. These insights are impossible to obtain with models solely focused on flood simulation.

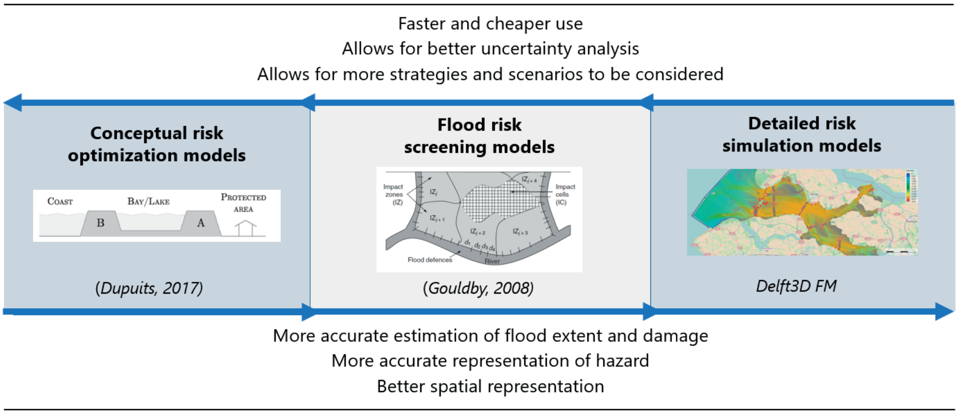


Figure 1-3: Model concepts used in flood risk management

Because of these challenges, there are also other approaches, which focus less on case-specific data and more on the comparison of concepts, see Figure 1-3. These conceptual risk optimization models are often analytical and aim to teach stakeholders about the importance of one hydraulic process, influence or parameter (Vrijling et al., 1998, Kind, 2014, Dupuits et al., 2017b). Although this can be helpful in understanding the underlying processes of flood risk and how these are influenced by flood risk management decisions, these conceptual models lack the spatial information and accuracy needed for detailed decision support.
Therefore, several models have been developed in recent years that aim to find the middle ground between these types of models, indicated here as "flood risk screening models" (Lhomme et al., 2008, Jamali et al., 2018, de Ruig et al., 2019). These models use numerical modelling, similar to more detailed flood simulation models, but generally simplify the schematization of the project area. This leads to fast and cheap simulations, which in turn allow us to include and explore many more options, processes and unknowns. Naturally, also the model accuracy is affected. The aim of such models should therefore be to balance simple and fast simulation with a model accuracy sufficient to support decision-making in the early phases of design. It should be sufficiently accurate to substantiate a choice of one strategy over the other. For example, to invest in coastal protection over enlarging parts of the drainage system. Hence these models are called flood risk screening models.

This type of model is not commonly used as decision-support tool. The general way of conducting this early part of design already zeroes in on a few strategies, chosen based on expert knowledge. Subsequently, the impact of these strategies on the flood risk is calculated using detailed flood simulation software, even though the level of detail of the input data often does not align with the claimed accuracy in the flood simulation. This leaves much room for improvement, as some of the most impactful decisions need to be made early on in the design process, when input information is still very limited.

1.4 Knowledge gaps

In this dissertation, we will explore the characteristics and challenges of flood risk screening and develop an improved modelling approach. Through the development of such a model, and its application in real-life case studies, multiple knowledge gaps will be addressed:

1. There is a **lack of generally applicable flood risk screening approaches.** Although several models have been developed with rapid simulation in mind, these are generally focusing on one case study, a specific spatial layout, and take one flood hazard into account. They are therefore hard to adjust to other situations. Building a framework that is specifically meant to be easily adjustable to any situation can help future modelling in flood risk management.
2. Also, no models yet exist that can **rapidly model cities that are threatened by compound flooding** (e.g., a storm that causes both storm surge and extreme rainfall). These require much more simulations to build a clear profile of the flood risk. There is a need to investigate rapid flood risk screening to better understand the risk as a result of compound flooding.
3. Furthermore, in many situations only v**ery limited data is available** for schematization of the city, the exposed value and people, or the incoming flood hazard. This is especially the case for cities in developing countries, where records on population, buildings, and historic hydrological events are often incomplete. There is a growing library of global open data available, based mostly on satellite measurements and imagery, but up to very recently the resolution of this data was much too rough for use in local flood risk management. A recent jump in quality of global open data sources (e.g., DEMs with ~30m resolution globally) can mean a lot for its applicability, especially in flood risk screening models, which don't focus on highly detailed simulations. The applicability of these relatively new data sources has not been explored in this context yet.
4. Finally, there is an opportunity to implement some of the many **new approaches for policy analyses under uncertainty**, which have been developed in recent years. Many of these approaches specifically focus on robust decision making (Walker et al., 2013), which focusses on developing strategies that are effective over across all different futures. This is especially interesting in flood risk management, where often structural measures with a very long-term effect, are implemented based on incomplete information. These detailed policy analysis tools often require many simulations and are therefore not compatible with regular high-resolution flood simulation of a limited number of scenarios. There is a need to investigate the options to use these types of policy analyses in the context of flood risk management.

1.5
Research objective and approach

The points listed in the knowledge gaps show a common theme, where there is an opportunity to use screening methods in flood risk management that is being wasted due to a lack of information, examples and clear goals. Therefore, the aim of this dissertation is:

> ***To develop new and generically applicable methods for flood risk screening, and to demonstrate their use to support decision-making in the early phases of planning and design of risk reduction strategies.***

The following questions have been formulated to further focus the research process towards answering the main needs in this field:

i. What are the main characteristics of an effective flood risk screening model?

ii. How can the parameters of compound flood events be modelled both rapidly and accurately enough for use in flood risk screening?

iii. How can free global DEMs be used within flood risk management and flood risk screening in particular?

iv. How can the rapid flood risk screening approaches be used to facilitate more advanced policy analysis techniques, such as robust decision-making?

These questions will be the focal points of our research around the development of a flood risk screening model: the Flood Risk Reduction Evaluation and Screening (FLORES) model. This model is designed as a fast and widely applicable tool. The development of the FLORES model is used to demonstrate the viability of flood risk screening as a whole. By implementing the model on increasingly complex case studies, we learn about the requirements that stakeholders set for such models, and what type of information can be provided. Throughout this process, the experiences with the model will be used to support the ongoing discussions on the topics mentioned in the knowledge gaps. The goal is to provide a model that can be useful for all types of stakeholders, while still being well-grounded in scientific literature. As such, the FLORES model will be part of real-life discussions surrounding the flood safety of vulnerable cities.

1.6
Study regions

In this dissertation, the use of flood risk screening will be demonstrated in two regions: the Houston-Galveston Bay Area in the United States and the city of Beira in Mozambique. These case studies were chosen in coordination with local partners, who also contributed to the research directly and indirectly (e.g., providing data and contacts, discussing strategies). The regions represent two fairly different situations, but both face extreme flood hazards in the form of tropical cyclones . Here, both areas will be shortly introduced.

1.6.1 Houston-Galveston Bay Area

The area surrounding the Galveston Bay, in the eastern part of Texas, is both one of the most populated and flood-prone areas in the United States. The region is characterized by the large contrast in land use for both sides of the bay. The eastern side is mainly occupied by marshlands and wildlife reserves, while the western side is highly populated, with several million-people. Three other notable locations are the low-lying barrier islands, Galveston Island and Bolivar Peninsula, as well as the Port of Houston. The Port of Houston is one of the most important petrochemical ports in the world.

Figure 1-4: Overview of the Galveston Bay Area

The region is prone to both coastal flooding and extreme rainfall. The impact of coastal flooding was clearly shown in 2008, when Hurricane Ike swept through the bay and caused over 30 billion US Dollars of damage and claiming more than a hundred lives. In 2017, Hurricane Harvey hit the region again, this time hovering over Houston for several days, causing unprecedented amounts of rainfall and widespread flooding. After Hurricane Ike hit in 2008, several institutions started investigations into protecting the region from coastal flooding. The situation was especially complicated because of the size of the region and the interaction between the Gulf of Mexico and the Galveston Bay. Flooding could clearly not be mitigated through one type of measure. Flood protection at the entrance of the bay could still leave port and city of Houston vulnerable to flooding due to wind set-up, and protection near the city would leave the rest of the bay unprotected. Hurricane Harvey showed that not only coastal protection is necessary, but also inland measures that control rainfall in urban areas. The analysis of the Houston-Galveston Bay Area in this dissertation mostly took place before Hurricane Harvey and as part of studies on coastal protection, and it is therefore mostly focused on coastal flooding. This case study is used in Chapter 2.

1.6.2 Beira

The city of Beira is one of the largest cities of Mozambique, with roughly 600,000 inhabitants. It is located at the coast of the Indian Ocean and the mouth of the river Pungwe and houses the most important harbour of the country. This harbour is also used by a vast hinterland, including a main highway to Zimbabwe. The first settlements were located on the higher elevated parts of the city on the dunes near the coast, and further inland. In between lies a lower-elevated area, where water hardly drains and is therefore less suited for housing. To combat the health risk of living near this otherwise swampy area, and to use this area for farming, a drainage system was built during the time of Portuguese colonial rule, in which the city grew as a harbour city and tourist destination.

Figure 1-5: Overview of Beira

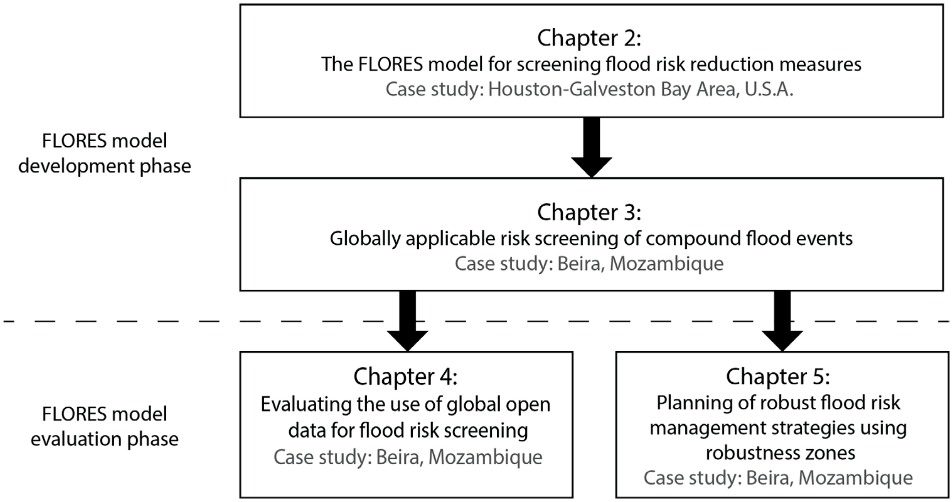
However, after the independence of Mozambique and the civil war, the local economy and infrastructure was severely damaged. As the population grew, more people started living in flood-prone areas of the city. Most notably the areas surrounding the still recognizable but overgrown drainage system. Decades of poor maintenance have also taken their toll on the coastal defences. The sandy dunes are eroding due to the slow degrading of the groynes, while the yearly storm season is also taking its toll on the floodwall protecting the main road along the coast. As a result of the poor flood management and a harsh climate of heavy rainfall and yearly cyclones, the city of Beira has been in a constant state of recovery. Apart from the almost yearly flooding due to extreme rainfall, two notable events caused major damage to the city. First of all, the 2000 Mozambique flood, and more recently Tropical Cyclone Idai in 2019. The latter made landfall very close to Beira, damaging almost 90% of all buildings in the city, before continuing further into Mozambique affecting 1.85 million people and causing roughly 700 million US Dollars as the worst natural disaster in southern Africa in the past decades (IOM, 2019).

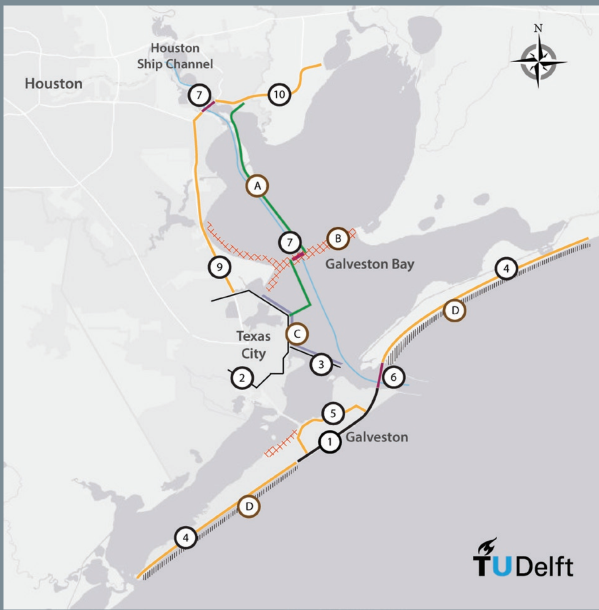
Several organizations are trying to manage and lower the flood risk in the region, namely the local government, water board, and the national disasters management institute (INGC). With international support, they managed to implement several structural and non-structural measures. For example, a flood early warning system was built and implemented, as well was a detailed mapping of shelters and evacuation routes. On the structural side, several water management structures were built, most notably a rehabilitation of a part of the old drainage system. Although many measures are already implemented, it is clear that much more is needed, especially considering the growing population, industrial activity, and the probability of extreme events due to climate change. This case study has many of the characteristics that we specifically focused on when formulating the knowledge gaps and the research questions: Beira is threatened by compound flooding, and the lack of data forces us to use global open data. Therefore, this case study is widely covered in this dissertation and the subject of chapters 3, 4, and 5.

1.7 Thesis outline

This dissertation describes the structure and development of the FLORES model through the case studies mentioned above. The case studies have been chosen based on current questions concerning the flood risk in the cities. Please note that the model itself also evolves in terms of complexity throughout the course of the case studies. Especially Chapter 2 and 3 can be seen as a model development phase, whereas Chapter 4 and 5 are part of the evaluation phase. In these last two chapters, no fundamental changes were made to the model. Because some parts of the model might change throughout the research, each chapter will mainly discuss the key features added in the relevant study. Chapters 2 through 5 mainly focus on each of the knowledge gaps and the accompanying research questions.

Chapter 2 describes the main rationale and structure of flood risk screening, focusing on its potential role within the current process of designing and choosing flood risk reduction strategies. As a generally applicable example of a flood risk screening model, FLORES is described. At this point, the FLORES model is solely developed to show the effects of storm surge, concentrating on the case study in the Houston-Galveston Bay area. Chapter 2 also presents the main model framework, which serves as the backbone of FLORES, even though some of the general features will be updated and extended in later versions.
Addressing the general applicability of the FLORES model, Chapter 3 introduces some basic rules to apply the model to any city or region. The schematization of the urban environment is extended to allow for this variety in urban layouts. Simultaneously, schematizations of other flood hazards, such as extreme rainfall, are added, along with the option to combine both hazards in a compound flood event. The application of the FLORES model is shown through a case study based on the city of Beira.
Following the previous chapters, which presented the main framework and components of FLORES, Chapter 4 focuses on the impact of using free global DEMs for flood risk screening, and especially the added uncertainty that stems from the use of sparse data. Flood risk screening models are meant to be useful at a moment in design where input data availability and resolution is limited. The topography, often shown in the form of a DEM, is at the heart of the simulation. This chapter therefore focusses on how free global DEMs can be used in a flood risk screening model.
In Chapter 5, the FLORES model is expanded to explore the potential of flood risk screening in the context of developing robust flood risk management plans. For this application, the model is adjusted to allow for different investment strategies throughout the lifetime of a flood risk reduction strategy. This chapter introduces an approach for developing dynamically robust flood risk management plans, including a new form of visualising robustness in the form of robustness zones.





Chapter 2

The FLORES model for screening flood risk reduction measures

The content of this chapter has been published in:

Van Berchum, E. C., Mobley, W., Jonkman, S. N., Timmermans, J. S., Kwakkel, J. H., & Brody, S. D. (2018). ***Evaluation of flood risk reduction strategies through combinations of interventions.*** *Journal of Flood Risk Management, e12506.*

In the early stage of developing an effective flood risk reduction strategy, computer models can help to identify promising measures and compare different options. This chapter introduces the Flood Risk Reduction Evaluation and Screening (FLORES) model as a widely applicable example of how decision making in the conceptual phase can be supported by computer models. This chapter focusses on the main rationale and framework of FLORES, which is the backbone of the model and guides many of the choices made throughout the model's development process, as described in this dissertation.
The application is shown in a case study in the Houston-Galveston Bay Area in the United States. Here, FLORES was used to inform local decision makers the importance of coastal protection for reducing risk in the entire region, as well as their effect on other (nature-based) measures in the Galveston Bay itself. For this case study, the model is only developed to calculate the effects of coastal storm surge and the interaction with the bay.

2.1 Introduction

2.1.1 Background

A storm surge can heavily affect a coastal region, causing both direct and indirect damage to people, structures, and the environment. The impact of storm surges can be reduced by implementing flood risk reduction measures, in the form of structural interventions like levees and storm surge barriers, or non-structural measures such as wetlands and oyster reefs. However, coastal zones that combine multiple coastal morphologies, like dunes, barriers islands, bays and estuaries, often require a combination of flood risk reduction measures, which complicates the search for the best strategy.
For flood protection systems purely consisting of structural elements, several studies have used probabilistic risk analysis to elaborate on the interdependence – how one measure affects the performance of the other - between structures (Tsimopoulou, 2015, De Bruijn et al., 2014, Courage et al., 2013). These studies have shown that a flood risk reduction measure can strongly influence the effectiveness of other elements of the flood defence system. This is true for both defences placed adjacent, protecting the same area (resembling a series system, which is as strong as the weakest link), and for defences placed in multiple lines of defence, like a parallel system. This interdependency amongst measures complicates the assessment of the risk reducing abilities of the overall flood protection system. Besides flood defence structures, non-structural measures like flood risk zoning and flood proofing of local structures can also contribute significantly to reduce flood risk (Aerts et al., 2014, Dawson et al., 2011, Kreibich et al., 2005). Additionally, Nature-based Solutions can be considered, which provide both risk reduction and ecological value. It is important to take into account these different interventions (and their combinations) in the development of flood risk reduction strategies for flood-prone areas. A key question is which combination of

these interventions is the most effective.

2.1.2 Literature and knowledge gaps

Although the optimization of risk reduction provided by single structures has been investigated extensively in the past (Eijgenraam et al., 2014, Kind, 2011, Tung, 2005), only specific combinations of two interventions (levees, hard structures, natural foreshores) have been analysed by hand (Courage et al., 2013, Vuik et al., 2016). Common techniques for mathematical optimization (i.e., mixed integer or dynamic programming) fail for these cases, as the flood defences cannot be viewed separately. Therefore, studies on this subject often assume total independence (Kind, 2014) or focus on small-scale decisions and processes, making it harder to represent complex systems (Dupuits et al., 2017c).
The use of multiple lines of flood defence in flood management strategy was introduced under various names (Tsimopoulou, 2015). Examples are 'hierarchical flood protection system' (Custer, 2015) or 'multiple lines of defence strategy' (Lopez, 2009), among others. Lopez (2009) focussed on the inclusion of both structural and non-structural measures, but offers a qualitative model, where results are harder to reproduce or compare. Instead, Custer (2015) used hierarchical probabilistic modelling to quantify the impact of multiple structure in a parallel system. Although this does result in quantitative risk analysis, flood risk management is often part of a broader context - i.e., inclusion of non-structural measures - which cannot be captured with this method.
Risk analysis on the scale of regional floodplain systems has been described in earlier research (Moser, 1996, Woodward et al., 2013, Gouldby et al., 2008, Aerts et al., 2014). Similar to this chapter, Woodward et al. (2013) attempted to combine simplified hydraulic modelling with common optimization techniques for comparison of flood management strategies. Although they managed to gain satisfactory results for systems with multiple defences placed in a series system, their approach is not applicable to systems with multiple lines of defence. Current approaches do not capture the complexity of implementing and combining different interventions and their effects on risk and other dimensions. To address these shortcomings, this chapter presents an approach combining quantitative risk assessment of interdependent structural and non-structural interventions (e.g., Nature-based Solutions, spatial planning, and disaster management) with multi-layer flood protection.

2.1.3 Objectives and scope

Decision making in flood risk management would greatly benefit from a clearer understanding of the effects of a portfolio of interventions on flood risk throughout a coastal region. However, probabilistic flood risk assessment for combinations of flood defence structures can be computationally intensive and time consuming. This chapter presents the Flood Risk Reduction Evaluation and Screening (FLORES-model) as a viable model for the evaluation of coastal defence strategies. FLORES is a fast risk-based model that simulates and evaluates the impact of many alternative flood risk

reduction strategies, each consisting of a combination of measures. The computation time is significantly reduced, as basic (hydraulic) formulas are used for the flood and damage simulation, which allows for many strategies to be compared.
The main characteristics of the model include the ability to (1) consider both structural and non-structural measures, (2) allow for economic and non-economic performance indicators and (3) have a generic setup, which is easily adapted to other flood-prone regions around the world. In this chapter, the model will be demonstrated with a conceptual and simplified case study in the Houston-Galveston Bay area in Texas.
The main purpose of the model is to support decision making in the early phases of design. Especially when large, complex flood-prone regions are concerned, many planning decisions are required in these early design stages, while only limited information is available. This method therefore focusses on the simulation and evaluation during initial screening or the conceptual design phase. The assessment of flood risk reduction strategies is based on a multiple-objective approach.
The economic assessment compares the construction costs of a combination of interventions with its ability to reduce flood risk. Here, risk is defined as a combination of scenarios, each of which has a probability of occurrence and a potential negative consequence (Kaplan and Garrick, 1981). The consequence includes damage to the region itself as well as damage to the flood protection structures. Besides the economic assessment, the flood risk reduction strategies will also be evaluated separately based on non-economic impact criteria such as environmental impact. These impacts will be ranked using simplified indicators. The model evaluates the flood risk reduction measures, which allows the model to compare strategies in terms of costs, risk reduction and other impacts.

2.2 Methods

2.2.1 Structure of the FLORES model

2.2.1.1 General

The 'Flood Risk Reduction Evaluation and Screening' (FLORES)-model can simulate and evaluate the impact of numerous flood risk reduction strategies in a large, complex region. FLORES is implemented in Python and consists of two parts: The Simulation Model and the Evaluation Model (Figure 2-1).

The Simulation Model combines three layers of information for its simulation: data on the spatial layout of the region, the flood risk reduction strategy (which is a chosen combination of interventions) and the incoming storm (represented as hydraulic boundary conditions). This is shown in Figure 2-2 (left).

In the simulation model, the study area itself is schematized as a combination of lines of defence and protected areas (see Figure 2-2, right). The lines of defence are the locations where structural flood defences can be placed to retain water. Here,

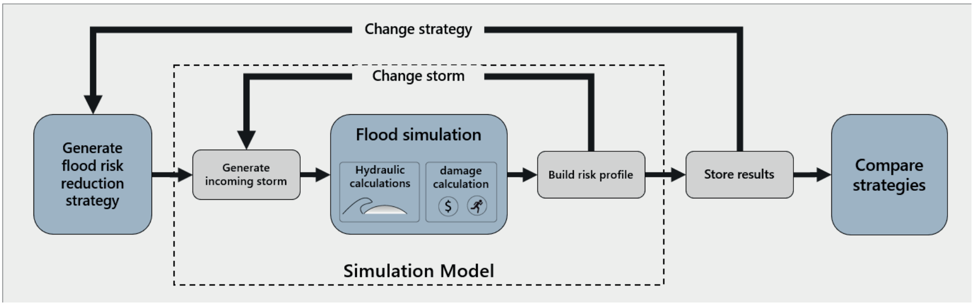
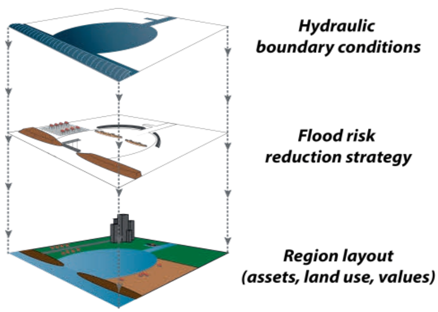


Figure 2-1: Methodology flowchart of the Flood Risk Reduction Evaluation and Screening (FLORES)-model. Calculations of the Simulation Model are repeated for different storm intensities, after which the results are combined to build a Risk Curve of that particular strategy. This information is stored for later analysis and comparison in the Evaluation Model.

calculations on failure probability, construction cost and discharge are made. The protected areas consist of basins between lines of defence, for which water levels and damages are calculated. In the schematization of Figure 2-2, defence A1 (land barrier) and A2 (storm surge barrier) are located adjacent. Damage to one will hardly change the load on the other. Barriers A and B are in different lines of defence. Damage to the barriers A1 or A2 will greatly affect the loads on B1 and B2. The flood risk can be grossly underestimated when this effect is not considered.

The simulation model includes two types of calculations: the hydraulic calculations and the damage calculations. The hydraulic calculations result in inundation levels across the region, which the damage calculation uses to calculate the amount of damage caused by the flood. To speed up the calculations, important characteristics of the measures and the region are determined beforehand. For example, the strength of a flood protection structure is defined by a fragility curve, which is a graphical



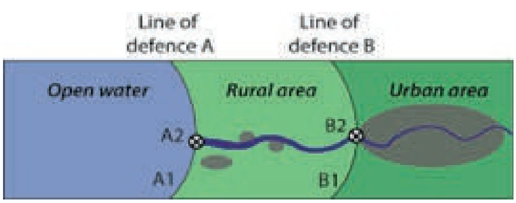


Figure 2-2: (left) Three layers of information as used in the model. (right) Schematization of a coastal region with multiple lines of defence. The rural areas are protected with Line of defence A. the urban area, where the largest potential damages are, is protected by lines of defence A and B.

representation of how the failure probability of a structure depends on its main load (USACE, 1996). Likewise, the inflicted damage in the affected basins is linked to the local water level in the form of a damage curve, which will be derived based on local damage estimates and land use data.
The Evaluation Model uses the simulations to compare numerous different strategies. First, it repeats the simulation for different storm intensities to build a 'risk curve' (Figure 2-3). This shows the potential inflicted damage for an event and the probability of that event. By comparing this risk curve with the risk curve of the initial local situation, the risk reduction can be computed.

Subsequently, this risk curve is built for numerous strategies. This is possible because of the short computation time (i.e., 10 seconds on a consumer machine for a single storm). The number of different strategies required to sufficiently explore the design space depends on the regional complexity and the number of potential measures. The resulting data is stored and used for further analysis and evaluation.
Currently, the model is presented for present conditions i.e., for a static situation. In future versions, the lifetime of measures (e.g., degradation) and potential future scenarios (e.g., SLR and subsidence, economic growth) will be included as factors. Using the current model, the effect of future changes can be assessed by means of a sensitivity analysis.

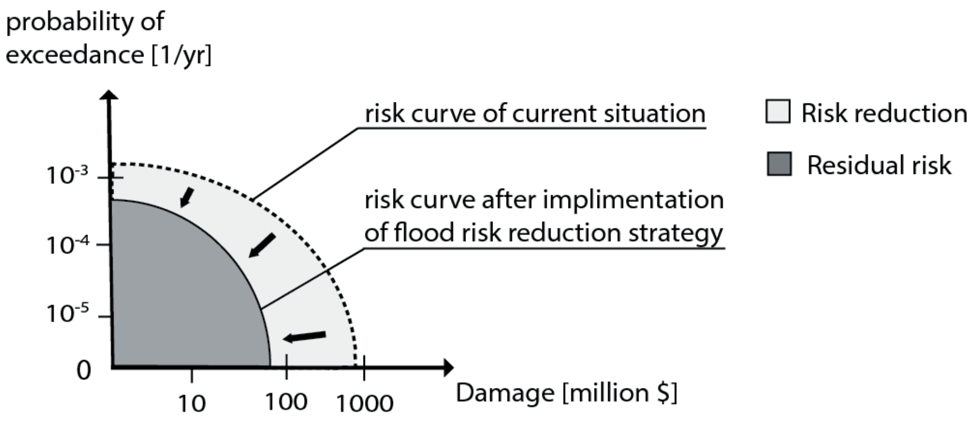


Figure 2-3: An often-used version of the risk curve is the Frequency-Damage Curve. This shows the probability of exceedance of damage. The dashed line represents the risk curve in the current situation (without additional risk reducing interventions). Implementing flood risk reduction measures aims to lower the probability of experiencing damage or to lower the amount of damage resulting from a flood. As a result, the curve shifts towards the lower-left and the total risk decreases.

2.2.1.2 Schematization

As the flood progresses into the project area, it encounters lines of defence and protected areas, one by one (Figure 2-4). When the flood encounters a line of defence, FLORES calculates the failure probability and the discharge into the next area. The protected areas in between are divided into several basins, based on watersheds. Here, the water levels in the basins and the hydraulic conditions going forward are calculated. The expected impact of one storm depends on whether the implemented flood risk reduction interventions will hold or fail. Given a few flood risk reduction measures, scenario outcomes can differ significantly within the same strategy. This is considered by simulating all scenarios.

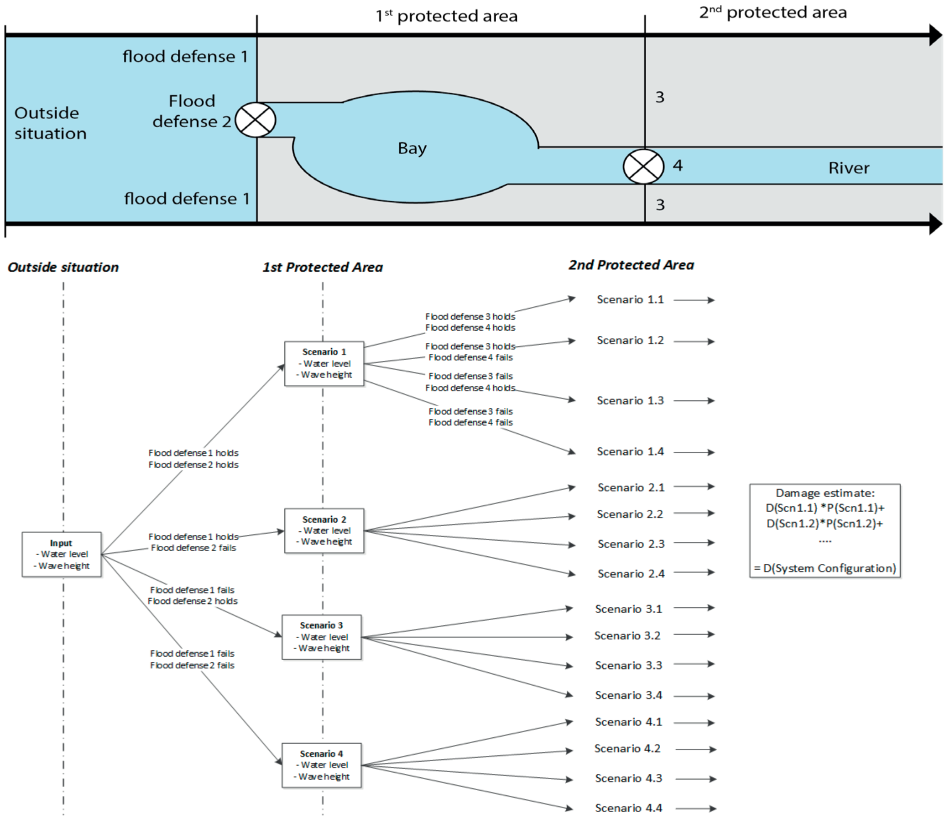


Figure 2-4
schematization of how different outcome scenarios are taken into account. In the example region (up), there are two lines of defence with each two flood defence types. The chart (down) shows how the expected value of damage can be calculated from the different possible outcome scenarios.

Figure 2-4 shows a schematized example, where each line of defence consists of two flood defences, each of which can fail or hold. This system can lead to 16 potential scenario outcomes. After the simulation, the expected values of damage for each scenario are weighted according to their probability and summed to result in the expected damage for that flood risk reduction strategy for one storm.

2.2.1.3 Flood risk reduction measures

A flood risk reduction strategy consists of a combination of potential measures. It is a choice between several locations, effects and (if applicable) barrier heights. The location and effect varies based on the type of measure. Therefore, they are divided into four different categories as shown in Table 2-1.

Table 2-1: Categories of flood risk reduction measure types. This list is purely an indication of the type of measures that can be considered with the FLORES-model.

Measure Type	Examples	Location	Has an effect on
Flood defences	Levee Storm surge barrier	Between hazard and vunerable area	Flow into vulnerable area
Nature-based Solutions	Wetlands Oyster reefs	Outer side of flood defence	Wave height
Damage restricting measures	Slab elevation Flood-proof buildings	Vulnerable areas	Damage curve Vulnerable property value
Changes in policy	Zoning Evacuation	Vulnerable areas	Vulnerable property value Damage curve

The effect of flood risk reduction measures differs between structural and non-structural measures. Structural measures are mostly protective measures such as barriers and levees and reduce the likelihood of flooding. Non-structural measures could affect the risk in several ways. Measures like Nature-based Solutions are often not sufficiently effective by themselves. Economic benefit and safety provided by these measures are hard to quantify, while they often offer co-benefits like ecological value or a better living-environment (Vuik et al., 2016). These type of measures are mostly used to reduce waves for damage reduction (Mazda et al., 2006) or to reduce wave impact on nearby flood defences as a part of a hybrid solution (Vuik et al., 2016). Non-structural measures can thus also be incorporated by modelling their effect on different components of risk.

2.2.2 Simulation Model

2.2.2.1 Hydraulic calculations

The simulation of the storm revolves around the water flow through the region. The storm surge encounters either a line of defence or a protected area. The hydraulic calculations consist of three relations that are used throughout: Within the lines of defence, the model calculates the failure probabilities of the flood protection structures and the discharge flow into the next layer. Within the protected areas, water levels in the basins are calculated. The Appendix shows pseudo-code for how these choices are made within the model. It also shows the common hydraulic formulas used in the model.

The failure probability is calculated by comparing the incoming storm surge water level with the fragility curve of the flood defence structure. A fragility curve is a graphical representation of the conditional probability distribution (Van der Meer et al., 2009, Schultz et al., 2010). It represents the strength of the structure by showing how the probability of failure depends on one type of loading (see Figure 2-5). To limit the model's computation time, the strength related calculations for the fragility curve are performed beforehand. Without additional knowledge of the structure, a fragility curve can be used in the form of a cumulative normal distribution. Because a fragility curve only takes one load into account, other loads (e.g., waves) must be included when the fragility curve is made. In this model, additional loading will affect the μ and σ in equation 1.

$$Pf = F(h|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{h} e^{\frac{-(h-\mu)^2}{2\sigma^2}} dz \qquad [1]$$

where:

Pf = failure probability [-]

h = water level [m]

μ = mean value. Based on flood defence type and incoming wave height [m+MSL]

σ = standard deviation. Based on flood defence type and incoming wave height [m]

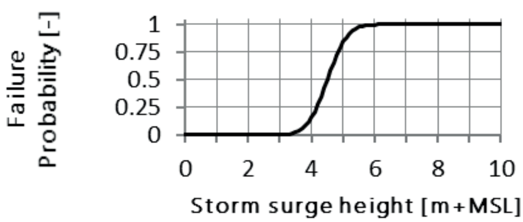
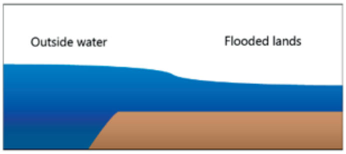
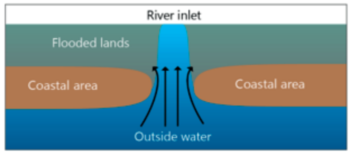
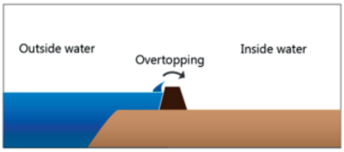
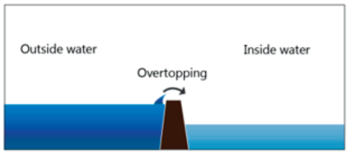
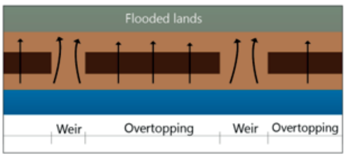
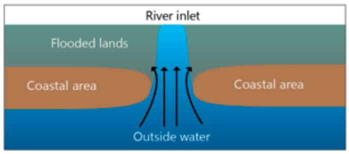
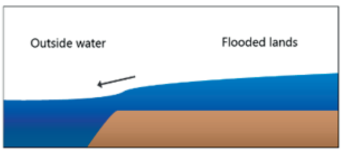
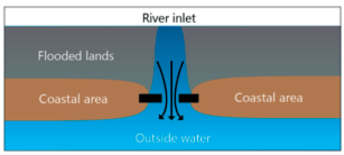


Figure 2-5: example of a fragility curve for a levee at 4 m +MSL.

Surge flow to the next layer is calculated using simple hydraulic relations. In this model, there are three forms of flow: Overtopping/Overflow, Broad Weir and Open channel flow, calculated with formulas from EurOtop (2016), Brunner (1995) and Stoeten (2013), respectively. Table 2-2 shows which situations are possible and how they are considered. The water level on the inside of the line of defence changes based on the discharge.

Table 2-2: Schematizations for all different hydraulic situations at a line of defence and the used formulas.

	Land barrier	Storm surge barrier
No defence present	Broad Weir 	Open channel flow 
Defence present	Overtopping 	Overtopping 
Defence fails	Partly overtopping / partly broad weir 	Open channel 
High inside water levels	Broad weir /overtopping 	Backflow 

In the model, the storm surge is represented by a time series. For every time step, the inside water level can be found with

$$h_p(i+1) = h_p(i) + \frac{Q(i) \cdot \Delta t}{A_p(i)}, \quad [2]$$

where,

h_p (i),h_p (i+1) = Water level in area protected by the line of defence at time step i, i+1 [m]
Q(i) = Sum of all discharges across the flood protection [m^3]
Δt = length of the time step in seconds [s]
A_p (i) = Surface area protected by the line of defence [m^2]

The maximum water levels in the watershed basins can be found by focussing on the Protected Areas between the lines of defence. The discharge calculated at the line of defence fills the area, leading to a time series of the water level at the inside. Here, the maximum water levels in all basins are calculated, taking wind set-up into account (see Figure 2-6). In earlier research on the Galveston Bay, this method showed to be effective in predicting water levels resulting from past storms (Stoeten, 2013, Dupuits et al., 2017a). The wind set-up peaks in the direction of the wind. The area is divided into eight wind directions. The primary wind direction is included as a time series. With the centre of the inundated area as reference point, using the deviation of every basin from the main wind direction, the water level in each basin is calculated:

$$h_b = h_p + S \cdot C_b \quad [3]$$

where:

h_b = maximum water level in the watershed basin [m+MSL]
h_p = maximum average water level in the protected area [m+MSL]

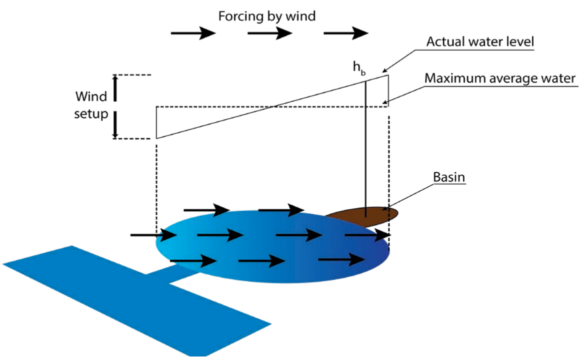


Figure 2-6: Schematization of how the wind set-up and the maximum basin water level are related. Forcing from the wind pushes the water to a new actual water level. The model calculates for each watershed basin the relative location and the maximum basin water level (hb in the figure). A further explanation is provided in the Appendix.

S = wind set-up [m]
C_b = wind direction factor (between-0.5 and 0.5) [-]

This calculation also plays a role in the transition to the next layer. Hydraulic conditions at the following line of defence depend on its relative position to the protected area. For example, wind set-up will lead to different water levels for flood defences placed in different wind directions as seen from the source of the flood. The surge at this next line of defence is built by scaling the time series of the water level in the protected area. The maximum significant wave height is highly influenced by local conditions and therefore hard to predict. For conceptual design, a generally used rule-of thumb is to assume the significant wave height to be half of the water depth (Molenaar and Voorendt, 2018).

2.2.2.2 Damage calculations

Damages are calculated by finding the inundation level, as a function of the difference between the maximum water level and the land elevation. To increase accuracy, every basin is divided into height contours, which consists of several land use types (see Figure 2-7). Flood height(h_f) is inserted in the damage curve to find the portion of property damaged for one land use type. This is divided in damage to the structure and damage to the content. This is summed for every land use type {1,2,..,u} to find the damage for one contour (D_T). In turn, this is summed across all contours {1,2,..,n} , all watersheds {1,2,..,m} and weighted for the probability of each outcome scenario {1,2,..,s} to result in the expected damage for one flood risk reduction strategy(D_s):

$$D_s = \sum_{l=1}^{s}\left[\sum_{k=1}^{m}\left(\sum_{j=1}^{n}\sum_{i=1}^{u} D_{T,ijkl}\right)\cdot P_{s,l}\right] \quad [4]$$

$$D_{T,ijkl} = V_{st,ijkl}\cdot p_{st,ijkl}(h_{f,j}) + V_{ct,ijkl}\cdot p_{ct,ijkl}(h_{f,j}) \quad [5]$$

$$h_{f,j} = h_{b,kl} - h_{cr,j} \quad [6]$$

Where:
D_s = expected damage for one flood risk reduction strategy [$]
D_T = expected damage for one land use type [$]
P_s = Probability of outcome scenario [-]
V_{st}, V_{ct} = aggregate value of one land use type in terms of structures and content, respectively [$]
p_{st} (h_f), p_{ct} (h_f) = estimated portion of value damaged of structures and content, respectively [-]
h_f = flood inundation in contour[m]
h_b = maximum water level in watershed [m+MSL]
h_{cr} = elevation of contour [m+MSL]

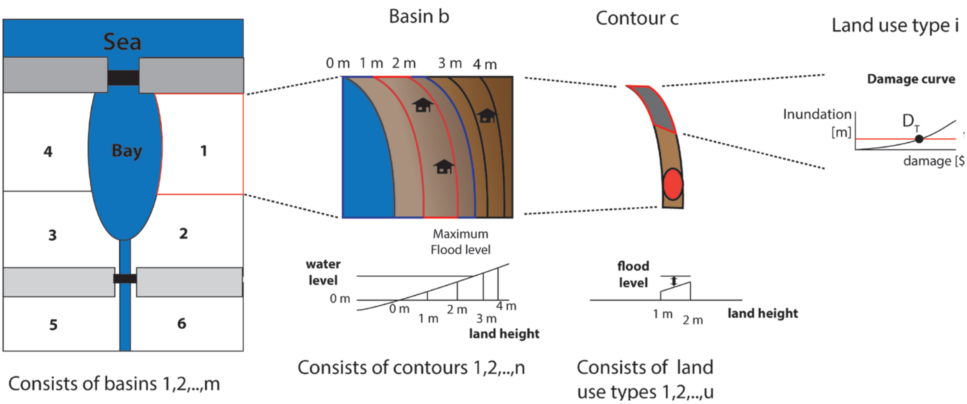


Figure 2-7: Process of calculating damages for a given flood level. Every basin is divided into height contours. Subtracting the elevation from the water level gives the maximum inundation. This is input for the damage curves, which estimates damage for one land use.

2.2.2.3 Construction and repair cost calculation

Construction and repair cost are important performance metrics to compare strategies. For every simulation, the construction cost of the measures is estimated, based on local research or reference projects. The cost of construction depends on the type of measure and its length (which is assumed constant). For some measures, height can also be adjusted. This creates additional costs, which are considered as 'variable costs'. Repair cost of a flood risk reduction measure is included as a percentage of the construction cost and is only added in situations where that measure fails.

2.2.2.4 Environmental score schematization

Large scale coastal interventions can have a significant impact on the environment. For example, the construction of dams in the Netherlands has changed part of the environment in these estuaries (Smits et al., 2006). On the other hand, Nature-based interventions, like nourishments and wetland recreation, may even improve environmental conditions. It is therefore important to include an assessment of these impacts in decision-making. However, no uniformly accepted method is available to evaluate environmental impacts of coastal interventions, leading to previous studies struggling to quantify environmental impact (Kind, 2014, Lopez, 2009). To illustrate how environmental impacts can be included, an environmental score is included to compare between strategies. The score takes two processes into account:

- Structural measures negatively impact their direct surroundings. This impact increases with construction height, as a higher structure will have a relatively higher impact on natural habitats.
- Inundation of ecologically important areas. Flooding in the watersheds that house nature reserves causes damage and should be avoided. Higher water levels in

these watersheds result in a more negative environmental score.
The inclusion of an environmental score allows for comparison between strategies. It is emphasized that this score is highly simplified, not verified and is included to illustrate how environmental factors can be included. A verified approach can be added in later research, which will benefit the broader applicability of the model.

2.2.3 Evaluation Model

The FLORES-model allows us to discover how the risk profile of the region reacts to different flood risk reduction strategies and identify interesting trade-offs. These analyses are done with the use of the 'Exploratory Modelling and Analysis (EMA)-workbench' (Kwakkel, 2017a, Kwakkel, 2017b). It has been used for a variety of research topics in the past (Halim et al., 2016, Kwakkel and Cunningham, 2016, Kwakkel and Jaxa-Rozen, 2016). In this context, it generates potential flood risk reduction strategies, which are then evaluated using the FLORES model. By systematically sampling potential strategies spanning the entire design space, we can investigate and quantify the impact of design choices.
The EMA-workbench includes a variety of analysis and optimization tools. Currently, the used techniques are Feature Scoring, Pair Wise Plotting, and Scenario Discovery (Bryant and Lempert, 2010, Kwakkel and Jaxa-Rozen, 2016). Feature Scoring is a form of sensitivity analysis which ranks the input parameters based on their impact on the output parameters. Pairwise plotting visualizes the relation between different output parameters. Scenario discovery is a relatively recent approach for identifying subspaces within the model input space that have a high concentration of results that are of interest. The dominant machine learning algorithm for Scenario Discovery is the Patent Rule Induction Method (PRIM, see Friedman and Fisher (1999)). This analysis finds input ranges which meet a set of performance thresholds, which can be defined by the modeller. With these three analysis techniques, it is possible to explore the design-space and investigate the impact of design choices.

2.3 Case study: the Houston-Galveston Bay Area

2.3.1 Introduction

The Houston-Galveston Bay is prone to a variety of water-related hazards. It is characterized by large variety in land use. The eastern side is mainly occupied by marshlands, while the western side is highly populated with several million inhabitants. Three other notable locations are the low-lying barrier islands, Galveston Island and Bolivar Peninsula; and the Port of Houston. The Port of Houston is one of the most important petrochemical ports in the world.
In 2008, Hurricane Ike caused an estimated 30 billion USD in damage, mostly due to coastal storm surge. Moreover, studies have shown that the damage could have been several times higher, should the hurricane have kept its original course 50 kilometres south (Bedient and Blackburn, 2012, GCCPRD, 2015). In that case, the hurricane would

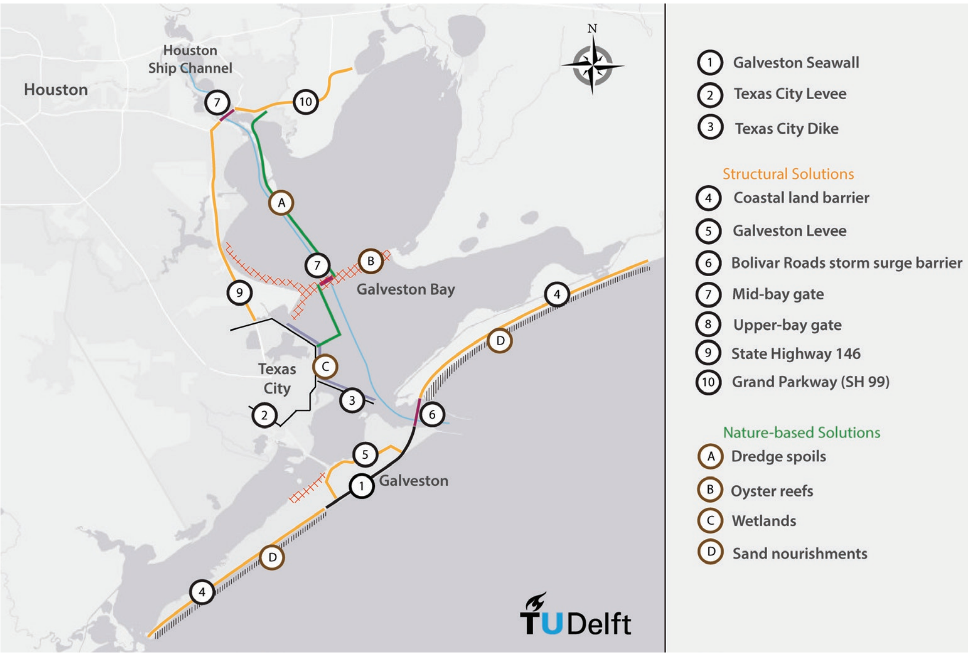


Figure 2-8: Overview of the Houston-Galveston Bay Area. Denoted in the figure are two existing defence structures (black) and the Houston Ship Channel (blue). Also listed are potential flood risk reduction measures.

have directly hit Houston and the Port of Houston, which would result in an even more devastating disaster.

The FLORES-model compares different strategies for reducing flood risk in the Houston-Galveston Bay area. These strategies consist of combinations of measures shown in Figure 2-8. Here, the coastal flood protection measures are schematized as the first potential line of defence. The second line of defence is assumed to separate the urban areas of Houston and Texas City from the Galveston Bay. All measures shown are included in the model; although some are combined because of simplifications in the model (see Table 2-3).

2.3.2 Model conceptualization

2.3.2.1 Region layout

The layout of the region is based on several spatial datasets, which were used for two primary functions: quantifying losses of a given storm, and estimating additional surface area flooded during each time-step of the hydraulic model. The region is divided into watershed basins, according to the Hydrologic Unit Code (HUC) 10 scale. Each of these watersheds is divided into height contours of 0.3048 meters, according to a Digital Elevation Model (DEM), which has a 10-m spatial resolution (see Figure 2-9). Both the HUC-10 and the DEM are based on data from the US Geological Survey (Bassler, 2018). The damages are calculated by combining the land use data with

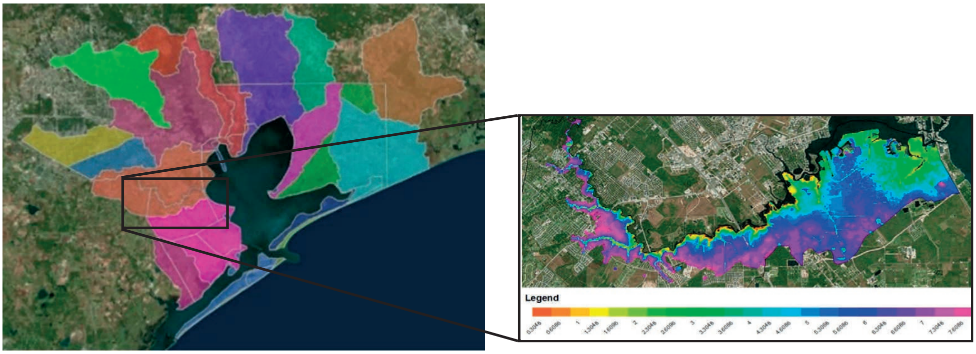


Figure 2-9: Exposed watersheds in the Houston-Galveston Bay, divided according to the HUC-10 classification. The right figure shows how a watershed is subdivided into contours of 0.31 meter (1 foot).

Table 2-3: Cost estimates for measures used in the FLORES-model for the Houston-Galveston Bay case study.

Location	Barrier type	Constant unit costs	Variable unit costs	References*
Galveston Island & Bolivar Peninsula	Levee** Seawall Sand nourishments^	7 M$/km 12 M$/km 100 M$	3 M$/km/m 4 M$/km/m -	[1],[2] [1],[2]
Bolivar Roads	Storm surge barrier**	3,500 M$	250 M$/m	[1],[3],[4],[5]
Northwest corner Galveston Bay (SH99 & SH146)	Levee Seawall	7 M$/km 12 M$/km	3 M$/km/m 4 M$/km/m	[1],[2] [1],[2]
Upper bay river inlet	Storm surge gate***	400 M$	50 M$/m (height)	[1],[3],[4],[5]
Galveston, bay side	Levee	300 M$	-	[3]
Galveston Bay	Dredge spoils^	15 M$/km	4 M$/km/m	[3]
West Galveston Bay	Oyster reefs^	12 M$	-	[6]
Texas City Levee	Wetlands^	10 M$	-	[6]

Note: Cost estimates in reference literature can vary and often not divides between constant and variable costs.

* used references: [1] (Jonkman et al., 2015), [2] (van Berchum et al., 2016), [3](Bedient et al., 2016), [4] (GCCPRD, 2016), [5] (Mooyaart and Jonkman, 2017), [6] (Kroeger, 2012)
**A levee on Galveston Island and Bolivar Peninsula combined with a storm surge barrier at Bolivar Roads is called the Ike Dike (Coastal Spine), a strategy proposed by Texas A&M University Galveston.
*** Combination of using dredge spoils and an in-bay storm surge barrier creates the Mid Bay barrier. In this case, the storm surge gate will not be place at the river inlet, but in the middle of the bay.
^ Nature-based Solutions: can be separately added to any strategy. Connecting dredge spoils inside the bay and building oyster reefs can mitigate wave impact on the (north-) western part of the Galveston Bay shore. Wetlands can be placed in front of the Texas City Levee to mitigate wave impact. Sand nourishments can mitigate wave impact and erosion at the coast. The cost of sand nourishments is roughly based on reference projects and can only be implemented along the entire barrier island.

damage curves. Type and value of structures on a parcel level are based on data from HCAD (2017). The damage curves are derived from FEMA (2010).
Little research has been done on the environmental impact of floods and flood risk reduction measures in the Houston-Galveston Bay. Therefore, this assessment is done on a qualitative basis with an 'environmental score' (see section 2.2.4), where a lower score signals a more negative influence on the local ecology. There are several parts of the region where nature reserves are present and where flooding would negatively impact nature and wildlife (Figure 2-10).

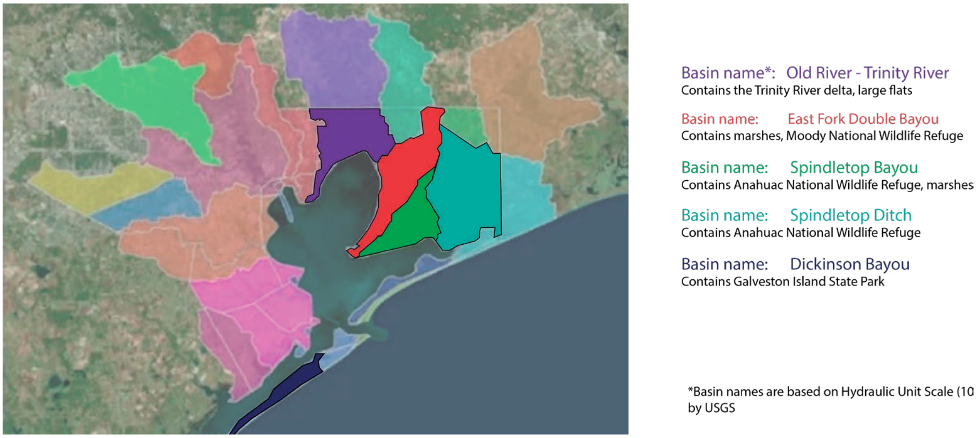


Figure 2-10: Map of the Houston-Galveston Bay area with the environmentally important watersheds highlighted. The basins are divided according to the HUC-10 classification.

2.3.2.2 Flood Risk reduction strategies

Table 2-3 lists the flood risk reduction measures as they are used in the FLORES-model. They are mostly based on reports focussing on the Houston-Galveston Bay area. From the categories mentioned in Table 2-1, only flood defences and Nature-based Solutions are used. Each measure has been mentioned in earlier research to be useful for reducing flood risk. The FLORES model will create strategies by randomly combining measures and varying their heights (if applicable).

2.3.2.3 Hydraulic boundary conditions

The hydraulic boundary conditions are based on incoming storms. The storm enters the model as a time series of water level and wave height at the Gulf of Mexico, as well as a time series of wind velocity and wind direction in the bay (see Table 2-4). The storm characteristics (i.e. storm track, hydrograph) are based on observations and characteristics of historical hurricanes, analysed by Sebastian et al. (2014) and Ebersole et al. (2017). Because all storms are hurricanes in this case, the wind direction in the bay depends greatly on the hurricane track. In all simulations, a path in north-western direction is chosen, with landfall near the western tip of Galveston Island. This is generally noted as the most destructive hurricane path (Bedient et al., 2015, Sebastian et al., 2014).

Table 2-4: Hydraulic boundary conditions used in the FLORES-model, based on research by Almarshed (2015). Also shown are the hydraulic boundary conditions used in the verification step (Hurricane Ike and Storm 36), based on research by Ebersole et al. (2017)

Return Period	Water level	Wave height	Wind Speed
10 years	1.3 m+MSL	5.0 m	25 m/s
50 years	3.7 m+MSL	6.2 m	30 m/s
100 years	4.7 m+MSL	6.8 m	40 m/s
300 years	6.0 m+MSL	7.4 m	43 m/s
500 years	7.1 m+MSL	7.8 m	45 m/s
Hurricane Ike	3.9 m+MSL	6.0 m	50 m/s
Storm 36	6.1 m+MSL	4.9 m	58 m/s

Other paths could lead to worse conditions locally, but because this path heavily affects (the port of) Houston, it is presumed leading for flood risk in the region.
The event frequencies - hydraulic conditions for different return periods - used in the Evaluation Model are based on analysis by Almarshed (2015), which includes extreme value analysis on FEMA datasets. Two additional sets of hydraulic boundary conditions are used, purely for verification. These are based on analyses conducted by Jackson State University (Ebersole et al., 2017) and simulate the conditions during Hurricane Ike and 'Storm 36', which is a synthetically generated worst-case scenario. Both events have been modelled by Ebersole et al. (2017), providing flood maps for verification. For the simulation of Hurricane Ike, historical data on the hurricane track is used instead of the hurricane track mentioned above.

2.3.3 Simulation Model validation

The Simulation Model consists of hydraulic calculations and the damage calculations (See Figure 2-1). Therefore, the validation will compare these steps with the more

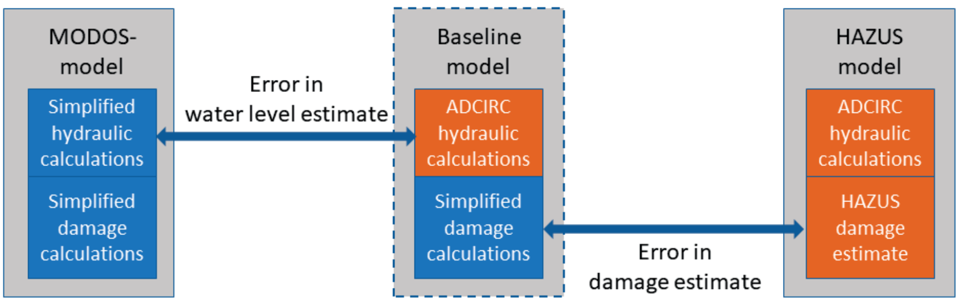


Figure 2-11: Validation methodology. Because both the hydraulic calculations and the damage estimates are simplified, an extra step (Baseline model) is added. By comparing FLORES to Baseline, the error in water levels can be assessed. Subsequently, the comparison between Baseline and HAZUS will show the error in damage estimate.

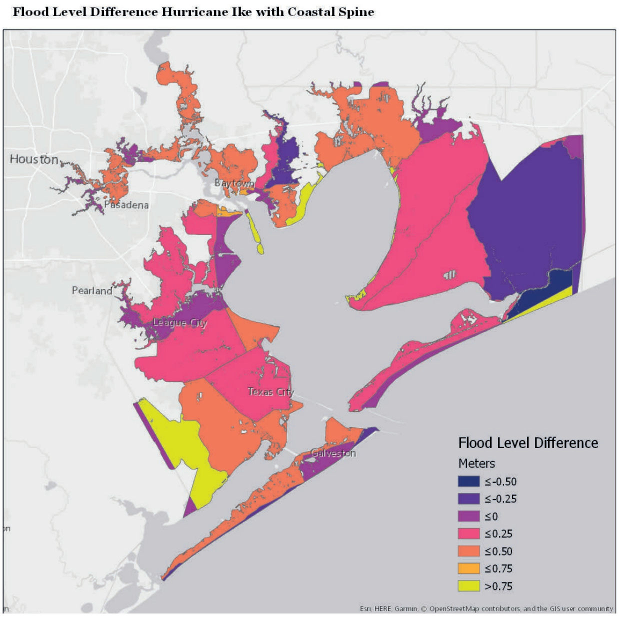


Figure 2-12: Comparing inundation extent between FLORES-model and ADCIRC-model. Modelled is the situation where Hurricane Ike would hit the region, given that the 'Coastal Spine'-strategy is implemented. The Coastal Spine is a locally proposed combination of intervention mostly focussing on coastal protection.

advanced, federally accepted models ADCIRC and HAZUS. ADCIRC is a model that allows for interactions between waves and circulation, which allows the model to predict storm surge. The ADCIRC model has been used to accurately hindcast Hurricane Ike (Hope et al., 2013). HAZUS is a multi-hazard impact model, which can estimate the human, property, and financial impacts (FEMA, 2010). The HAZUS model benchmark was assessed previously (Atoba et al., 2018). Because damage estimates of HAZUS also depend on water levels derived from ADCIRC, it is not possible to directly validate with damage estimates by FLORES. Therefore, a Baseline model is

Table 2-5: Validation of four situations (two storms, two configurations). Shown is the average percent error of flood water levels in watersheds, compared to ADCIRC results. Also listed is the difference in total cost estimate, where the HAZUS estimates are compared with the estimates of the FLORES Baseline Model.

Situation	Average error in basin water levels [%]	Error in damage estimate [%]
Storm 36, current protection	-4.8%	-49%
Storm 36 with Costal Spine	-11.4%	-25%
Hurricane Ike, current protection	-12.0%	-57%
Hurricane Ike with Coastal Spine	+15.8%	+30%

introduced (Figure 2-11), in which water levels from ADCIRC (By Ebersole et al. (2015)) are combined with damage curves and property value data from FLORES. When compared with actual HAZUS results, this shows the accuracy of FLORES damage calculations.

The flood water level and estimated damage was calculated for each watershed. This was done for the two storms – Hurricane Ike and Storm 36 – and two flood protection configurations: current situation and Coastal Spine. Figure 2-12 shows the verification of water levels in the watersheds, which shows how well different parts are represented.

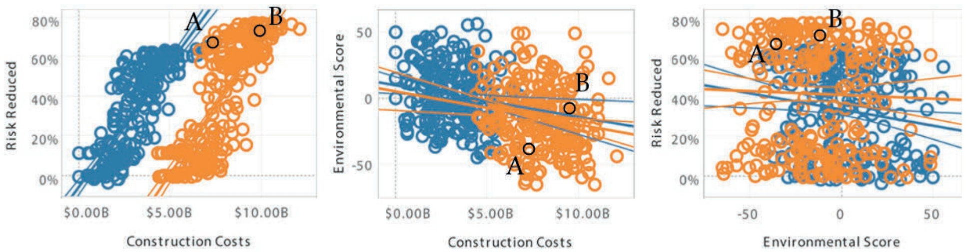
The validation (Table 2-5) shows a good fit for the hydraulic model (<20% error) compared to ADCIRC results, where the main differences are caused by local hydraulic processes and no systematic bias is expected. The difference in estimated damage can be the result of a difference in modelling or a difference in property inventory. HAZUS provides a better industrial and commercial inventory, which was not available for this study (FEMA, 2016). Residential losses are significantly overestimated when the flood levels are low. An issue that may explain these errors is the limited accounting of elevated structures. At these storm intensities, coastal flood protection can limit the flood level down to the point where an elevated house can make a significant difference (Jongman et al., 2012).Because elevated houses have not been taken into account, the damage for limited water levels is overestimated in comparison to actual flood events. However, this effect is equally present across all simulations and should be accounted for when formulating recommendations.

Because of the significant lack of property inventory and accurate damage curves available for the FLORES-model, most damage estimates are underestimating the impact of flooding. Nonetheless, because the estimates are consistent between simulations, it does allow for analyses in comparison to each other. Therefore, the risk reduction will not be quantified in dollars, but in the strategy's ability to reduce risk compared to the null-scenario (expressed in percentages). The damage calculations in FLORES have also been simplified to reduce computation time. Better accuracy can be achieved by decreasing the contour resolution, which is at 0.31 m (1 foot), or by increasing the amount of land use types taken into account.

2.3.4 Evaluation of flood risk reduction strategies

In order to thoroughly explore the full design space, numerous strategies have to be considered. However, this also increases the computation time. Given the number of measures, 500 different strategies were deemed sufficient. With this number, most combinations of measures will be represented with several different levee heights. Construction costs are determined using Table 2-3 and the environmental score is calculated using a formula listed in the Appendix. Three output parameters were chosen: Risk reduction, construction cost and environmental score.

When the risk reduction is compared with the construction cost (Figure 2-14), there are clearly two different trends, based on the placement of a storm surge barrier at Bolivar



Strategy A: Coastal levee (5.9 m); Bolivar Roads Barrier (3.1 m); Inner bay levee (2.4 m); Sand nourishments at the coast
Strategy B: Coastal floodwall (7.9 m); Bolivar Roads Barrier (5.1 m); river inlet gate (4.9 m); Oyster reefs in the bay; Wetlands near Texas City

Figure 2-13: Pair Wise Plot for the FLORES-model for the Houston-Galveston Bay area. Blue indicates strategies with the Bolivar Barrier implemented, while orange indicates no barrier in the inlet. Two trend lines can be distinguished when comparing construction costs with risk reduction. Also, Environmental impact has a low correlation with both construction costs and risk reduction. Two strategies, denoted by A and B, are marked across the plots.

Roads. This gate only results in higher risk reduction when the total construction costs are relatively high. If no coastal barrier is built on Galveston Island or Bolivar Peninsula, or when either is not strong enough to withstand extreme storms, significant damage will still occur around the Galveston Bay. The storm surge barrier at Bolivar Roads will only be effective when combined with large investments in other defences.

Taking a closer look at the individual strategies, two strategies that seek to optimize risk reduction are highlighted in Figure 2-14. Both include strong coastal defences, but the main difference is revealed inside the bay. Strategy A includes a relatively low levee along the north-western edges of the bay, while strategy B includes a gate in the river, oyster reefs in the bay and wetlands to lower wave attack. The use of Nature-based Solutions and limiting damage to nature reserves clearly has a positive effect on the environmental score of strategy B. The small difference in risk reduction also shows how dominant the coastal defences are in risk reduction. Similar comparisons show that the impact of inner-bay defences greatly depends on the placement of coastal defences. Without coastal defences, the high water levels in the bay combined with wind set-up will quickly overpower inner-bay defences, greatly reducing their effectiveness.Environmental impact is hardly correlated with the two other output parameters (see Figure 2-14). This is due to the Nature-based Solutions. These measures have a large effect on environmental impact, but are relatively cheap and have a small effect on risk reduction. They can therefore be implemented within every strategy, lifting the environmental score, while hardly affecting the cost and risk reduction of the total strategy.

The data can also be analysed using Random Forest Feature Scoring (Figure 2-13, based on Breiman (2001) and Pedregosa et al. (2011)). A higher number implies a higher impact of the measure (left) on the output parameter (down). The values are mainly useful in comparison to each other and enable the measures to be ranked. For

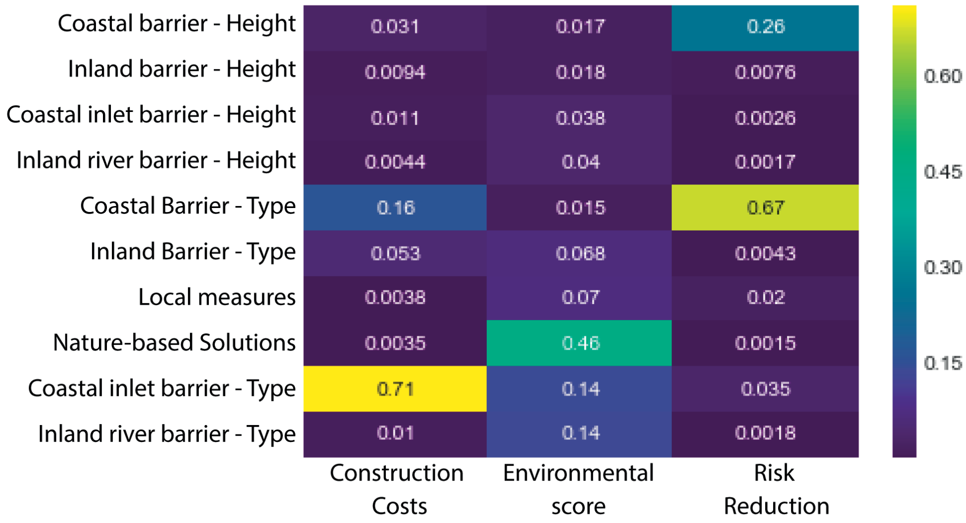


Figure 2-14: Feature Scoring table for the FLORES-model for the Houston-Galveston Bay area. Higher numbers imply higher impacts. For example, the most important factors that drive risk reduction are the type of coastal barrier, the height of the coastal barrier and the type of coastal inlet barrier. The number indicates its relative importance.

example, risk reduction is primarily impacted by the choice for the coastal barrier on Galveston Island and Bolivar Peninsula. In agreement with what was presented above, Nature-based Solutions greatly impact the environmental score, but have almost no impact on the construction costs or risk reduction.

Figure 2-15 is an example of a PRIM-analysis, which can find strategies that comply with specific demands. For example, we can search for a combination of low construction costs (< 5 billion USD) with high risk reduction (> 75%). The results show the importance of the coastal barrier on land. Moreover, it shows that the costs of storm surge barriers are too high in this case to find a system that includes the storm

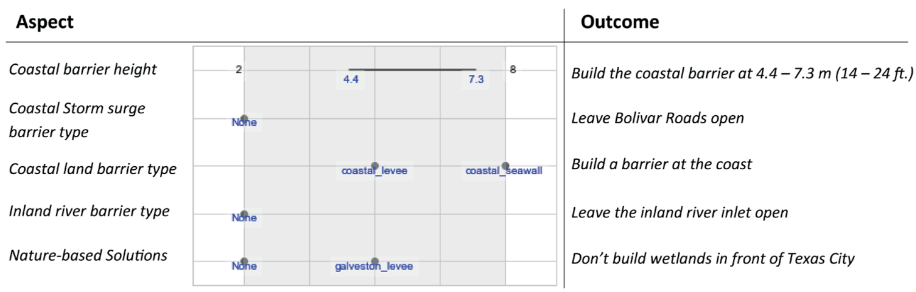


Figure 2-15: Result of PRIM analysis for 500 randomly sampled flood risk reduction strategies in the Houston-Galveston Bay area. The system is focussed on finding strategies that offer relatively high risk reduction (more than 75%), while keeping the construction costs below 5 billion USD.

surge barrier and still meets the thresholds, even though the impact on risk reduction is second highest (See Figure 2-13).
Because of the computational time of the simulation and the possibility of comparing a large number of flood risk reduction strategies, it is possible to discover how the risk profile in the region changes for different design choices, stakeholder preferences and other developments. These insights can support the decision-making process early on, when impactful decisions are required based on limited information, and lead to a better optimized strategy for reducing flood risk in the Houston-Galveston Bay area.

2.4 Discussion

The model presented in this chapter is built for use during initial exploration of flood risk reduction strategies and has been optimized to be fast and broadly applicable. Therefore, there are several limitations that should be considered. First, the verification showed a good fit for the hydraulic model to more advanced ADCIRC models (< 20% error for water levels). Damage estimates had a higher uncertainty (<50% error for damages around the bay), mostly due to the higher uncertainty in damage curves and lack of commercial data. Although the errors in damage estimates are relatively high, the errors are relatively consistent across strategies and storms, which allows for the strategies to be compared on their flood risk reducing abilities. Some types of measures (e.g., Nature-based Solutions) still have a large uncertainty in their effect on the system (Vuik et al., 2016). The current assessment of environmental impact in the form of a score needs further development to be as reliable as the other parameters. Other measures like buyouts, changes in (insurance) policy, and raising houses have not been evaluated yet.
Second, because the region is divided into lines of defence, it is hard to accurately include measures that work on a much smaller scale. This problem can be addressed by including more lines of defence. However, adding more lines of defence will exponentially increase the amount of possible outcome scenarios and therefore the computation time. This trade-off should be dealt with separately for every case study. The current runtime is about 10 seconds for one simulation and 7 hours for the entire evaluation on a single computer (500 strategies with 5 storm simulations each).
The FLORES-model allows inclusion of several other features that have not been shown in this chapter. The simulation only considered coastal storm surge, because of its destructive nature. However, most coastal regions like the Houston-Galveston Bay also suffer from inland flooding from rain or river runoff. In the future, the hydraulic module of FLORES can be extended to incorporate these types of events.
The connection with the EMA-workbench allows for the exploration of different future scenarios in terms of climate change or future land use. This can be used to find a robust design, able to provide sufficient safety in an uncertain future. Eventually, multiple-objective optimization techniques can also be used to identify the Pareto approximate set of optimal strategies. Here, the modeler can choose to include additional output variables, with practically no extra computational load. Finally, the model is specifically built to be applicable in different regions in the world, which can

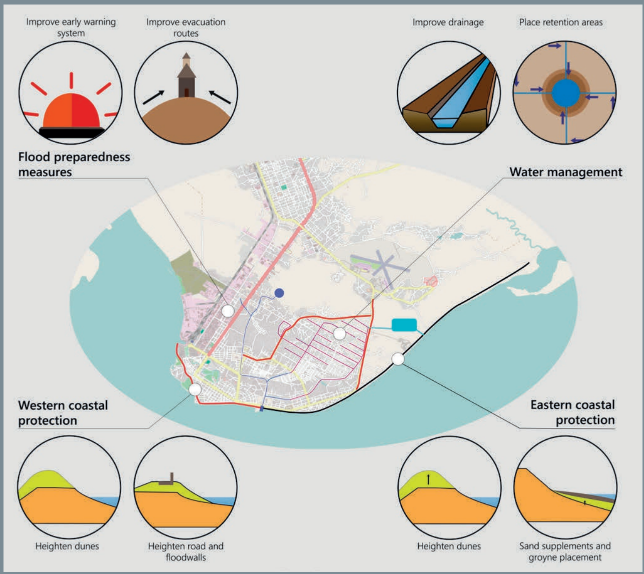
be established through additional case studies. Especially regions with large variation in land use and topography, where many flood risk reduction measures are possible, the model can provide valuable insights to the design discussion.

2.5 Conclusion

This chapter presents the Flood Risk Reduction Evaluation and Screening (FLORES)-model and shows its application and potential for the Houston-Galveston Bay area. The FLORES-model can (1) simulate the effects of a flood risk reduction strategy on a complex, flood-prone region and (2) evaluate the results of different strategies, consisting of multiple interventions, based on economic and non-economic performance indicators. With the FLORES model, it is possible to probabilistically assess the impact of both structural and non-structural measures on flood risk reduction. These interventions can range from levees and storm surge barriers to Nature-based Solutions like wetlands and oyster reefs. By using simplified hydraulics, the model is kept computationally workable, which allows for many different strategies to be compared. The model setup is kept generic, which enables the model to be transferred to other locations relatively easily.

A simplified case study based on the Houston-Galveston Bay Area in Texas was used to demonstrate the model. First runs showed that the flood risk reducing capabilities of the chosen strategy mainly depend on the choice of coastal land barrier, because most strategies that seek to maximize both risk reduction and cost efficiency included either a coastal levee or floodwall. Also, Nature-based Solutions are shown to have a small impact on the construction costs and the risk reduction of the total flood risk reduction system. However, they are expected to have a clear, but local positive effect on environmental impact of the constructed system.

The use of the EMA-workbench in the Evaluation Model enables the modeller to include analysis of uncertainties in design, and future scenarios like future land use scenarios or climate scenarios. This is not included in this research. The FLORES model is designed to support decision making during design discussions. Especially during the conceptual design phase, when design choices are impactful and information is scarce, it can provide valuable insights and save time and resources in identifying promising strategies for reducing risks for vulnerable flood-prone areas.



Chapter 3

Globally applicable flood risk screening for compound flood events

The content of this chapter has been published in:

Van Berchum, E. C., van Ledden, M., Timmermans, J. S., Kwakkel, J. H., & Jonkman, S. N. (2020). **Rapid flood risk screening model for compound flood events in Beira, Mozambique.** *Natural Hazards and Earth System Sciences Discussions, 1-18.*

As described in the previous chapter, the main idea of FLORES is to run rapid flood simulations for many different storms, flood risk reduction strategies, and future scenarios. This requires a computationally light flood simulation, built from basic hydraulic formulas. In the past, these types of models were built for a specific area and hazard. This chapter presents the main features of the FLORES flood simulation, which is built to serve a wide range of applications and be generically applicable, while minimizing the computational load.
The application is shown in a case study in Beira, Mozambique. This coastal city is threatened by coastal storm surge, as well as extreme rainfall. Many features of the flood simulation are updated to include the combined effects of these hazards, while keeping in mind the goals and framework described in Chapter 2.

3.1 Introduction

3.1.1 Background

Coastal cities are under increasing pressure of flood events. Currently, floods are the most recurring and damaging type of natural hazard, posing major threats to socio-economic development and safety of inhabitants (Fraser et al., 2016). Both social-economic activity and extreme weather events are increasing rapidly, and even though cities in many cases are becoming less vulnerable due to effective flood risk management, flood risk is growing in many flood-prone regions around the world (Doocy et al., 2013, Mechler and Bouwer, 2015, Salman and Li, 2018). The main processes leading to urban flooding are extreme rainfall (pluvial flooding), high river discharge (fluvial flooding), and storm surges (coastal flooding). For coastal cities, these flood hazards interact and can be correlated. Individual meteorological events, like hurricanes, can simultaneously cause extreme rainfall and high storm surges. These compound events further increase both the vulnerability and the complexity of flood risk management in coastal cities. Research on compound flooding is growing, as it plays an important role in flood risk management of cities along coasts and rivers, and the occurrence of compound floods is growing significantly (Wahl et al., 2015, Zscheischler et al., 2018, Paprotny et al., 2018).
The impact of flooding can be reduced through measures that improve the city's hydraulic ability to deal with the flood hazard – the probability of a flood event -, or reduce the damage caused by a flood event. Managing flood risk is often the role of local governments. The planning process can be supported through flood risk analysis which informs decision-makers on the most significant risks and how to best manage them (Sayers et al., 2013). The type and detail of risk information required varies throughout the phases of the planning process. This is, however, not always recognized in the tools that are used to generate the required information.
Quantitative flood risk analysis is often supported by computer models. The first models, limited by computational power and available input data, focused on analytical optimization in order to explain and compare concepts (Van Dantzig, 1956,

USACE, 1996, Vrijling et al., 1998). These models mostly focused on the economic impact of floods only. First because this was needed most, and second, because multi-objective optimization quickly complicates calculations. More recent developments allow the optimization to account for intangible damages (Kind, 2014), nature-based flood protection (Vuik et al., 2016), and multiple lines and types of defence within the same flood protection system (Custer, 2015, Dupuits et al., 2017b). These developments were made possible through highly schematized regional layouts that limit computational load. This does, however, limit the ability to model a city's layout sufficiently accurate.

On the other side of the spectrum, numerical flood modelling has developed into standard practice for the design of flood risk management systems. The use of high-resolution flood simulation software (e.g., Delft3D, SWMM, MIKE) is standard practice in large flood risk management design projects. These simulations build in-depth knowledge of fundamental hydraulic processes and the use of Geographic Information System (GIS)-based tools (Kovar and Nachtnebel, 1993), made possible by the growth in computational power. In recent years, several models have also been developed, specifically aiming to simulate compound flooding (Pasquier et al., 2019, Gori et al., 2020). These models provide accurate simulation for specific coastal cities. These simulations, however, are complex, labour-intensive to develop, time consuming to run, and expensive. In addition, their high accuracy demands lots of input data and computational power. This type of model is therefore not well suited for analyses where many simulations are required, such as uncertainty analysis, investment strategy analysis or the comparison of many flood risk reduction measures (Haasnoot et al., 2014).

The gap between conceptual, analytical models and high-resolution, spatial flood simulation models leaves room for models that take local spatial circumstances into account, but still can evaluate many scenarios and many flood risk management options. In recent years, several of these models have been developed, mostly for particular case studies (Jamali et al., 2018, de Ruig et al., 2019, Shen et al., 2016). These models run relatively quickly because of their simplified schematization of the project area and flood hazard. But this restricts their ability to be applied to other areas. This chapter describes a fast, widely applicable flood risk screening model. This model can be adapted to local circumstances. It can be used to investigate multiple flood hazards, many different scenarios, and many possible flood risk management options.

3.1.2 Objective and scope

This chapter introduces the Flood Risk Reduction Evaluation and Screening (FLORES) model as a generally applicable decision-support model for the early planning stages of flood risk management. It has been developed for exploring and evaluating the impact of many different flood risk reduction strategies within a flood-prone area. The FLORES model generalizes a model originally developed to study coastal flooding in the Houston-Galveston Bay area (van Berchum et al., 2018b). In this chapter, we describe how the model has been developed into a generally applicable flood risk screening model by including pluvial flooding of urban areas. The schematization has been generalized such that more types of urban layouts can systematically be modelled. In addition, FLORES can simulate multiple interacting flood hazards, in this case coastal and pluvial flooding. The main characteristics of FLORES are to (1) make risk-based assessments of flood risk reduction strategies, (2) minimize computational load, (3) enable considering structural and non-structural measures, (4) compare flood risk reduction strategies based on multiple performance metrics, and (5) be applicable to a wide range of urban layouts. FLORES is demonstrated using a case study of Beira, Mozambique, which represents a case with compound flooding in a data-poor environment.

3.2 FLORES model description

3.2.1 Model structure

The Flood Risk Reduction Evaluation and Screening model, FLORES, can assess and compare many different strategies for reducing flood risk in coastal cities. At the heart of the model is a flood simulation model, which calculates the extent and resulting impact (i.e., economic damage, number of people affected) of a flood event, represented by a storm surge and rainfall event, each with a specific return period (Figure 3-1). The use of FLORES in the design of flood risk management system for a coastal city, requires many simulations that evaluate a range of hazards and risk reduction strategies, under many scenarios on multiple impacts. Simulating the resulting number of possible scenarios is computationally heavy and only feasible when individual simulations are fast (in the order of seconds).Therefore, the flood simulation uses basic hydraulic formulas and hydrological balances instead of detailed simulation software. To assess a single flood risk reduction strategy, consisting of multiple soft and hard measures, the simulation is repeated for a range of different hazard combinations to build a complete risk profile (Kaplan and Garrick, 1981). This

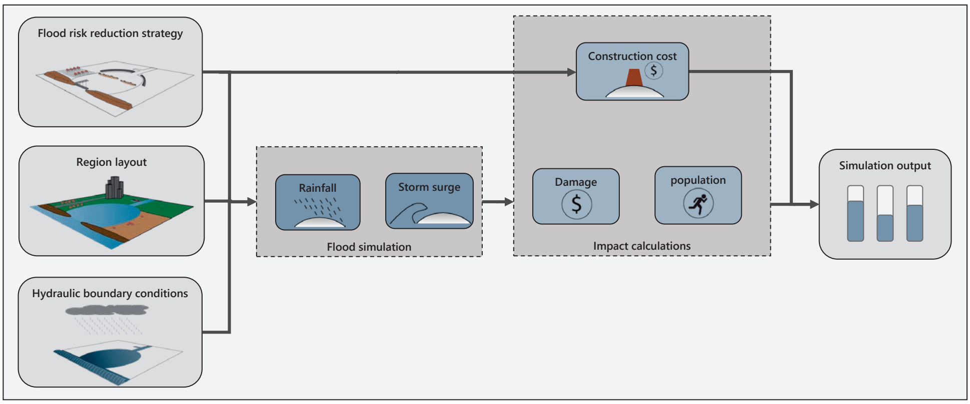


Figure 3-1: Schematization of a flood event simulation

can be compared with the original situation, showing the risk reduction as a result of implementing the measures. Multiple strategies can be assessed, as well as different possible future scenarios (i.e., climate scenarios) to get a clear picture of the options and their consequences.

3.2.1.1 Flood event simulation model

A flood simulation consists of two parts: the hydraulic flood simulation and the impact calculation. The first part simulates how water flows into and through the urban area during the storm event, resulting in maximum water levels throughout a city. The impact calculation uses these maximum water levels to estimate impact in terms of economic damage and number of people affected.
The hydraulic flood simulation takes both rainfall and storm surge into account. Urban flooding is schematized through a combination of an urban inundation model and a drainage system model. For the schematization, the city is divided into drainage basins, which are areas where all water drains towards the same place, see Figure 3-2. Similar schematizations have been used before, for example by Gouldby et al. (2008) and Shen et al. (2016). Throughout the simulated storm, the hydraulic response is calculated by viewing the hydrological balance for each of basins for each time step:

$$V_i=V_{i-1}+(Q_{r,i}+Q_{s,i}+Q_{fi,i}+Q_{di}-Q_{in,i}-Q_{rt,i}-Q_{do,i}-Q_{fo,i})\cdot t \qquad [1]$$

The volume of water in a drainage basin after time step i (V_i) depends on the volume at the previous time step (V_{i-1}), the length of the time step (t), and a number hydrological processes that cause an in or outflow of water. Inflows are: rainfall (Q_r), storm surge overtopping nearby barriers (Q_s), surface flow from neighboring basins (Q_{fi}), and drainage of upstream basins (Q_{di}). Outflows are: infiltration (Q_{in}), drainage flow (Q_{do}), and surface flow towards neighboring basins (Q_{fo}). The difference between inflow and outflow is stored in the basin itself (Q_{rt}), starting with retention. When the retention capacity is fully utilized, water floods the streets, starting at the lowest part (often the drainage point) of the basin.The schematization of the storm surge routing is based on van Berchum et al. (2018b): the borders between land and water are schematized as line elements (lines of defence) that separate the outside water from the drainage basins inside. Here, barriers can be placed in the form of dunes, levees, storm surge barriers, etc. For each time step, basic formulas calculate the amount of overtopping or overflow passing a barrier. This counts as inflow for the drainage basins behind the barrier. By dividing the area into layers (e.g., coastal zone, bay side, inner city), the model can simulate flood protection based on multiple lines of defence. For structural flood defences, the probability of failure is also taken into account through fragility curves, as levee failure has a huge effect on the flood impact. The fragility curves are currently schematized as cumulative normal distributions. The simulation considers all possible scenarios (which structures fail) by running the entire hydraulic flow model for all scenarios, which leads to different combinations of outcomes (flood structural scenarios) and their resulting inundation depths.

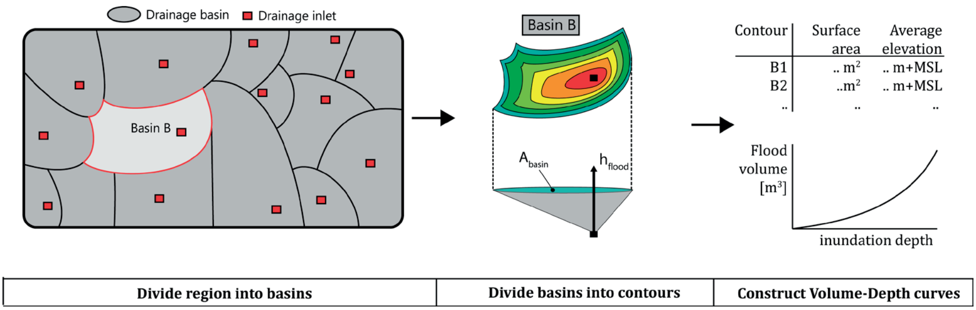


Figure 3-2: Schematization of the city from GIS data into input data for the FLORES model. Based on the DEM, the region is divided into basins and contours, leading to a Volume-Depth Curve of every basin. This schematization does not include coastal boundaries yet.

As part of the impact calculation, the damages due to inundation are estimated using three metrics: the expected damage in dollars, the estimated number of people affected, and the cost of new constructions and repair. The first two metrics are calculated in a similar manner, based on the inundation depth of each of the drainage basins. To increase accuracy, the drainage basins are divided into elevation contours. Focusing on the expected number of people affected, the inhabitants of one area (defined by the basin and elevation contour) are considered to be affected when inundation is more than 10 cm. This is summed for each elevation contour [1,2,...,n], drainage basin [1,2,...,m], and weighted by the probability of each flood structure scenario [1,2,...,s]. This results in the expected number of people affected for one flood simulation, see Eq. (2):

$$N_p = \sum_{k=1}^{s}\left[\sum_{j=1}^{m}\left(\sum_{i=1}^{n} N_{c,ijk}\left(h_{f,i}\right)\right) \cdot P_{s,k}\right] \qquad [2]$$

Where N_p is the expected number of people affected, N_c (h_f) is the expected number of people affected in one elevation contour [-], h_f is the flood inundation in one contour in meters [m], and P_s is the probability of the scenario [-]. Following the same principle, the economic damage is calculated. Here we include not only elevation contour but also land use type. The damage per contour is calculated by summing the expected damage per land use type, which follows from the inundation depth through a damage curve. This type of curve shows the expected portion of value damaged by a certain inundation (van Berchum et al. (2018b)).

The third performance metric is the expected cost of new constructions and repair. This depends on the choice of measure and the scenario (which measures fail and require repair). Construction cost depends on the length and height of a structural measure. The length of a measure cannot be changed, as a measure is placed on a predefined border between land and water. Besides these constant costs, some costs depend on the chosen structure height, such as material and manpower. When a structure fails, it is assumed that it will be repaired up to its original value. Maintenance cost currently not taken into account.

3.2.1.2 Risk profile assembly

The performance of a flood risk reduction strategy cannot be based on a single flood event scenario. Therefore, multiple scenarios are combined to build a more representative risk profile. Here, risk is defined as a combination of scenarios that can affect you, each of which has a probability of occurrence and a potential consequence (Kaplan and Garrick, 1981). When modelling, it is impossible to look at all possible scenarios. Therefore, a number of simulations is numerically integrated to represent the entire risk profile. For each individual scenario, the impact is weighted by its probability, which depends on the return period of the incoming flood hazard (and the correlation between hazards if there are multiple). By varying the intensity and return period of the incoming hazards, the risk profile shows how the city and the implemented measures perform under different circumstances.

The development of a risk profile is complicated by compound flooding, where both extreme rainfall and coastal storm surge are threatening the city. This influences the performance of some measures. For example, the efficiency of a drainage system, which drains to outside water, can decrease when outside water levels are raised due to storm surge. Several different combinations are simulated, resulting in a risk profile that depends on two variables – the probability of occurrence of the rainfall and storm surge. For each flood hazard, 5 different storm intensities are used, which means that 25 simulations are needed for one risk calculation. An example, based on the case study, can be seen in Figure 3-7.

A common problem of risk analysis of compound flood events is correlation between the flood hazards (Wahl et al., 2015). Several types of large storms, such as cyclones, generally lead to both storm surge and rainfall. Considering the hazards separately and independently would be underestimating the potential risk. Although complicated, correlation can be estimated based on historical data and expert judgement. In many countries, these data are not or only sparsely available. In FLORES, the same flood hazard combinations (e.g., a 10-year storm surge and a 100-year rainfall event) are simulated, regardless of correlation. However, each combination will have a different probability, also depending on the correlation. This correlation value can be adjusted in the model.

3.2.1.3 Screening flood risk reduction strategies

FLORES can quickly asses how a flood risk reduction strategy affects the risk profile. Subsequently, it is also possible to look at many different strategies, covering the entire design space of different combinations of measures (and elevation of measures, if applicable) under different scenarios. This leads to a huge amount of data available for analysis, which will be processed using the Exploratory Modelling and Analysis (EMA) workbench (Kwakkel, 2017a). This Python-based toolset runs common analysis- and optimization algorithms to visualize and support decision making and planning (e.g., Feature Scoring, Scenario Discovery). It has been used in several research fields in the past (Rostampour et al., 2019, Ciullo et al., 2019). FLORES uses these tools to visualize screening results, prioritize measures, and search for trade-off and trends.

3.2.2 Model data usage

FLORES is intended to be applicable to flood-prone cities worldwide. Therefore, it should work based on easily accessible data sources. Examples are global elevation maps (often GIS-based DEMs) or reports containing global estimates of damage curves. As many of the most vulnerable cities are located in developing countries which often lack detailed datasets, FLORES should run with only minimal need for detailed local data. Therefore, open-source datasets can be used for most of the required data, such as elevation, population density, damage curves, hazard data, and future scenarios. However, for some types of data, local information is necessary. For example, information on the local hydrology (e.g., drainage system, sewerage), considered measures, and the structural exposure. If for these inputs, no data are available, they can also be based on qualitative assessment, in cooperation with local authorities or organizations. However, this does affect the results and their accuracy, which should be taken into account. A list of required input and their minimum requirements can be found in Table 3-1.

Table 3-1: minimum requirements for FLORES data sources.

Required input	Minimum required data	Source example
Elevation	Digital Elevation model [12m][1]	Global DEMs
Structural exposure	Qualitative assessment per district	Assessment by local authorities
Population exposure	Population density map	Global dataset (Florczyk et al., 2019)
Damage curves	flood depth-damage functions	Global functions (Huizinga et al., 2017)
Measures	Reference projects	Design reports
Surge and tidal data	storm surge for different return periods, local tidal profile	GAR15 (Cardona et al., 2014)
Rain data	rainfall intensity for different return periods	Various, depending on region
Wind data	Wind speed estimates for different return periods	GAR15 (Cardona et al., 2014)
Future scenarios	Global scenario reports	Global scenario reports (IPCC, 2014)

[1] This is based on earlier model runs. In future research, we hope to show that Global open-source DEMs [~30m resolution] can also be used.

3.3 Case study in Beira, Mozambique

3.3.1 Background

To demonstrate the capabilities of FLORES, we use it to analyse flood risk in the coastal city of Beira, Mozambique. Beira is one of the largest cities of Mozambique with more than 600,000 inhabitants. It is also home to an important port, connecting an extensive hinterland – which includes Zimbabwe – with the Indian Ocean. In the past, Beira has been subjected to large-scale flood events, resulting from both coastal storm surges and extreme rainfall events. Most notably, the city was in the centre of global attention when tropical cyclone Idai made landfall only a few kilometres from the centre of Beira in March 2019. The cyclone continued through Mozambique, affecting about 1.85 million people and causing roughly 700 million dollars in damage (IOM, 2019). Extreme rainfall inundated the lower parts of the city, mostly occupied by informal settlements. Beira's flood vulnerability was recognized long before Idai. Rainfall events have been causing large-scale floods of lower-lying areas on a nearly yearly basis. At the coast, beaches are eroding quickly, due to degrading of the groins and poor coastal management. Several studies have analysed the problems and suggested a number of possible measures and strategies to reduce flood risk (Arcadis, 1999, Deltares et al., 2013, CES and Lackner, 2013). Some of the suggested strategies have been implemented, most notably a large-scale rehabilitation of a part of the drainage system, financed by the Mozambique government through the IDA.

Flood risk in the city is still considerable, and growing due to urban expansion and climate change. The process of developing a flood risk reduction strategy is complicated by a number of factors. Many different hydrological processes and interventions are interacting. For example, the city is threatened by both storm surge and rainfall, and many of the possible actions will interact with each other and the hazards. Moreover, future development of the city is highly uncertain. Outside of the complexity of system itself, the analysis is further complicated by lack of data and the need for multi-objective evaluation.

3.3.2 Model setup

3.3.2.1 Input data

For each type of information, the most detailed, yet easily obtainable, data source is used. The data sources used in this case study are listed in Table 3-2. Regarding the elevation data, this LiDAR DEM dataset has been developed as a part of an earlier project financed by the World Bank, aiming to enhance local research. The DEM was calibrated with locally used elevation units (meter above Chart Datum [m+CD], which is equal to the lowest astronomical tide).

For damage estimates, the structural exposure is combined with damage curves. Huizinga et al. (2017) provides maximum damage estimates for all countries and flood depth-damage curves per continent for different land use types. As the number of land use types with a damage curve in Africa is limited to three (Residential, Industrial, Agricultural), the structural exposure will be divided into these three groups as well.

Table 3-2: Data sources for the FLORES model in Beira

Required input	Source	Reference	Data type [resolution]
Elevation	LiDAR DEM		Local data [2 m]
Structural exposure	ADFR - Building exposure	Eguchi et al. (2016)	Satellite measurements [450 m]
Population exposure	ADFR - population exposure	Eguchi et al. (2016)	Satellite measurements [450 m]
Damage curves	Global flood depth-damage functions	Huizinga et al. (2017)	Global open data [-]
Measures	Expert mission report, earlier research		Local information
Surge data	GAR15 storm surge	Cardona et al., 2014)	Global open data [-]
Rain data	Beira adaption to climate change study	CES and Lackner, 2013)	Local data [-]
Wind data	GAR15 cyclonic wind	Cardona et al., 2014)	Global open data [-]
Future scenarios	Global scenario reports	IPCC (2014)	Global open data [-]

3.3.2.2 Compound flood hazard setup

The hydraulic boundary conditions are based on extreme-value analyses of coastal storm surge- and extreme rainfall events. Input for the model is the return period of both types of flood hazards. A coastal storm surge is simulated as a time series of water levels at the coast, also taking tide into account, see Figure 3-3. Rainfall is simulated as a constant inflow for duration of the storm.At events where both hazards are occurring, the joint probability is important. For this particular case, first analysis using ERA-Interim (Dee et al., 2011) suggests independence between coastal

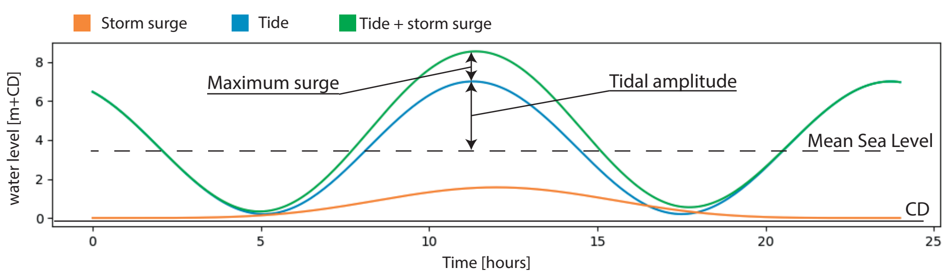


Figure 3-3: Example time series of coastal storm surge event. (orange) run up due to storm surge, (Blue) elevation of tide, and (green) total elevation of tide plus surge.

Table 3-3: hydraulic boundary conditions for FLORES application in Beira. Note that the maximum surge level is calculated above the still water level. Other factors like the tide (3.4 meter amplitude) and the mean sea level (3.6 m+CD) should also be taken into account. The FLORES model will assume a storm duration of 24 hours.

Return period [years]	Max surge level [m]	Rain intensity (24h) [mm/hour]	Rain intensity (48h) [mm/hour]	Rain intensity (72h) [mm/hour]
2	0.2	7	4	3
5	0.3	9	6	4
10	0.5	11	7	5
50	1.6	14	9	7
100	2.2	16	10	8

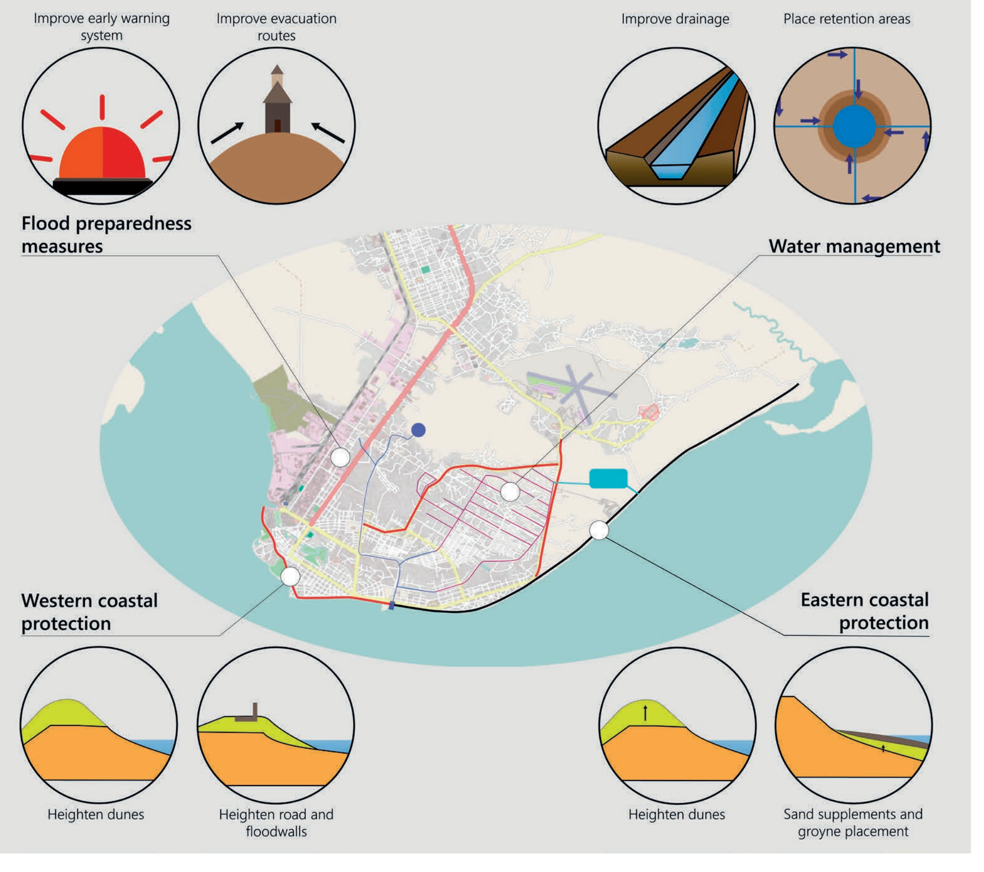


Figure 3-4: Map of Beira, Mozambique. Denoted are a few examples of flood risk reduction measures. Background image © OpenStreetMap contributors 2018. Distributed under a Creative Commons BY-SA License

storm surge and extreme rainfall, which was therefore also used for this screening. Future analysis should examine whether this assumption is valid for extreme cases. The hydraulic boundary conditions for several return periods are shown in Table 3-3. Two climate change scenarios are taken into account, which will affect the boundary conditions by increasing the surge level and rain intensity.

3.3.2.3 Flood risk reduction measures

We consider various measures for improving flood risk management in Beira, including measures considered by the local government, measures suggested by local stakeholders, and measures explored in scoping studies (Deltares et al., 2013, Letitre et al., 2018). The set of measures showcase the different types of measures that can be considered with FLORES, including structural flood defences, drainage systems, retention basins, and non-structural emergency measures. Note that a part of the overgrown drainage system has already been rehabilitated through widening of the canals and addition of a retention basin and a coastal inlet structure. A map of Beira, with some of the measures, is shown in Figure 3-4. A complete list of all measures used in this case study can be found in the appendix.

3.3.3 Model evaluation

Limited data for evaluating the accuracy of the flood simulations is available. Cyclone Idai provided some insight into one situation, with verifiable data and known hydraulic conditions. During other extreme events, however, no detailed measurements were taken. Only few detailed flood simulations have been conducted (CES and Lackner, 2013). As a part of the design of the drainage system, which completed in 2018, a 10-year rainfall event was simulated. This simulation is compared with a FLORES flood simulation (Figure 3-5). FLORES predicts lower flood levels in lower areas of the city, especially in areas with steep slopes. Other than this comparison, some benchmark tests were available to test the accuracy of the flood simulation. For example, storm surge events up to the 5-year storm surge hardly affect the city, and larger storm surges affect areas known for their relatively weak flood defences and storage capacity (south-eastern part of Beira).

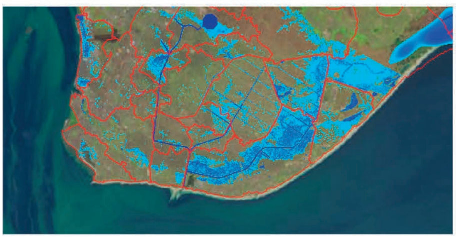


Figure 3-5: flood extent resulting from a 10 year rainfall event for FLORES (left) and an ANUGA simulation, which was part of the Rio Chiveve feasibility study. Background image: Sentinel-2 (© ESA).

3.3.4 Results

FLORES is used to analyse the current situation, as well as potential future situations and strategies for the city of Beira. First, we examine the current risk profile of Beira, without any new measures in place, as a benchmark. Next, we quantify the effects of different possible flood risk reduction strategies under different potential future scenarios in Section 3.4.2. Their effectiveness is evaluated based on their ability to decrease flood risk compared to the current situation. With FLORES, we analysed 500 strategies, consisting of random combinations of flood risk reduction measures. For structural measures, also a random crest elevation will be chosen. These 500 strategies were evaluated for two future climate change scenarios. The runtime was roughly 10 hours for the entire screening on a single computer with an 8-core (3.2GHz) processor using parallelization.

3.3.4.1 Current risk profile

Looking closer to the hydrological situation in Beira, a number of phenomena stand out. First, the city has a large lower-lying area, which does not have a natural connection to open water. Not surprisingly, the most common cause of flooding is extreme rainfall, as also shown in historical reports and flood simulations. The lower parts of the city experience flooding on an almost yearly basis, although this has decreased due to the new drainage system, see Figure 3-6 (left). For more severe rainfall events, the entire city is affected, see Figure 3-6 (middle). Between these two simulations, the percentage of people affected has grown from 6% to 21%. Only the city centre, located on higher ground in the southwest, is able to drain effectively towards the Rio Chiveve and the drainage system. When coastal storm surge occurs in combination with a 10-year rainfall event, the impact is amplified strongly, see Figure 3-6 (right). Here, even areas that are not directly affected by the storm surge are flooded due to the reduced effectiveness of the drainage system. As a result, damages due to compound flooding are more than the sum of damages of the individual flood hazards. Please note that this does not have to hold true for all cases. More extreme

Figure 3-6: flood map for a 2 year rainfall event (left), 10 year rainfall event (middle), and a 10 year rainfall event plus a 10 year coastal surge event (right). Background image: Sentinel-2 (© ESA).

storm surge or rainfall events (100-year return period) can damage most of the city, and an added hazard leads to little added damage.

Historically, coastal storm surge is most problematic when resulting from a tropical cyclone. These situations do not occur regularly, which is why the effects of coastal storm surge only become significant for more extreme events. The model results also show little damage for up to a 5-year storm surge, see Figure 3-7. Smaller storms create coastal surges up to 0.5 meter, which are insignificant compared to the tidal range, which can grow up to 6-7 meters. This also shows the importance of timing. For example, the 3.5-meter storm surge from Cyclone Idai hit during neap tide, and damage due to coastal flooding was relatively small. In some scenarios compound flooding can occur, where the effects of coastal storm surge and extreme rainfall strengthen each other. In Beira, the capacity of the drainage system depends on outside water levels. Due to high water, there is a time window where no drainage is possible. This time window grows during a storm surge and is also growing due to sea level rise.
The risk profile of the current situation can be estimated based on simulations of multiple different storms. Both flood hazards – coastal storm surge and extreme rainfall - are represented by five intensities, based on their return period (0-, 5-, 10-, 50-, 100-year event). A zero-year event is used in the model to signify no storm surge or no rainfall. The resulting risk profile can be seen in Figure 3-7. Integration of probabilities and consequences of events result in the expected annual damage (dollar/year), which in this case is roughly 16.5 M$ per year. Please note that the model can also use different future scenarios which will have a large effect on the expected annual damage.

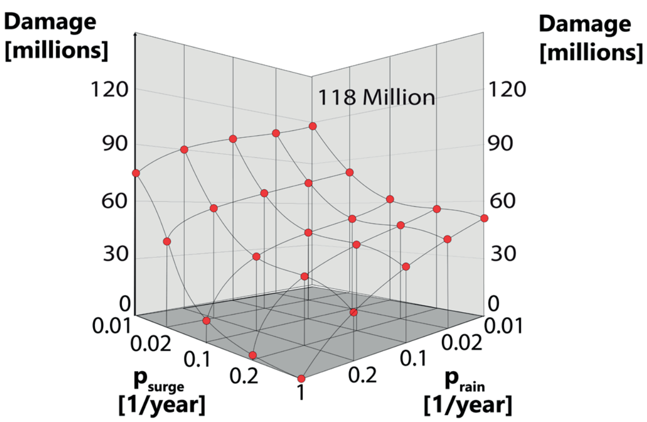


Figure 3-7: Risk profile of the current situation in Beira, Mozambique. Shown is the expected damage of a compound flood event with a probability of occurrence of the storm surge (p_s) and the rainfall (p_r).

3.3.4.2 Screening of flood risk reduction strategies

In order to assess the effectiveness of flood risk reduction strategies, their performance is compared with the current situation and with each other based on their risk profile. The screening of flood risk reduction measures is based on 500 randomly sampled strategies, for two different future climate scenarios. Here, we show the results of several analyses of this data. Figure 3-8 shows how each strategy performs on their output parameters (Risk reduction, reduction in number of people affected, and construction cost). Each dot represents one flood risk reduction strategy and the two colours denote the climate scenarios.

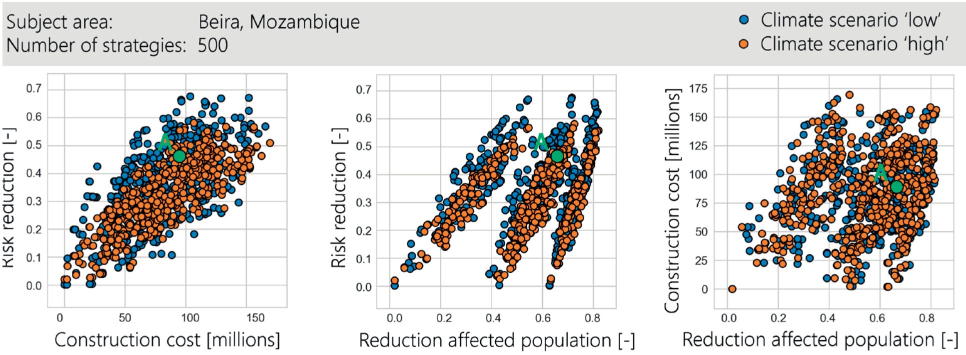


Figure 3-8: Pair wise plotting graphs for the Beira case study. Each dot represents one flood risk reduction strategy. Each strategy can be assessed by their risk reduction, reduction of affected population, and cost of construction. Here, those outcomes are plotted against each other. Different colors indicate two different future climate scenarios. A represents a strategy consisting of four measures: (1) dunes on the eastern coast [10.5 m+CD], (2) a flood wall on the southwestern coast [9 m+CD], (3) enhancement of the drainage system, and (4) enhanced evacuation of vulnerable neighborhoods.

Figure 3-8 shows a clear positive correlation between construction cost and risk reduction. However, individual strategies can deviate greatly from the trend, which indicates that some low-cost combinations can make a large difference. Moreover, these outliers are more prominent in a less extreme future climate scenario (blue dots in the figure), especially in the low-cost range. This indicates that some cheaper measures are relatively effective in moderate storm conditions, but are quickly overpowered in more extreme situations. For Beira, this most likely points to the inland measures (improving the drainage system, adding retention areas), which are less costly than coastal measures and are most effective for small to moderate rainfall conditions.
Figure 3-9 quantifies the dependency of output variables on the input choices and uncertainties through a feature scoring analysis (Breiman, 2001, Jaxa-Rozen and Kwakkel, 2018).

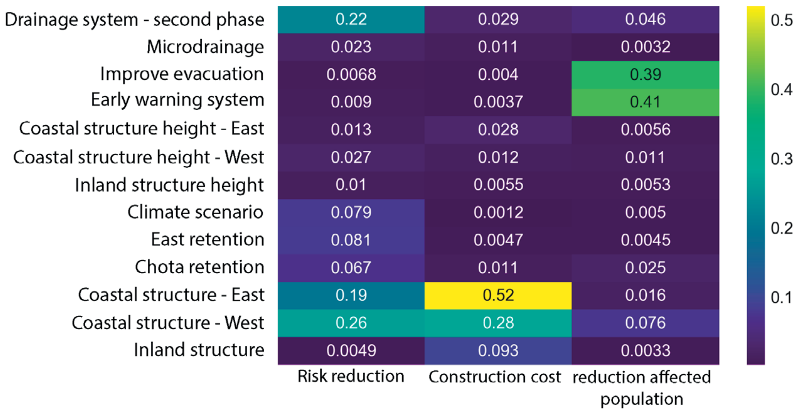


Figure 3-9: Feature scoring analysis for the Beira case study. It shows the relative importance of the choice of measures and uncertainties (listed on the left) for the outcomes (below). Higher numbers indicate higher importance.

On the left, all potential measures are listed, as well as the future climate change scenario. The numbers indicate how much the outcome variables (below the table) depend on the choice on the left. A higher number indicates a higher importance, where 0 means that the measure has no influence and 1 indicates that the output is fully dependent on the choice for that input. The results underscore the importance of both coastal measures and inland measures, in particular further improvement of the drainage system. Increasing retention areas are relatively less effective. Simulations show that retention areas are effective only for smaller pluvial events, but have insufficient capacity when a storm surge overpowers the coastal defences and reduces the effectiveness of the drainage system (see Figure 3-6). This effect is increased because the high outside water level during storm surge events prevents the drainage system from functioning. This is an example of how compound flood events lead to high damages by affecting hydrological processes in ways that are of less importance when considering individual hazards.
Finally, we identify promising combinations of options using Scenario Discovery (Bryant and Lempert, 2010, Kwakkel and Jaxa-Rozen, 2016), using the Patient Rule Induction Algorithm (PRIM) (Friedman and Fisher, 1999) . Specifically, we use scenario discovery to identify which combinations of design choices are most effective when pursuing a predetermined set of goals. A design choice can be the choice to use (or not to use) a particular measure, or a minimum/maximum build elevation. The aim is to find a combination of design choices that will maximize the chance of reaching a predetermined set of goals. PRIM calculates which are most effective and removes strategies out of the comparison that do not include this option. Finally, a number of strategies is left, of which many comply with the goals set in advance, see Table 3-4.

Table 3-4: Results of PRIM-analysis for Beira case study 'Goals' shows what output we are looking for (i.e., minimum risk reduction, maximum budget), 'Start' shows how many strategies out of initial 500 comply with the goals, called strategies of interest. 'Results' shows design choices that are made, focusing on these strategies of interest. 'Final' indicates how many strategies are left– after filtering for the design choices listed under 'results' – and how many of those are still strategies of interest.

Goals	**Start** Strategies of interest	**Results** Design choices (priority from top down)	**Final** Strategies of interest
Focus on risk reduction and construction cost			
For 'low' climate scenario: *Risk reduction > 0.35* *Construction cost < 80 M$*	**84** out of 500	1. Drainage system second phase 2. **No** coastal structure east 3. Coastal structure west	**43** out of **64**
For 'high' climate scenario: *risk reduction >0.25* *construction cost<75 M$*	**88** out of 500	1. **No** dune heightening at eastern coast 2. **No** inland barrier 3. Height coastal structure west > 8.5 m 4. Retention Chota	**41** out of **67**
Balanced goals			
For 'low' climate scenario: *risk reduction >0.40* *construction cost<125 M$* *reduction in affected population > 0.65*	**89** out of 500	1. Drainage system second phase 2. Coastal structure west 3. Height coastal structure west > 8.6 m 4. Improve evacuation 5. **No** dune heightening at eastern coast	**42** out of **52**
For 'high' climate scenario: *risk reduction >0.35* *construction cost<125 M$* *reduction in affected population > 0.6*	**114** out of 500	1. Coastal structure west 2. Height coastal structure west > 8.5 m 3. Coastal structure east 4. Improve evacuation	**50** out of **57**

Table 3-4 highlights the importance of both coastal and inland design choices. Most of the strategies that reach the goals on both risk reduction and construction cost included an improved drainage system, as well as coastal protection in the urban area at the southwestern side of Beira. When a lower affected population was added as a goal, emergency measures such as evacuation were added because of their relatively low investment costs.

3.4 Discussion

The aim of FLORES is to provide useful information in the early planning stages of flood risk management, when limited time and input data are available. Therefore, several limitations should be taken into account. Many physical processes are simplified. First, the simulation mainly revolves around solving the hydrological water balance for a defined number of drainage basins for every time step. Measures acting on a smaller scale are therefore hard to represent correctly. Second, storm surge is modelled as a time series of water levels during a storm, leading to inflow into coastal basins through overtopping or overflow. A coastal barrier can prevent this, but could also fail. The moment of failure, as well as the portion of the barrier that fails when it does, is set beforehand. Sensitivity to these choices has not been investigated as part of this study, but could be included by integrating fragility curves and breach models (Ciullo et al., 2019). Third, the drainage system is simplified compared to common urban drainage models (Butler et al, 2018). For example, water drainage between basins is limited by the downstream basin. Therefore, water cannot flow in the upstream direction, which would occur if the outside water level is especially high. FLORES is under active further development. In earlier case studies, the coastal storm surge simulation and the resulting damage have been extensively evaluated (van Berchum et al., 2018a). However, lack of data prevents similar testing for Beira. Also, several model variables require further sensitivity analysis. For example, storms are simulated using a 6-minute time step, which provided reasonable accuracy and computational speed in earlier case studies. However, this is not tested for compound flood simulations. Similar assessments are needed for other variables, such as the step-in elevation for the contours – which was 0.25 meter – and the number of simulations required to construct a realistic risk curve. The optimal choice for these variables will mostly depend on the complexity and size of the project areas, as well as the available input data. For this case study, a combination of publicly available and local data was used. In general, most required data are available publicly, with the exceptions of information about the measures, local hydrology, and structural exposure. Most crucial is the choice of DEM, which is available almost globally.

3.5 Conclusion

This chapter presents the Flood Risk Reduction Evaluation and Screening (FLORES) model as a generic model for investigating compound flood risk and shows its application through a case study of Beira, Mozambique. The project area is schematized such that a single flood simulation only takes a few seconds and calculating a complete risk profile can be done in a few minutes. This allows for the comparison of many different storms, flood risk reduction strategies, and future scenarios. Using basic hydraulic formulas, FLORES simulates the flood impact for cities with sufficient accuracy for comparing large-scale concepts of flood risk reduction strategies.

For the Beira case study, FLORES provided insight into the prioritization of measures and long-term effects. Both the drainage system and coastal protection were identified as crucial elements in an effective flood risk reduction strategy, which is in line with earlier reports (CES and Lackner, 2013, Deltares et al., 2013, Letitre et al., 2018). Effects of both coastal storm surge and extreme rainfall were taken into account, including storms where both hazards occurred simultaneously. This led to flood damages that exceeded the impact of simulating individual hazards. For example, coastal storm surge led to a long interval where drainage was not possible, greatly restricting the city's ability to withstand extreme rainfall. On the short term, the expansion of the current drainage system would provide the highest benefits in terms of reducing economic damage and people affected. On the longer term, especially in case of higher end climate change, the coastal system is expected to become the dominant factor in the flood risk management of Beira. These results have contributed to current efforts for planning for future events in Beira.

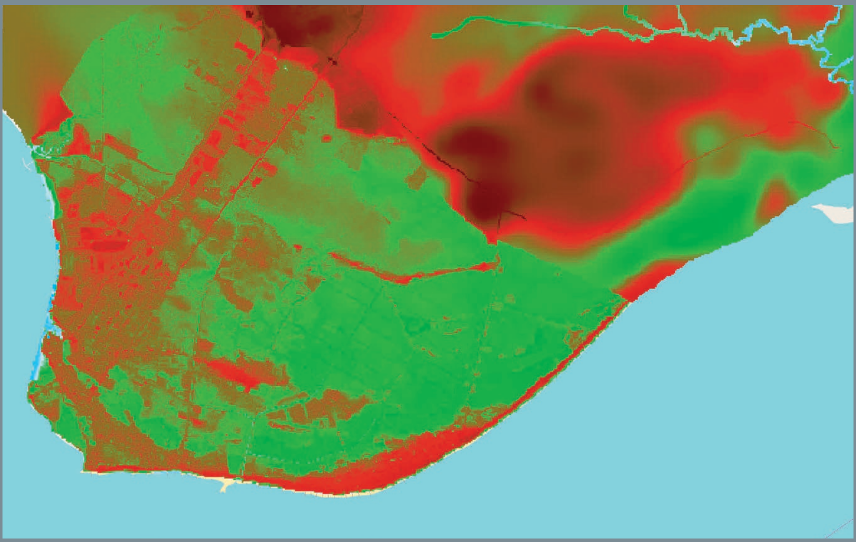
Further research should explore the impact of using global open DEMs compared to commercial or locally obtained DEMs, as used in Beira. For further development of FLORES, it is crucial to gather more information on the accuracy of the model compared to historic events, as well as the correlation between different flood hazards. This is possible by formulating a new case study, where more detailed information is available. This is also useful to demonstrate and expand the range of possible situations (e.g., cities threatened by river flooding, cities with large lakes). Other possible extensions focusing on social or environmental impact can be added in a later stage as well through additional performance metrics.

FLORES is developed to be easily transferred to other flood-prone cities. For the Beira case study, we used input data of varying resolution, including global open data sources. For other cities, this data are either available or easily obtainable, making the application of this model to a new case study relatively simple and a process that can easily be standardized. The goal of the model is to provide useful risk information early on in the flood risk management process, when information is often scarce, but important decisions need to be made. By screening the many potential flood risk reduction strategies and quantifying their impact with multiple parameters, decision makers can fall back on a range of useful risk information in their aim to develop an effective flood risk management plan.

Appendix A: Model input

Table 3-5: Flood risk reduction measures used in the FLORES model for Beira, Mozambique. Cost estimates are based on local reference projects.

Name	Type	Fixed cost	Variable cost	Remarks
Heighten dunes east	Structural	3 million $/km	1.5 million $/km/m	Rural area
Sand supplements east	Structural	2 million $/km	0.5 million $/km/m	Rural
Heighten dunes west	Structural	4 million $/km	1.5 million $/km/m	Urban area
Floodwall west	Structural	5 million $/km	1 million $/km/m	Urban area
Heighten inland road	Structural	3 million $/km	0.5 million $/km/m	
Second phase drainage system	Drainage	12 million $		
Micro drainage	Drainage	8 million $		
East retention	Retention	5 million $	Located east of city border	
Chota retention	Retention	2 million $	At lowest point in Chota	
Improve evacuation	Emergency	1.5 million $		
Early warning system	Emergency	0.4 million $		



Chapter 4

Evaluating the use of free global DEMs for flood risk screening

Previous chapters described the main rationale of flood risk screening and the main schematizations of the FLORES model. Running such models in a conceptual planning or design phase, especially in developing countries, is complicated by a lack of reliable input data, the most important of which is the local topography. For flood simulation, this is often required in the form of a Digital Elevation Model (DEM), which is expensive to develop locally. In recent years, a number of free, (near-)global DEMs have become available, based on satellite measurements. This research examines the use of several DEMs (SRTM, ALOS World 3D, and TanDEM-X WorldDEM) as part of early flood risk screening and compares their performance against that of a locally acquired LiDAR dataset in a case study in Beira, Mozambique.
First, the comparison consists of a quantitative analysis on the ability to map the local topography. Then, the best of these three (near-)global DEMs, the TanDEM WorldDEM, is compared with the LiDAR DEM on four levels: the flood simulation, flood impact, flood risk and the effectiveness of measures and strategies. The goal is to clarify whether the lower resolution leads to similar advice on which measures to prioritize or whether the results are significantly impacted by the choice of DEM.

4.1
Introduction

4.1.1 Background

Many cities are experiencing a rapid growth of flood risk. Flood hazards like coastal storm surge, extreme rainfall and high river levels are increasing in intensity, and due to urbanization, more people and assets are exposed to flooding than ever before (Doocy et al., 2013). This leaves the challenging task to find an effective and durable strategy to reduce the flood risk to an acceptable level. Measures can be implemented, either to reduce the probability of a flood occurring, or to limit the damages. However, many of the most rapidly growing urban areas in the world are located in developing countries, where flood risk management policy is not fully developed or sufficiently implemented yet (Simpson et al., 2014).
Managing flood risk is often the responsibility of governments, either local or national. Through analysis of the flood hazards and potential impacts, an assessment can be made on the flood safety and the possible actions to take. Finally, decisions should be made to develop policy or implement measures to reduce the flood risk, if needed. This process of decision making in flood risk management can be supported with the use of computer models. Well-known are the detailed flood simulation models (e.g., Delft3D, SWMM, MIKE). The use of these models has become common practice for any large flood management project, because of their relatively accurate simulations, even for large, spatially complex project areas. However, these models are complicated, labour-intensive and therefore expensive to set up. Also, the high spatial

resolution demands a large amount of input data. These drawbacks have hampered the use of such models or any other standardized decision support models in the earlier stages – the planning phase – of the flood risk management process. In recent years, some models have been developed aiming to provide useful information for the planning phase in flood risk management (Woodward et al., 2014, van Berchum et al., 2018b, Falter et al., 2015). By using smart and relatively simple schematization, it is possible to provide useful risk information based on limited input data in the early stages of the planning process.

For flood risk analysis, the representation of the local topography is crucial. In most flood risk software, this is required in the form of a Digital Elevation Model (DEM). Especially in an urban environment, the local topography is the main factor that influences where water will flow or accumulate (Council, 2009). There are several observation techniques to acquire data for developing DEMs, such as stereo-optical imagery (Lillesand et al., 2015) – used for example by SPOT DEM, ASTER GDEM, and ALOS World 3D – and Interferometric Synthetic Aperture Radar (InSAR) (Hanssen, 2001), which is used for the SRTM DEM and the WorldDEM (based on TanDEM-X data) (Gesch, 2012). These techniques use satellites (or a shuttle in the case of SRTM) for their measurements, which leads to DEMs with near-global coverage and consistent quality. For high-resolution, high-accuracy elevation data, most researchers turn to Laser altimetry or LiDAR (Vosselman and Maas, 2010), which is mostly done with airplanes, but nowadays is also possible with drones. This limits the range and is therefore often only commercially available on a local scale, although also nationwide datasets exist.

As elevation data is crucial for flood simulation, most flood risk management projects are forced towards LiDAR or commercial Global DEMs, such as ASTER GDEM, ALOS World 3D, and WorldDEM, each of which offer a more accurate, paid version next to their free DEM. However, the free-to-use global DEMs are steadily improving. Where the resolution was roughly 5 arcminutes (~10km) in the 1990s for the first global DEM (ETOPO5), the current models have near global coverage in a resolution of 1-3 arc-seconds (~30-90 m). The latest step forward came with the release of the TanDEM-X WorldDEM in 2014 (Wessel et al., 2018). This new full-global DEM has a horizontal resolution of 12 meters for their commercial product, which is reduced to a 90-meter resolution in their free version. It has been shown in multiple occasions to provide more consistent and more accurate measurements compared to other available DEMs (Grohmann, 2018, Pa'suya et al., 2017).

Despite their low resolution, global DEMs have been used for flood hazard research throughout the years. For example in global flood risk analysis models, which usually do not require high-resolution elevation data because of their scale (Hirabayashi et al., 2013, Ward et al., 2015). Currently, also flood models on a smaller, regional scale have shown to be able to provide useful information based on global DEMs (Hawker et al., 2019, Farooq et al., 2019). However, this still mostly entails research on the scale of entire river catchments or floodplains. Flood modelling in an urban environment is still mostly done with high-resolution hydrodynamic models, which requires even more accuracy. As a result, free global DEMs have hardly been used in urban flood risk management yet.

4.1.2 Objective, approach and scope

This chapter explores the potential of free global DEMs for flood risk assessment and management, particularly for purposes of flood risk screening in the early phases of planning and strategy development in an urban environment. Flood risk screening models are typically used in early design to compare the effectiveness of flood risk reduction strategies and require rapid flood simulation to do so. To be able to compare many strategies, these revolve around more schematized rapid urban flood simulation models, which are less demanding in terms of the DEM's resolution. As such, they are better fit as a first use for free global DEMs in flood risk management. This is an important distinction with later stages of planning, where individual measures are designed in more detail. At that moment, a higher level of detail is necessary, which requires more accurate models and a more accurate DEM.
First, in Section 2, a number of DEMs is selected, which will be compared and assessed for their applicability in a flood risk screening model. The comparison will focus on the city of Beira, Mozambique. This city has already been investigated in earlier research to compare many different flood risk reduction strategies against both coastal storm surge and extreme rainfall (CES and Inros Lackner AG, 2013, Deltares et al., 2013), using a DEM based on high-resolution LiDAR measurements. By comparing the global DEMs amongst each other and with the LiDAR-based DEM, we can assess the accuracy of these low-resolution data sources. In order to compare the usefulness of these datasets for flood risk management purposes, they need to be applied in a model for flood risk assessment. Therefore, we will use the FLORES model (van Berchum, 2019b). This model has been developed over the past few years, specializing in providing useful risk information for decision-makers early on in the planning process.
In Section 3, the FLORES model will be used to perform flood risk analysis based on the most promising dataset and compared with the analysis done based on LiDAR data. We will compare the DEMs on a number of different levels of detail, by comparing (1) the hydrological effects of a single flood event, (2) the economic and social impact of a single flood event, (3) the resulting flood risk profiles, throughout all possible events, and (4) the type of flood risk management decisions made based on the provided information. These decisions mostly entail strategic decisions on the type of flood risk reduction measures to prioritize, and which options deserve more research in a later stage of design.
Section 4 discusses the chosen methodology and results. Section 5 will summarize and conclude the research.

4.2 Methodology

4.2.1 Materials and methods

4.2.1.1 Global Digital Elevation Models

To compare the usefulness of different free (near-)global Digital Elevation Models, three global DEMs will be compared in a case study with each other and a local LiDAR dataset, which was commissioned by the local government and financed by the

World Bank as part of a rehabilitation project of the local drainage system (CES and Inros Lackner AG, 2013). This dataset was acquired by airplane in 2014 and provides a 2-meter spatial resolution. The three global DEMs are: Shuttle Radar Topography Mission (SRTM), Advanced Land Observing Satellite (ALOS) World 3D, and TanDEM-X World DEM. Of these, SRTM is the oldest and most well-known. It was developed by NASA and is based on an 11-day shuttle run in 2000. Over the years, the DEM based on this data has been updated several times. Since 2014, it provides a free 1-arc second (~30 meter resolution), near-global DEM. Both the ALOS World 3D (AW3D) and the TanDEM-X World DEM (WorldDEM) are examples of more recently developed DEMs. In comparison to the SRTM dataset, they have shown to provide more accurate elevation data, mostly because both are downsampled versions of measurements with a 5 meter spatial resolution (Kramm and Hoffmeister, 2019, Alganci et al., 2018). More information on the three DEMs used in this analysis can be found in Table 4-1.

Table 4-1: Details of free global DEMs and the LiDAR-based DEM, based on (Proietti et al., 2017, Farr et al., 2007, JAXA EORC, 2021, Wessel, 2018)

	SRTM	AlOS World 3D (AW3D)	TanDEM-X World DEM (WorldDEM)	LiDAR DEM
Owned by[1]	NASA	JAXA	DLR & Airbus	AIAS
Period of observation	2000	2006-2011	2010-2015	2014
Horizontal resolution	30 m	30 m	90 m	2 m
Vertical resolution	1.0 m	1.0 m	0.1 m	<0.1 m
Horizontal accuracy[2]	7-12m CE90	7m CE90	<10m CE90	-
Vertical accuracy[2]	6-9m LE90	7m LE90	4m LE90	-
Horizontal Datum	WGS84	WGS84	WGS84-Gu50	WGS84/UTM-36S
Vertical Datum	EGM96	EGM96	WGS84-Gu50	Geoid model
Coverage	60° N to 56° S	Global (land)	Global	Global

[1] NASA = National Aeronautics and Space Administration, JAXA = Japan Aerospace Exploration Agency, DLR = German Aerospace Center, AIAS = Water and Sanitation infrastructures administration (Mozambique).

[2] Horizontal and vertical accuracy is specified in CE90 and LE90, respectively. CE90 is the circular error at the 90th percentile, meaning that 90 percent of the measured points has a horizontal error less than the stated CE90 value. LE90 is the 90th percentile linear error, which has a similar meaning for the vertical error.

The datasets are based on measurements at different moments in time (see also Table 4-1), what could lead to small differences, e.g., by urban expansion or subsidence. These differences are neglected in this comparison.

The three (near-)global DEMs will be compared on their potential to be used in flood risk screening. First, they are assessed based on their elevation difference to the LiDAR data. This is quantified in terms of the mean difference for a map of the entire city of Beira, and the RMSE value. Subsequently, they will be used to schematize the case study area. This schematization will not work properly when the underlying data is too rough and is therefore a good indication for the DEM's fitness to be used in flood risk screening.
To enable the comparison of the DEMs, they should be referenced to the same datum. Using GIS-software (QGIS 3.4), all DEMs are warped to the horizontal datum of the LiDAR data (WGS84/UTM zone 36S). Regarding the vertical datum, a different approach is chosen, using a local reference point. The reason is twofold. First of all, the objective is to reduce potential biases in the global DEMs, thereby improving the local accuracy. Second, since the geoid model used for the Lidar dataset could not be retrieved (see also Table 4-1), a direct datum transformation was not available for this data. The local reference point, near the Beira harbour, was obtained by GNSS as part of a local quay works improvement project. For the GNSS height a vertical accuracy of <5 cm can be assumed. The height was defined with respect to the Lower Astronomical Tide (LAT), which is thereby the vertical datum used in the further analysis. The DEMs are referenced in the form of a constant offset, based on the difference between the GNSS height and the DEM value at the GNSS location. This offset was +6,0 m for the WorldDEM and +3,08m for the LiDAR DEM. SRTM and AW3D required no offset. Note that possible spatial height trends between the different vertical datums are hereby neglected. Local height trends between geoid models will be small, but especially between geoid and ellipsoidal based datasets this trend could be significant. Even for a relatively small area as the city of Beira, this could lead to slope effects in the order of decimetres. Therefore, ideally transformations between the various vertical datums should be applied first, in combination with multiple distributed reference points.

4.2.1.2 Flood risk screening model

The flood analysis will be done with the Flood Risk Reduction Evaluation and Screening (FLORES) model. This model has been used in the study area as part of an earlier research (van Berchum, 2019b). FLORES compares different flood risk reduction strategies, aiming to support decision-making early in the planning phase. It revolves around a rapid flood simulation model using basic hydraulic formulas to minimize the computational load. The flood simulation can be adjusted to account for different flood hazards – coastal storm surge and extreme rainfall -, flood risk reduction measures, and future scenarios. In Beira, FLORES examined the current flood risk and compared many different flood risk reduction strategies, consisting of both coastal and inland measures. This information is useful to get a clear understanding of the current

situation and the impact that design choices may have.
To minimize computational load, the study area is schematized as a collection of drainage basins, which are defined as areas where all water flows towards the same lowest point, see Figure 4-1. Because this schematization is based on the DEM, the use of different DEMs will therefore also lead to different schematizations. The flood simulation effectively runs hydrological water balances for each of these basins at each time step. Water can flow into the basin through rain, storm surge, drainage and surface flooding from adjacent basins. Similarly, outflow can occur through infiltration, drainage and surface flooding towards adjacent basins. A DEM is used to (1) define the drainage basins, (2) define the contour areas (areas which are bounded by elevation contours, see Figure 4-1), and (3) calculate and map the flood depth. This highlights the importance of a DEM with high resolution – especially vertical – and accuracy.

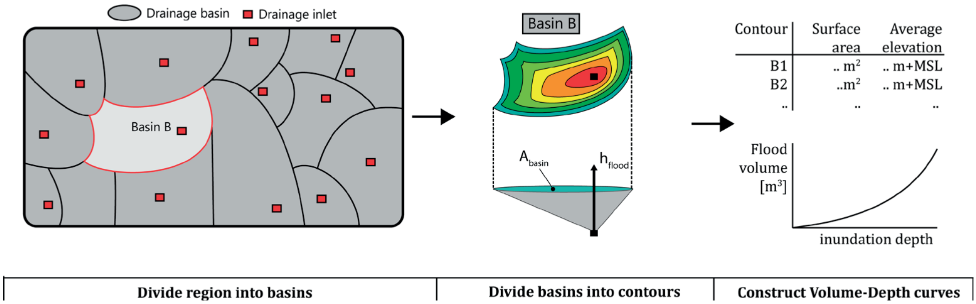


Figure 4-1: Schematization of the city. Based on a DEM, it is divided by drainage point and elevation. In the model, contours are areas delimited by elevation contours.

4.2.2 Evaluation method

The DEMs and flood simulations are used in different parts of the flood risk management process. In order to assess the usefulness of the free global DEMs, first they will be compared on their ability to accurately measure areas for large-scale application. This comparison will focus on resolution and the usefulness for the flood risk screening model. Out of this comparison, the DEM with the most potential will be used for flood risk screening and compared with the LiDAR results. Performance and usefulness can be compared on roughly four levels:

1. Single event hydrology
2. Single event impact
3. Flood risk profile
4. Effectiveness of measures and flood risk management actions

These four levels are used to clearly distinguish between the different uses that a flood simulation may have and how this is affected by a change in DEM. On the first level, the hydrological outcome of a single flood simulation is compared. This focuses on the flood extent and water depths throughout the flooded area. Second, we compare the impact. With the model, economic damages and amount of people affected can be estimated. This impact calculation also depends on the underlying DEM. Third, we focus on the entire risk profile. In this study, flood risk is defined as the combination of all possible events, each of which has a probability of occurrence and a potential negative consequence (Kaplan and Garrick, 1981). The risk profile represents and visualizes the economic damages across all possible storms and is measured in expected annual damages ($/year). Lastly, we will highlight the usefulness to support decisions in a flood risk management process. Using the results of a flood risk screening model, it is possible to construct and compare flood risk profiles for many different flood risk reduction strategies. This comparison can support decision-making in planning process by identifying trade-offs and trends. For decision-makers, this is the most important step. After all, a flood simulation is expected to perform worse when it is based on a lower-resolution DEM, but if it leads to comparable advice for decision-makers in terms of the suggested measures, this can be seen as acceptable in the early stages of planning.

4.2.3 Study area

The influence of the DEM on the flood modelling is evaluated using the city of Beira, Mozambique. This is one of the largest cities in the country, situated at the coast of the Indian Ocean. It floods almost on a yearly basis as a result of extreme rainfall. On top of that, it is threatened by tropical cyclones, which can lead to high coastal storm surges, as well as heavy rain. In March 2019, Cyclone Idai made landfall at the coast of Beira and caused major damage, mostly through wind and rainfall (OCHA, 2019). Recently, much effort has been put into finding an effective and sustainable flood risk management strategy. However, as most reports were based on qualitative assessment, detailed information concerning the local topography, flood hazard, the exposed structures and population, and their future predictions were still lacking. To support future research, a LiDAR-based DEM was financed through the World Bank(CES and Inros Lackner AG, 2013). Since, this data has been used in several projects, including a preliminary design of a new drainage system and research focused on screening the local flood risk and potential flood risk reduction measures. The topography of Beira resembles that of many other coastal cities. It is located at the mouth of the Pungwe River, where it connects with the Indian Ocean. Beira was formed on dune ridges at the coast. Behind the dune ridges is a lower-lying area, which regularly floods due to rainfall. More to the north-east, the elevation rises again, see Figure 4-2. The entire city is situated above mean sea level. Overall, the elevation differences between lower and higher elevated parts of the city are relatively small, with a difference of roughly 10 meters between the lowest parts of the city and the higher grounds inland.

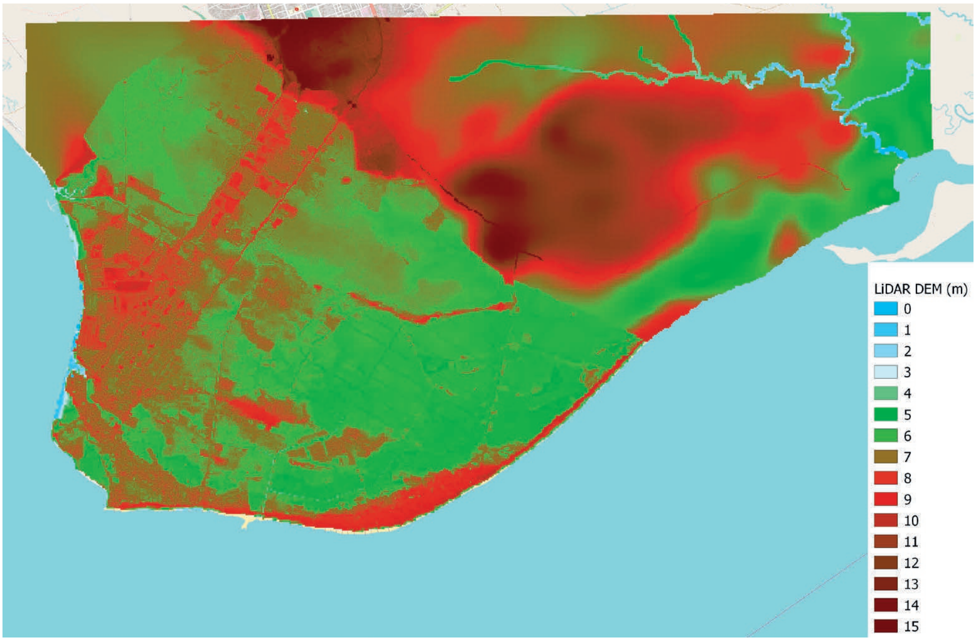


Figure 4-2: Elevation of Beira in m+LAT (Lower Astronomical Tide), produced with LiDAR © DLR.

4.3 Results

4.3.1 Comparison of DEMs

For the study area in Beira, there were clear differences between the DEMs, also when compared to the LiDAR results. All elevation models were calibrated with local measurements in the harbour, close to the city centre. The differences between the LIDAR data and the other datasets are quantified in Table 4-2 through the mean difference and the Root Mean Squared Error (RMSE). This is also visualized in Figure 4-3.
Figure 4-3 shows the difference of each datapoint between the three considered DEMs and the LiDAR dataset. For this comparison, the horizontal resolutions of each dataset were interpolated to match the LIDAR, meaning that the figures show the same amount of datapoints. The input for the comparison can be seen in Figure 4-4, which

Table 4-2: Comparison of Global DEMs with regards to the LiDAR measurements.

	Mean difference	RMSE
STRM	0.4 m	2.4 m
AW3D	0.2 m	1.8 m
WorldDEM	0.3 m	1.5 m

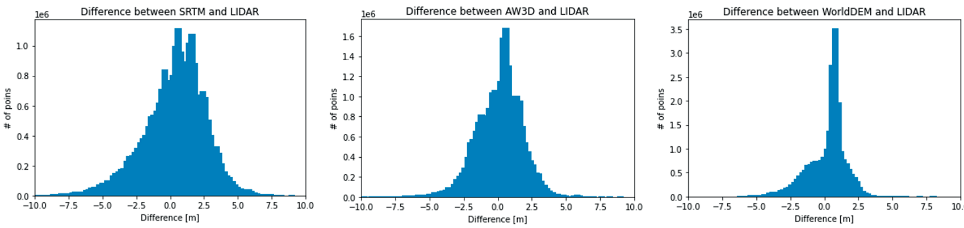


Figure 4-3: Difference of DEMs compared to LiDAR dataset. Shown is SRTM (left), AW3D (middle) and WorldDEM (right). The figures show the amount of datapoints within a certain range.

shows measured elevation in Beira for each dataset, all referenced to the datum of the LiDAR dataset. The figures show that the SRTM measurements have a much larger uncertainty, with large differences in elevation close to each other and many extreme values. Figure 4-4 shows that AW3D and notably the WorldDEM are a much clearer depiction of where the high and low parts of the city are. This explains the results in Figure 4-3, where all three datasets have a similar mean difference, but the spread is significantly higher for the SRTM data compared to AW3D and especially WorldDEM. The schematization in FLORES, explained in Section 2.2.2, uses the DEM to divide the city into drainage basins, where individual basins are areas where all water would flow

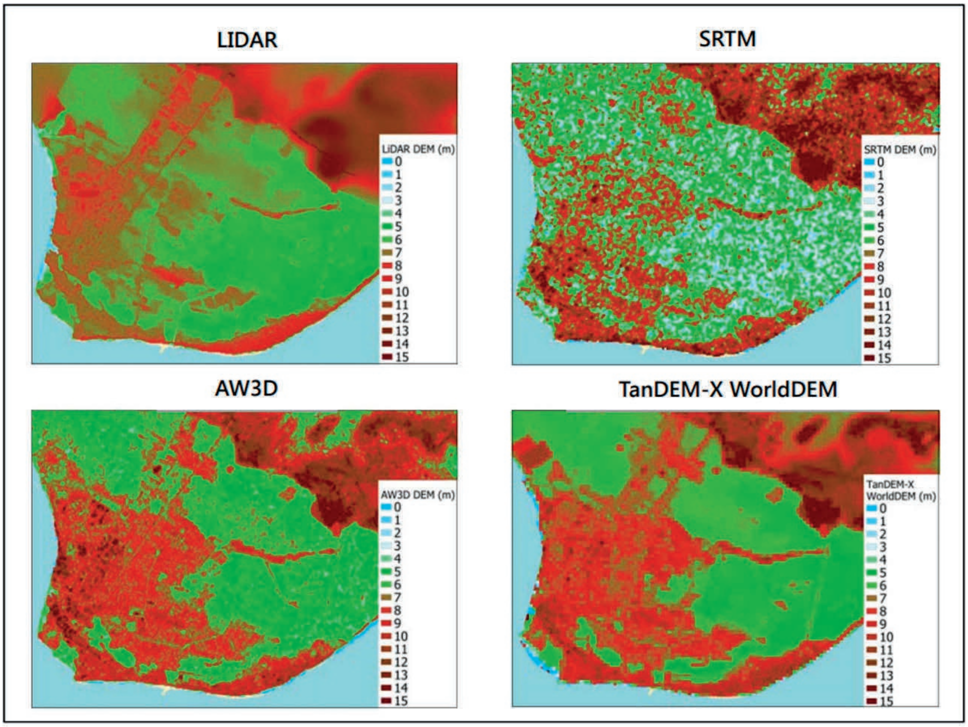


Figure 4-4: Elevation map of Beira using LiDAR, SRTM, AW3D and WorldDEM data. The elevation is shown in meters above Lower Astronomical Tide (m+LAT). North is up.

towards the same point. SRTM and AW3D have a relatively low vertical resolution (1.0 m) and were unfit to accurately model a relatively flat coastal area. Using the schematization for these datasets led to drainage basins not based on real physical landscape but mostly on coincidental outliers of the data. WorldDEM, even though the horizontal resolution was worse (~90m compared to ~30m), had a much better vertical resolution and was therefore able to model the city's topography better. The schematization led to drainage basins mostly resembling those of the LiDAR schematization, although the higher resolution of the LiDAR allowed for smaller and more basins to be defined as smaller differences in the landscape elevation are noticed. This comparison is visible in the red lines of Figure 4-5.

4.3.2 Comparison of flood risk assessment results

4.3.2.1 Level 1: Single event hydrology

Because of the better accuracy and vertical resolution, the WorldDEM schematized the area sufficiently well for the flood risk screening model, and will therefore be compared with the LiDAR data and results. Figure 4-5 compares flood simulations executed on the LiDAR and WorldDEM datasets. This is done for a rainfall and storm surge event with a return period of 10 years, which amounts to a rainfall event of 264 mm in a day and a storm surge event with a maximum surge level of 7.5 m+LAT. Please note that

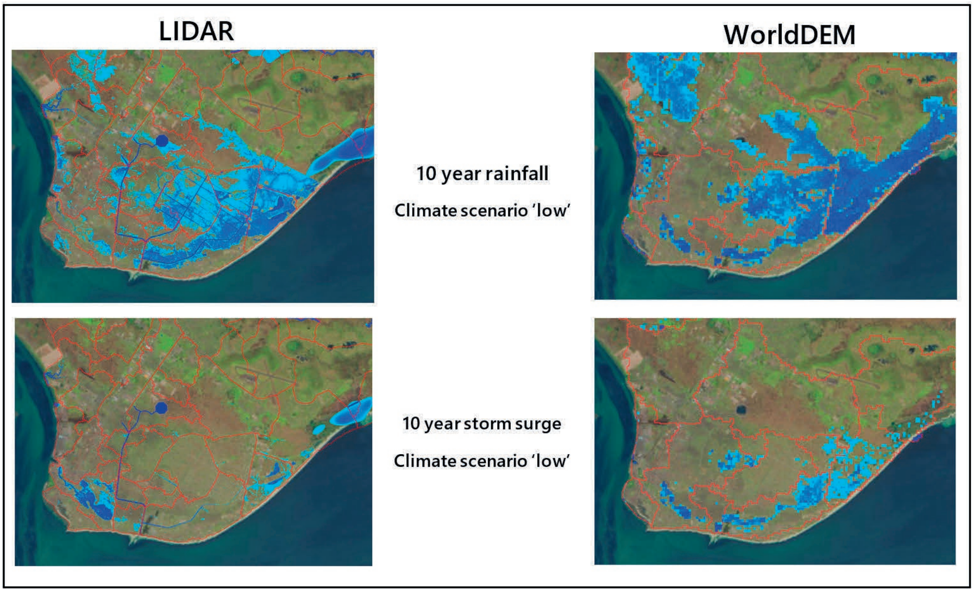


Figure 4-5: Comparison of flood simulations for three different events between the models based on LiDAR data (left) and the WorldDEM data (right). Denoted in red are the drainage basins in which the FLORES model divides the city.

the flood risk screening model FLORES schematizes the city based on the DEM, which means that different DEMs will lead to different schematizations (red lines in Figure 4-5). This also shows why the SRTM and AW3D datasets were not suitable for this step, as the data was too rough for the schematization step.
The simulations based on WorldDEM show similar patterns and flood extent compared to the simulations based on LiDAR. Interestingly, flood areas are more concentrated, because the lower resolution had led to a rougher schematization with less drainage basins compared to the simulations based on LiDAR data. Water accumulates at the bottom of these basins. With a larger area flowing towards the same point, flooding increases in areas where the topography is relatively flat. In the flood simulation based on the LiDAR DEM, this volume is distributed between more local minima, leading to less flooding overall. Information on the datasets used for this simulation and the rest of the screening can be found in Appendix A.

The flooded area is comparable for both DEMs in both situations. However, for the LiDAR-based simulation, the storm surge scenario had less flooding overall. It was able to identify several places of (natural) retention or drainage and store significant amounts of the flood water in these places, especially in the western part of the city, near the Rio Chiveve and drainage system.
The average flood was comparable in both simulations, see Table 4-3. Closer examination of the simulation show that the LiDAR allows more water to flow to outlets on the north-eastern side of the area, which are barely distinguishable on the WorldDEM.

Table 4-3: Comparison of flood simulations based on LiDAR and WorldDEM data. The figures are based on the 10-year rainfall event.

	LiDAR	WorldDEM	Difference
Flooded area	27 km^2	30 km^2	+15%
Average depth	0.1 m	0.1 m	
Maximum depth	2.8 m	2.3 m	

4.3.2.2 Level 2: Single event impact

To quantify the flood impact, the simulation distinguishes economic damage and amount of people affected. The drainage basins are divided into elevation contour areas to improve the amount of detail. Damage and amount of people affected is determined for each elevation contour, and subsequently summed for the entire city to get total figures (van Berchum et al., 2018a). Table 4-4 shows the impact of a number of flood simulations with the FLORES model in terms of economic damage and number of people affected, where the schematization is based on either LiDAR or WorldDEM.

Table 4-4: Comparison of various flood simulations with the FLORES model indicating the estimated economic damages and number of people affected. The schematization is based on either LiDAR data or WorldDEM data.

Simulation	LIDAR	WorldDEM	Difference
10-year rainfall	37M$ 136,000 people	33M$ 160,000 people	-11% +18%
10-year storm surge	8.8 M$ 23,000 people	9.0 M$ 30,000 people	+2% +30%
10-year rainfall + 10 year storm surge	50 M$ 158,000 people	45 M$ 190,000 people	-10% +20%
100-year rainfall	50 M$ 181,000 people	57 M$ 190,000 people	+14% +5%
100-year storm surge	74 M$ 289,000 people	69 M$ 223,000 people	-7% -23%
100-year rainfall + 100-year storm surge	118 M$ 415,000 people	150 M$ 272,000 people	+27% -34%

The table above shows clear differences up to 30% in flood impact, which should be kept in mind when individual simulations are used for flood risk management purposes. However, in the application where flood risk screening models should be used – conceptual design and prioritization of strategies – this will mostly be within the uncertainty range of the simulation. It is more useful to understand where the differences come from, and whether they can lead to a systematic preference for certain types of measures. From the flood extent simulations (Figure 4-5), we can see that the larger drainage basins, denoted by the red outlines, in the low-resolution simulation in the low-lying parts of the basin are flooding sooner and the higher elevated areas hardly flood, even for bigger storms. This explains some of the differences, especially for the amount of people affected.

4.3.2.3 Level 3: Flood risk profile

To assess the effectiveness of a flood risk reduction strategy, we compare the flood risk profile with the initial conditions, or with other strategies. The flood risk profile represents the entire set of possible storm conditions. This is calculated by considering a range of representative simulations. In Beira, coastal storm surge and extreme rainfall are considered. Therefore, the risk profile is represented by 25 simulations, where each flood hazards is approximated by 4 different return periods of the event, combined with the absence of (0-, 5- ,10-, 50-,100-year event).

In general, the two risk profiles are mostly similar. Both show that extreme rainfall already causes significant damage from a 5-year rainfall event (p_{rain}=0.2), while the coastal defenses minimize damage from coastal surge up to a 10-year storm surge event (p_{surge}=0.1). Also, for compound flood events – where both coastal storm

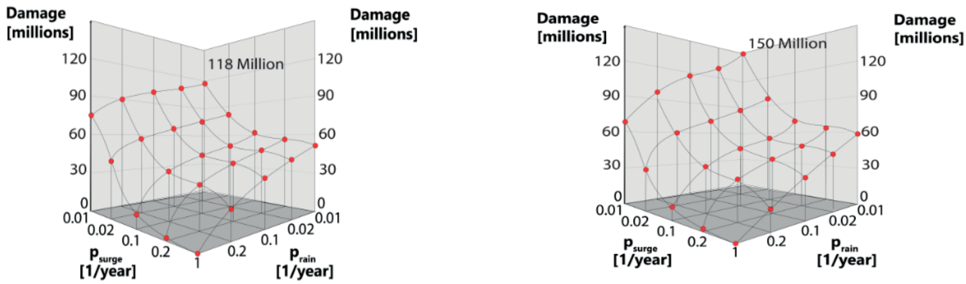


Figure 4-6: Risk curves for the city of Beira based on simulations by the FLORES model, based on schematizations with LiDAR data (left) or the WorldDEM (right). Each risk curve is represented by 25 simulations (red dots).

surge and extreme rainfall occur – the jump in expected damage because of the moreextreme 50-year coastal storm surge events is clearly visible in both. Assuming independence between pluvial flooding and storm surge, the total risk amounts to 26 M$ and 35 M$ for the LiDAR- and WorldDEM-based analysis respectively.

Closer comparison of the two risk curves shows how the difference between the impact of the two hazards – storm surge and rainfall – is even more pronounced in the WorldDEM screening. The city was able to cope with storm surge more than rainfall, which was also the case for the LiDAR-based results. However, the difference between failure and non-failure of the coastal system can be seen even more clearly. This can be a consequence of the larger size of the drainage basins and the fact that most economic value is relatively higher elevated. While in the higher-resolution LiDAR simulations, some of these buildings could already be affected by rainfall, larger drainage basins mean that a large coastal storm surge was needed to produce the required volumes to flood these areas. Summarizing, although some smaller scale influences were lost due to the lower resolution, comparable conclusions can be drawn about the impacts of the flood hazards and the city's response.

4.3.2.4 Level 4: Effectiveness of measures and flood risk management actions

Lastly, we compare the screening results in terms of suggested (types of) interventions. Depending on the user-defined goals, these tools can be used to develop preferences and compare flood risk reduction strategies. For decision-makers, it is crucial to know that the preferences from the results are not heavily influenced by DEM input. To compare the results, a screening was executed based on LiDAR and WorldDEM data, using the FLORES flood risk screening model. More information about the data sources can be found in Appendix A.

Two methods of visualizing the screening results are show below. Figure 4-7 shows the results of a screening of 500 flood risk reduction strategies for two different future climate scenarios. Each dot represents one flood risk reduction strategy consisting of a set of interventions such as heightening dunes, expanding drainage systems, and implementing early-warning systems. Each strategy is simulated for a large number of storms, similar to the risk profiles in Figure 4-6. Compared to the more detailed LiDAR data, the low-resolution results show a larger variability between strategies. As a result, the impact of different future scenarios is easier to distinguish for the LiDAR-based screening.

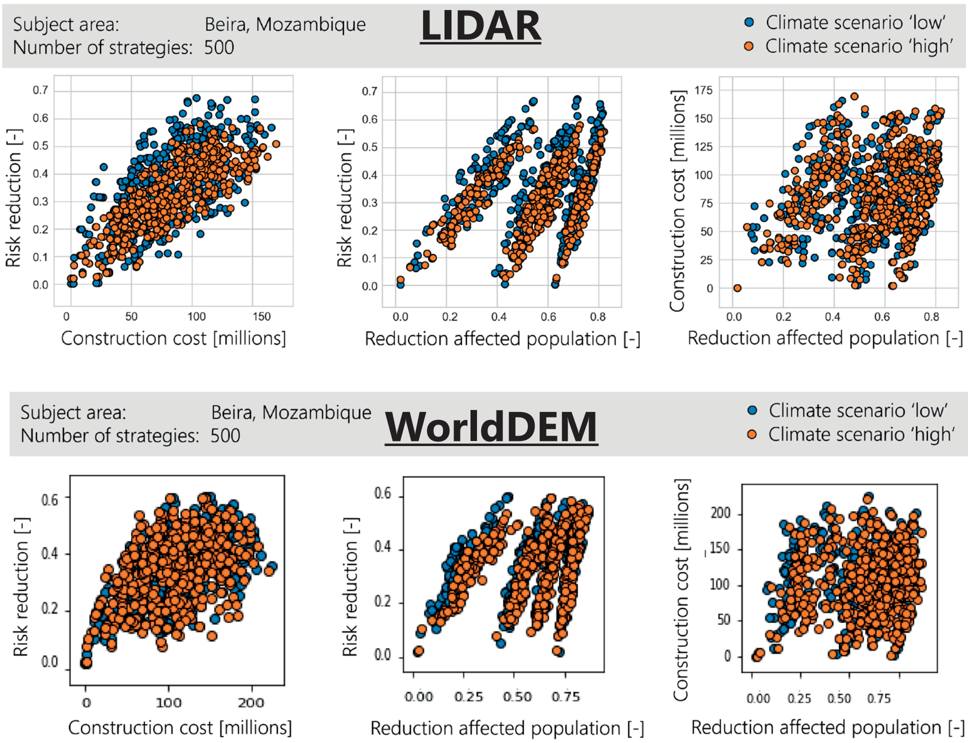


Figure 4-7: Comparison of the screening results, where the three outputs (risk reduction, construction cost, reduction affected population) are plotted in pairs. One dot is one flood risk reduction strategy. The colors indicate two different future climate scenarios. Please note that the scales can differ.

Table 4-5 compares the prioritization of flood risk reduction measures. This is done through Scenario Discovery, where an algorithm searches for the most effective combination of measures that lead to present goals. The goal of this analysis is to find the most interesting measures and combinations thereof.

In the LiDAR-based screening, scenarios that assume a moderate future climate change scenario (closer to the current situation), recommended strategies focusing on drainage. More extreme future climate outlooks however, are leaning more towards improving coastal structures. The WorldDEM-based results show similar conclusions. In both screenings, the importance of improving drainage and the western coastal protection are part of the preferred strategy. Also, both show a shift towards coastal solutions in a more extreme future scenario. However, there are also differences on the scale of individual measures. For example, the WorldDEM screening highly prefers

Micro drainage, which has a smaller impact in the LiDAR-based screening. Also, the impact of the structure on the eastern coast has reduced greatly. From simulations, it can be seen that the area behind the eastern coastal defence floods relatively quickly because of its low elevation, and not necessarily due to storm surge. This would negatively affect the impact a coastal structure would have.

Table 4-5: Scenario discovery results for strategies focused on risk reduction. 'Goals' shows what output we are looking for, 'Start' shows how many strategies out of the initial 500 comply with the goals. 'Results' show which design choices are made by the algorithm, focusing on the most promising strategies. 'Final' indicates how many strategies are left – after filtering for the measures listed under 'results' – and how many of those comply with the goals.

Goals[1]	**Start** Strategies of interest	**Results** Design choices (priority from top down)	**Final** Strategies of interest
LiDAR			
For 'low' climate scenario: *Risk reduction > 0.55*	**51** out of 500	1. Drainage system second phase 2. Retention east 3. Coastal structural west 4. Coastal structure east 5. height coastal structure east > 9.4 m	**42** out of **55**
For 'high' climate scenario: *risk reduction > 0.45*	**86** out of 500	1. Coastal structure west 2. Coastal structure east 3. Drainage system second phase 4. Height coastal structure west > 8.9 m	**60** out of **67**
WorldDEM			
For 'low' climate scenario: *risk reduction > 0.45*	**57** out of 500	1. Drainage system second phase 2. Coastal structural west 3. Micro drainage	**47** out of **50**
For 'high' climate scenario: *risk reduction >0.45*	**58** out of 500	1. Micro drainage 2. Coastal structure west 3. Second phase drainage 4. Height coastal structure west > 8.3 m	**43** out of **50**

[1] Please note that the exact goal boundaries might differ. Due to differences in input data sources, the entire solution space can shift. In this case, using the same boundaries can result in unworkable situations (too little/ too many strategies to search for). Therefore, the goals were adjusted to a similar portion of strategies being interesting (e.g. aiming for 10% most risk reducing strategies).

In short, the screening results lead to similar conclusions, although the lack of DEM resolution can impact the perceived effectiveness of individual measures. The flood simulations themselves have shown noticeable differences, which also led to different flood impacts. However, because these differences are mostly consistent across simulations based on the same DEM, the resulting risk reduction and therefore the prioritization of flood risk reduction measures is quite similar. The same conclusions can be drawn from other realizations of the Scenario Discovery tool, which can also be focused on e.g., decreasing amount of people affected or a more balanced set of goals. It must be noted that screening based on the low-resolution DEM did have a broader bandwidth in results (larger uncertainty) and the difference between different future scenarios was less pronounced.

4.4 Discussion

DEMs are crucial for a clear understanding of the local hydrology and the basis for flood simulation models. Although they have been constantly improving over the past decades, there are a number of limitations that should be kept in mind. First of all, the represented surface by the DEM should be considered. DEMs can be categorized as Digital Terrain Models (DTM, representing ground level) and Digital Surface Models (DSM, representing the surface level including objects). The success of removing objects to create a DTM, which are used in this study, is largely dependent on the acquisition technique and spatial resolution. That is, with an original Lidar data set with a point density of multiple points per square meter, objects can be detected relatively easily. With satellite radar-based observations with a resolution in the order of meters, such as used for the SRTM and WorldDEM DEMs, this is more challenging, affecting the final height level obtained. Secondly, the horizontal resolution affects the applicability. Especially a mountainous area could suffer more from lower horizontal resolution, as the elevation varies more in each pixel. These variations can greatly influence the local hydrology, which would be missed in lower resolutions. Third, the vertical resolution and accuracy have a direct influence on the result. Certainly, a relatively flat area, such as a coastal area, is very susceptible to absolute errors. For this case study, which focused on a coastal city, the SRTM and AW3D were clearly insufficient by account of their poor vertical resolution (1.0 meter).

To reduce a potential bias in a global DEM, a dedicated calibration to local reference points can be applied. As noted above, an absolute error can make a large difference, especially in a coastal area. In this case, the DEMs were calibrated through one ground control point. This showed that each DEM had some absolute difference compared to the LiDAR dataset. Especially when different vertical datums are involved, either based on a geoid or ellipsoid model, the calibration should be preceded with the associated datum transformation. By using multiple reference points the accuracy of the local calibration can be further improved.

The ability to use DEMs in flood risk analysis also depends on the flood simulation and flood risk analysis model, in this case FLORES. This model is especially built to work with low-resolution data and in a phase of design where large-scale choices need to be made. For flood simulation models that focus on a more detailed design phase and require more accurate input data, the use of these global DEMs might not be accurate enough. For example, more detailed design of coastal protection would need better elevation measurements to be able to estimate required amounts of material. In an urban environment, planning drainage is very much dependent on the local topography. Using low-resolution elevation data could at that point lead to underestimating the flow and required dimensions of structural elements of the drainage system. In short, in a later design stage more knowledge on the flood routing, and water volumes and velocities is needed to prevent flood risk reduction measures to be wrongly dimensioned.

This also underlines the role of the expert in the use of conceptual design models such as FLORES in data scarce areas. The FLORES model is specially built to be workable with very little information. Nonetheless, it will still produce detailed risk profiles and show flood maps on the resolution of the DEM. In this case, it is up to the expert to judge whether the detail level of the input data and analysis type is sufficient to answer the client’s questions.

It should also be noted that this DEM analysis specifically focusses on free globally available DEMs. This excludes the range of paid global DEM products. For some of the mentioned DEMs, namely AW3D and WorldDEM, also a more accurate paid version is available. How such datasets compare to free products and to more expensive LiDAR data, especially with the goal of quick flood risk screening, is a promising topic for future research.

4.5 Conclusions

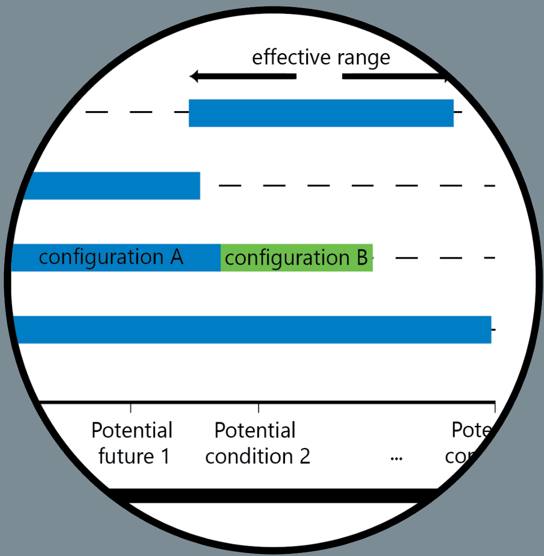
This chapter assessed the usefulness of three publicly available (near-)global DEMs for the use in flood risk management purposes, through a comparison of SRTM, AW3D, and TanDEM-X WorldDEM. These models were, after calibration with a local reference point, compared on their resolution, accuracy, and compatibility for flood risk screening software. The comparison was done for a study area in the city of Beira, on the coast of Mozambique, of which also high-resolution LiDAR data was available. SRTM and AW3D have a relatively low vertical resolution (1.0 m) and were unfit to accurately model a relatively flat coastal area. The WorldDEM, even though the horizontal resolution was worse (~90 m compared to ~30 m), had a much better vertical resolution and was therefore able to model the city’s topography better. Second, the WorldDEM – being the only of the three models that was sufficiently accurate for flood simulation software – was compared on its usefulness in flood risk management. This comparison took place on four levels: flood simulation, flood impact, flood risk, and effectiveness of measures and strategies. On all levels, the difference was noticeable, but lead to similar insights and conclusions for the conceptual design. The flood simulation showed a small skewedness towards flooding in lower-lying areas and higher average water depths, although these differences do fall within the uncertainty range.

The damages and the flood risk based on the WorldDEM were higher but showed the similar patterns when comparing different storm intensities and flood hazards. This resulted in very similar flood risk management conclusions, when it comes to prioritization of measures or strategies. Both for the results based on the WorldDEM dataset and the LiDAR dataset, a short-term prioritization for increasing drainage capacity was key. For more extreme future climate conditions, strengthening of the western coastal flood defences was a crucial part of any effective flood risk reduction strategy.

The resolution of free global DEMs is still relatively low compared to that what is commonly used in flood risk simulations or flood risk management. Especially the vertical resolution can be problematic, as differences within the uncertainty bounds can greatly impact the slope and therefore the flow of water. However, this research has shown that for conceptual flood risk management planning purposes on a city or regional scale, it is possible to draw useful conclusions from flood risk screening based on the WorldDEM. As both flood risk models and global DEMs keep improving over the coming years, this may lead to better informed decisions for the flood risk management in flood-prone cities.

Further research on this topic is recommended, as both the flood risk management and remote sensing are highly developing fields, and a wider knowledge of the possibilities to combine free elevation data with flood risk management can greatly stimulate the knowledge on flood risk in developing, data scarce areas.

A recommended step is the development of more flood risk models meant for conceptual design, capable of using low-resolution data. On the remote sensing side, developing more reliable DEMs and testing these in a flood risk management environment can show its potential as a new standard tool for future flood risk management experts.



Chapter 5

Planning of robust flood risk management strategies

Through the past four chapters, FLORES is established as a widely applicable model for screening flood risk reduction strategies in order to provide useful information early in the design process. It identifies promising flood risk reduction measures and shows effective combinations of measures, taking into account uncertain variables, both when they can be described probabilistically or when they are deeply uncertain. Due to external factors, such as climate change and rapid socio-economic development, these uncertainties are growing rapidly. The design of future flood defence systems is complicated further by new flood risk management technologies like nature-based solutions, mega-nourishments, and flood mitigation approaches like multi-layered safety. Consequently, the complexity of flood risk management planning is increasing thus enlarging the range of options, called the design space.
This chapter presents a generic approach that builds on methods for robust decision-making to deal with the combined challenge of increasing uncertainty and the growing design space in planning flood risk management strategies. The presented approach uses the FLORES model to structure, simulate, and screen flood risk reduction measures and strategies. Next, it identifies robustness zones for these measures as an easy-to-understand way of visualizing the range of future scenarios for which a measure can be effective. The method is demonstrated for the case study of Beira, Mozambique, where it led to the development of a dynamically robust flood risk management plan for the short, medium, and long term, taking several deeply uncertain parameters – in this case sea level rise, rainfall intensity and urban development – into account.

5.1 Introduction

Planners and engineers in flood risk management (FRM) face the challenge of dealing with an increasingly uncertain future and an expanding design space. Climate change results in sea-level rise, changes in storm and wave climate, and modified rainfall patterns and river discharges. Al these factors influence the probability of disastrous flood events (Winsemius et al., 2016, Hinkel et al., 2014, Tingsanchali, 2012) in a currently unknowable manner and thus are deeply uncertain (Lempert et al., 2006). At the same time, the consequences of these events rise because of the socio-economic developments and the associated growth of investments and population (Okazawa et al., 2011, Huizinga et al., 2017). Already, floods are the most common weather, climate, and water-related disaster (Zhongming et al., 2021). The resulting growing attention for safety from flooding results in the development of new approaches and strategies for FRM. Besides investments in dikes, levees and storm surge barriers, now also multi-layered safety (Tsimopoulou et al., 2013), nature-based solutions (Narayan et al., 2016), mega nourishments (Stive et al., 2013), and coastal wetlands (Zhu et al., 2020) populate the expanding toolbox of flood risk engineers and planners. Also, flood mitigation strategies such as raising buildings, insurance and emergency management can contribute to reducing risks. These developments in flood risk management complicate the situation, as the large design space requires many expensive and time-consuming calculations and simulations to identify promising measures and strategies. This topic has already been explored in the previous chapters of this thesis (2 and 3) albeit with limited attention for the consequences future uncertainties.

A common way to deal with both deep uncertainty and extensive design space is through exploratory modelling (Bankes, 1993, Walker et al., 2013, Kwakkel, 2017a). Exploratory modelling uses fit-for-purpose models (Haasnoot et al., 2014, Jafino et al., 2021) for what-if scenario generation and exploration, to identify combinations of uncertainties and strategies that make a difference for design. The explorative use of models is common in policy sciences, where several methods to support planning and design under deep uncertainty have been developed (Walker et al., 2013). Methods such as Assumption-Based Planning (Dewar, 2002), (Many Objective) Robust Decision Making (Groves and Lempert, 2007, Kasprzyk et al., 2013), Adaptive Policy-Making (Walker et al., 2001, Hamarat et al., 2013, Kwakkel et al., 2010), Adaptation Options (Wilby and Dessai, 2010), Adaptation Tipping Points and Adaptation Pathways (Wise et al., 2014, Haasnoot et al., 2012), Adaptive Policy Pathways (Haasnoot et al., 2013), that rely on an exploratory use of models, are applied in planning and policy practice, for example under the name of adaptive delta management (Bloemen et al., 2019). In flood risk management, exploratory modelling has been used to explore an extended design space (van Berchum et al., 2018b, Timmermans et al., 2020). In this approach, numerous alternative designs – for example for a flood risk management system – are evaluated on the robustness of their performance under plausible future operating conditions (Haasnoot et al., 2013). In this context, robustness is generally defined as the ability of a flood risk reduction measure to perform satisfactorily for a wide range of future scenarios.

Earlier application of exploratory modelling to flood risk management focussed on the exploration of the available flood risk reduction measures (van Berchum et al., 2018b, Ciullo et al., 2019) and the complexity of compound flood events (van Berchum et al., 2020, Oddo et al., 2017, Garner and Keller, 2018). However, the application of model-based decision support under deep uncertainty in the design of flood risk management strategies is still limited.

This contribution builds on the methods that are already well-known and implemented in other fields but focusses specifically on their usefulness in the planning of flood risk management strategies. This often involves complex systems, with an accompanying large design space and many future uncertainties. Here, the main added value would arise from a better understanding of the drivers of flood risk and the impact of measures – as well as interaction between them– under uncertain future conditions. It is a deliberate choice not to aim for analytic profoundness, but to develop a method that is easy to understand, easy to use, and easy to implement in engineering practice. This has led to the notion of robustness zones. Robustness zones highlight the ranges of external parameters (e.g., urban development, flood hazards under climate change) under which a particular measure or combination of measurers performs well. They are not only easy to explain and visualize, but in addition quickly show how the performance of measures is influenced by external parameters, as well as other

options in the design space.
In the next section, we describe the general framework for the design of flood risk management systems under uncertainty. First, we introduce the use of exploratory modelling in the design of infrastructure systems under deep uncertainty. We then proceed to introduce robustness, how to quantify robustness, and how to plan and design for robustness. Third, we introduce a step wise approach for robust flood risk management planning. This includes structuring and analysing the FRM system, as well as planning and designing an effective and robust flood risk management strategy, where a strategy is defined as a combination of flood risk reduction measures. In section 3, we apply the approach outlined to develop a robust flood risk management system for the city of Beira, Mozambique. We conclude this chapter with a discussion of the efficacy of the suggested approach for the design of flood risk management systems in the face of climate change and an expanding toolbox of flood risk management strategies.

5.2 Designing a robust flood risk management system

5.2.1 Assessing robustness

Broadly speaking, robustness is a measure summarizing the performance of an option over a set of scenarios. Literature offers quite a variety of different measures for robustness. McInerney et al. (2012) make a distinction between robust satisficing and regret measures. According to a robust satisficing perspective, the larger the number of scenarios under which minimum performance standards are achieved by a given policy option, the more robust the option is. In contrast, a regret perspective focusses on the difference in performance of a given policy option with the best possible performing option in each scenario. The lower the regret (the difference in performance) the better. The most robust option is the option that minimizes the regret. Giuliani and Castelletti (2016) and (Kwakkel et al., 2016) analyse a wide range of metrics from both the robust satisficing and regret family, as well as a third family of statistical metrics which rely on the various moments of the distribution of performance over the ensemble of scenarios. McPhail et al. (2018) offer an integrating framework and the most comprehensive comparison of metrics from these three families.
The conclusion from these comparisons is that there is no single best robustness metric. Which metric is suitable depends on the policy question at hand. It is, however, recommended to use multiple robustness metrics side-by-side, since the different metrics capture different aspects of robustness. In this chapter, we propose a graphical representation, robustness zones, that visualizes robustness effectively for policy makers and engineers involved in the early phase of flood risk management planning. Robustness zones show the range of future scenarios under which a flood risk reduction measure can perform satisfactorily. Flood risk management systems typically need to comply with (satisfy) predetermined safety standards. This makes robust satisficing the preferred criterion for flood risk management systems.

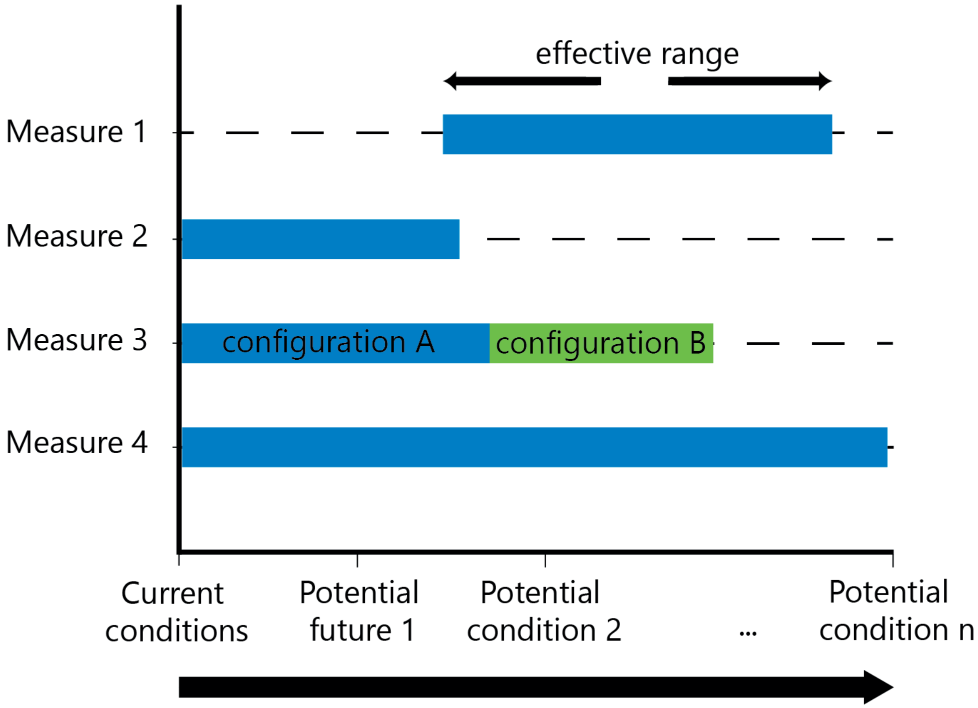


Figure 5-1: Schematic representation of robustness zones. The shaded areas show the range of potential future conditions for which a measure can be part of an effective flood risk management strategy. The potential conditions relate to the amount of change of an external factor (e.g., sea level rise, economic development)

5.2.2 Design principles for achieving robustness

There are various ways in which higher robustness can be achieved in the planning and design of infrastructure. For example, for a pumping-station, a structural design of the pump-house allowing for the installation of additional pumps and engines on the longer term might be a good idea (i.e. flexibility), while the electro-mechanical components of the same pumping-station can be designed to perform well enough over their expected life-time (Timmermans et al., 2020). Similar to the selection of a preferred robustness criterion, selecting a fitting approach for realizing robustness for a specific design, depends on the context and the characteristics of the design. To inform the selection of a suitable approach requires a clear definition of the available alternative approaches to robustness. Walker et al. (2013) present a typology that distinguish four approaches towards robustness. This typology may also yield a fruitful conceptualisation for the application of an approach to robustness in infrastructure design:

1. Resistance: design for the worst possible case or future situation. This comes at high costs and the potential of substantial overinvestments.
2. Resilience: whatever happens in the future, make sure that the design can quickly recover.
3. Static robustness: a design that performs satisfactorily under a wide variety of future conditions.
4. Dynamic robustness: a design that leaves options open and can be adapted to changing future conditions such that the design continues to perform satisfactorily.

In flood risk management, resistance is the default approach to realize robustness. Engineers design for future expected storm intensities associated with certain likelihoods, and often include conservative estimates for the impact of future climate change by applying safety margins. Under deep uncertainty, this approach results in a resistant design and will often result in over-investments. When designing under deep uncertainty, static and dynamic approaches might yield increased performance at lower costs, while satisfying predetermined safety standards. For long-lived, high-investment infrastructure like FRM systems, we assume dynamic robustness is the preferred approach. In the next section, we present a structured approach towards robustness in infrastructure design.

5.2.3 Model-based support for designing robust flood risk management systems

The XLRM framework (Lempert et al., 2003) was developed to structure decision problems under deep uncertainty and is, among others, used to structure decision and design challenges for the application of robustness decision making approaches and exploratory modelling (Kwakkel, 2017a, Bankes, 1993). The framework has successfully been applied to water allocation problems (Murray et al., 2012) and water quality management (Fischbach et al., 2017) and hydraulic structures (Timmermans et al., 2020). Here, we adopt the XLRM framework (Figure 5-1) for structuring the design of FRM systems in the early phases of the design process.

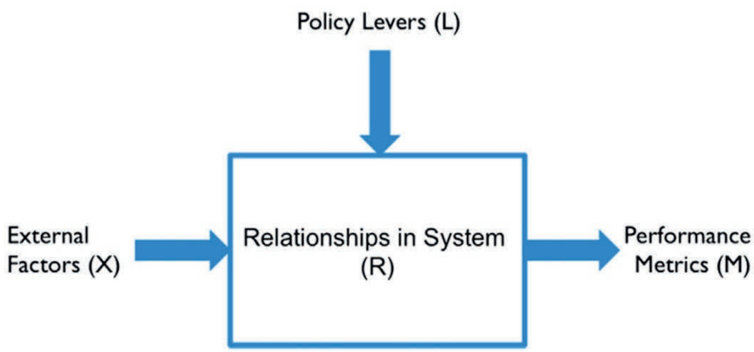


Figure 5-2: XLRM framework. Source: Kwakkel (2017)

The XLRM framework distinguishes four types of factors: external factors (X), policy levers (L), relationships within the system (R), and performance Metrics (M). External factors, X, are factors outside the control of decision-makers and engineers, they are deeply uncertain but may nonetheless determine the long-term performance of the FRM system designed. In the design of FRM systems external forces are generally related to uncertainties in current and future hydraulic loads resulting from lacking or unreliable data, statistical non-stationarity parameters – e.g., climate change and sea-level rise –, or uncertainties in future socio-economic developments determining future vulnerability and/or risk perceptions. In the context of FRM, policy levers, L, are design alternatives or measures that planners and engineers are considering as part of the future FRM strategy. From a planning perspective, this can be risk zoning or an evacuation plan. From an engineering perspective, these are the various flood risk reduction measures like dikes, storm-surge barriers, and nourishments. Relationships within the system, R, represent a model of the FRM system. They describe how the various engineering and planning alternatives (L) interact and how they influence the various criteria (M) that are deemed relevant for the evaluation of the design. They also describe how the various uncertainties (X) affect the outcome on these criteria. The criteria, or performance metrics, are not only evaluated on their present value but also on their value in the uncertain future. They are aggregated over time in a robustness criterion that quantifies the performance of the design under the future conditions specified by the external factors. A performance metric can for example relate to the residual flood risk or the amount of disaster events.

Starting from a fully specified XLRM framework, different approaches are available to develop a robust design. Some approaches rely on the use of optimization techniques and search directly for answers to relevant questions like, 'what is the worst that could happen?', 'What is the best that could happen?', 'What would a good strategy be given one or more scenarios?' (Kwakkel and Haasnoot, 2019).

Other approaches first explore the design and uncertainty space to create an extensive set of possible designs and complementary robustness scores and iteratively use these data to develop a robust design using additional analytic and graphical tools like scenario discovery and multi-plots (Kwakkel and Jaxa-Rozen, 2016, Timmermans et al., 2020). These exploratory approaches investigate the global properties of the uncertainty and the design (policy lever) space by answering questions like 'under what circumstances would this policy do well?', 'under what circumstances would it likely fail?', and 'what dynamics could this system exhibit? (Kwakkel and Haasnoot, 2019, Timmermans et al., 2020, van Berchum et al., 2018b).

These iterative approaches can easily be integrated in engineering practice, because they can easily be used in a hybrid setting in which engineering judgement and analytic tools are combined. Such a process complements engineering knowledge and experience and analysis with computational and analytic tools that help to tackle the additional complexity of extensive design spaces and deep uncertainty. This research specifically supports this engineering approach to design under deep uncertainty by developing robustness zones to present and use the results of the exploration in an iterative setting and facilitate the combination of engineering skills and knowledge with data-oriented analytical methods. Robustness zones graphically present the range for which a specific design is robust for a specific uncertain parameter, for example, sea level. A set of robustness zones for different design alternatives and uncertain parameters supplies the engineer with an overview of the robustness characteristic of alternative designs and thus supports the development of a robust design.

5.2.4 Step wise approach to robust flood risk management planning

In this chapter, we will demonstrate how to structure and model a complex FRM challenge, with several deeply uncertain parameters, and use robustness zones for planning and designing a robust FRM strategy. This requires a systematic approach for the analysis of the region, modelling of the flood risk reduction strategies, and the analysis of the model results. Our approach uses two phases with five steps.

1. **Structuring and modelling**
   1.1 *Structure the FRM system:* specifying the elements of the XLRM framework: external factors (X), policy choices or levers (L), relationships to model (R), and the performance metrics (M) for a specific FRM system.
   1.2 *Develop risk profiles for FRM strategies and future scenarios*. In this research, we use the FLORES rapid simulation and screening model.
2. **Planning and designing**
   2.1 *Screen for promising strategies*. Screening of flood risk reduction stratgies based on t he model results, using Feature Scoring. The goal is to show performance of possible strategies in relation to the other strategies and external factors.
   2.2 *Construct relevant robustness zones.* Develop robustness zones for promising flood risk reduction measures that visualise their robustness under different scenarios.
   2.3 *Develop a dynamically robust plan*. Use robustness zones to design a robust flood risk management system, for the short, medium, and long-term.

The first phase, focussing on the structuring and modelling, mostly makes use of an adapted version of the FLORES model (van Berchum et al., 2020). FLORES is a fast and integrated model that can be applied to explore the uncertainty and design space of FRM systems while keeping the computational load acceptable and practical. FLORES rapidly evaluates flood risk reduction strategies for a city or region using basic hydraulic formulas. Here, strategies are defined as combinations of flood risk reduction measures. The FLORES model schematizes areas as a collection of drainage basins, which are defined as areas where water flows towards the same point. The model runs a water balance for each of these basins for each time step, thereby simulating the surface flow during a flood. The schematization and the basic hydraulic relations are used to limit the calculation time, thereby maximizing the number of scenarios and strategies that can be assessed.
FLORES was developed with several characteristics in mind. For example, a city

or region should be schematized in a generic way, allowing for relatively quick adjustment to a new area. Also, it should be able to assess the effects of both structural and non-structural flood risk reduction measures distributed over time and space and allow for the use of multiple future scenarios and performance metrics. the FLORES model calculated the performance of the chosen flood risk reduction strategy in terms of risk reduction, the reduction of the number of affected people, and the construction costs. These characteristics make the FLORES model especially suitable for use in exploratory modelling for FRM. The exploration of the FLORES model and the analysis of the results, are performed with the help of the Exploratory Modelling and Analysis workbench (Kwakkel, 2017a).

The second phase, focusing on planning and designing, makes use of policy analysis tools to support the process of developing the robust FRM plan, namely feature scoring and robustness zones. Feature scoring (Breiman, 2001) calculates the sensitivity of a performance metric towards the levers, in this case measures. Basically, it shows how a specific measure influences the performance metrics. The results depend on the simulated situation, which can be the current situation or any combination of uncertain parameters like future rainfall intensity or sea levels. Robustness zones are constructed by comparing the measures that are part of the most effective strategies for each of the situations (current or any future scenario). The goal is to show under what conditions a measure is an effective part of the flood risk management system.

To illustrate the use of robustness zones in FRM, in this chapter we focus on the economic optimum. Thus, the nine strategies – combinations of measures - with the lowest total costs are selected, where the total cost is the combination of the yearly expected damage and the yearly costs of a strategy.

These steps are implemented in more detail for a case study below. Section 3 contains the first two steps, mostly focussing on gathering data and development of the risk profiles. The other steps are part of the results.

5.3 Structuring and modelling the Beira flood risk management system

This chapter demonstrates the first steps of planning for robust flood risk management proposed in chapter 2 in a case study for the city of Beira, Mozambique. Here, we apply a satisficing robustness criterion, meaning that we look for plans that meet minimal requirements in as many scenarios as possible. We also follow the design principles of dynamic robustness, which favours plans that leave options open to allow for adjustments later on, when necessary. Thus, a flood risk management plan is classified as more robust when it sufficiently limits flood risk in as many as possible future scenarios.

5.3.1 Beira case study

Beira is one of the largest cities of Mozambique with over 500.000 inhabitants. Originally, it is situated on relatively safe coastal dunes on the coast of the Indian

Figure 5-3: Map of Beira. The city centre is mostly on the western side and along the coast. In the Eastern part of the city, there is a large lower-lying neighbourhood Chota. More towards the northeast is the airport.

Ocean at the mouth of the Pungwe River (Figure 5-3). The city has seen a significant rise in flood risk in the last decades due to the urban expansion into lower-lying areas and large-scale erosion of the coast. Beira is threatened by both extreme rainfall events and coastal storm surges. These hazards can also occur simultaneously during tropical cycles, which occur roughly once every decade. As recently as March 2019, Tropical Cyclone Idai hit Mozambique, and Beira in particular, which affected a calculated 1.85 million people and caused roughly 700 million dollars in damages. Compound flooding is an especially grave risk for Beira, as the drainage system drains under gravity into the ocean, which is impossible during storm surge. Possible measures to reduce flood risk for the city of Beira are, amongst others, coastal protection, improvement of the drainage system, storage basins, improved evacuation, and shelters. In addition, FRM planning is confronted with uncertain external factors, such as climate change and urban development. The combination of multiple flood hazards, many possible flood risk reduction measures and external uncertainties, complicates FRM planning for Beira.

To support the planning process, the city's flood risk has been analysed in an earlier study, using the FLORES model (van Berchum et al., 2020). Through this analysis, several trade-offs and promising combinations of measures have been identified. However, many of the data are lacking, limited, or uncertain, such as data on (future) hydraulic boundary conditions or the effectiveness and cost of measures. This leads to large uncertainties in the robustness of the proposed measures. Because some of the data can only be improved by measurements over longer periods of time or are deeply uncertain because of climate change and uncertain socio-economic developments, a robust decision-making approach to FRM planning with the aim to develop an adaptive flood risk management strategy (that performs well under many future uncertainties), seems relevant.

5.3.1 Structure the FRM system

The flood risk analysis of the case study will be supported through the Python-based FLORES-model (van Berchum et al., 2020). For this study, the FLORES model was developed further to include the ability to phase measures at different points in time. According to the XLRM framework described, we start the robust decision-making approach by structuring the Beira case study in accordance with the XLRM framework: External factors (X), Policy levers (L), Performance metrics (M), and Relationships (R). Here, we describe these factors and the way they are derived, incorporated, and further detailed in the FLORES model.

External factors (X)

Over the years, some of the (hydraulic) boundary conditions will change because of external forcing. This may affect what the most effective flood risk reduction strategy would be. In this case study, we follow three relevant uncertainties as external factors: Sea level rise (SLR), Rainfall intensity, and Economic development. The ranges for these uncertainties are set within plausible limits.
Both SLR and Rainfall intensity are based on climatological changes, which are best described in the fifth assessment report of IPCC (2014). For this analysis, a range of up to 80% increase in rainfall intensity and a +0.8m SLR will be used. The development of a city is often represented through two different parameters, namely the economic growth and the population growth. To simplify the calculation – limiting the calculation to three dimensions instead of four - the growth of economy and population is linked under one 'Development'-parameter. Economic growth and population growth are estimated at a yearly increase of 3.75% and 2.25%, respectively (African Development Bank, 2018, Deltares et al., 2015).
The external factors are calculated on eight 'levels' of change for all three parameters. Table 5-1 lists how each step corresponds to a particular change for each parameter. Please note that only the first three parameters are shown in the calculation. The 'Development level' will act as a single value, signalling the economic and population growth denoted in the table under the chosen development step. The growth is measured in comparison to the current (2020) level, not to a yearly increase. For comparison, a 3.75% yearly increase for 100 years is equal to a +3970% increase compared to the level of first year. Please note that these levels are not linked to a specific future year. The levels are purely based on the change of that particular parameter, regardless of when this arises.

Policy levers (L)

Over the past decades, a number of studies have analysed the region and listed

Table 5-1: Conditions corresponding to levels in the run. The three parameters in the model are Rainfall intensity, Sea level rise, and Development. The levels in development simultaneously affect economic and population growth. The percentages of economic and population growth are relative to the 2020 figures.

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

measures to reduce flood risk (Arcadis, 1999, Deltares et al., 2013, Letitre et al., 2018). These measures range from coastal flood defences, such as levees and storm surge barriers, to urban water management (drainage, retention), emergency measures (early-warning systems, evacuation plans, shelters), and urban planning (relocating vulnerable neighbourhoods, improving crucial infrastructure). Out of all potential flood risk reduction measures, a representative selection of measures is included in the model for this case study. For a shortlist, see Table 5-2. These measures can roughly be divided in measures that focus on coastal storm surge, rainfall, or both. Of the measures in Table 5-2, the first four (Heightening dunes, sand supplements and placing a flood fall) can be seen as purely coastal storm surge-focussed measures. The next four (expand drainage and expand retention capacity) are primarily meant to deal with rainfall. The last four measures focus more on minimizing flood impact and therefore effect both types of flooding. A more complete quantitative description of the measures, please refer to Appendix A.

Table 5-2: Summary of included measures. More information is added in Appendix A.

1. Heighten dunes on eastern coast	7. Retention east of the city (3 different capacities)
2. Sand supplements on the eastern coast	8. Retention in Chota (3 different capacities)
3. Heighten dunes on the western coast	9. Improve evacuation
4. Floodwall on the western coast	10. Early-warning system
5. Expand the drainage system (second phase)	11. Strengthening houses
6. Increase small-scale drainage (micro drainage)	12.Prevent settlements in vulnerable areas

Performance Metrics (M)

An effective and robust strategy is achieved when it sufficiently reduces the flood risk under many plausible futures while minimizing the required investment. In the Beira case study, the robustness of a specific strategy is evaluated through three metrics: economic risk reduction, reduction in amount of people affected, and construction cost. These three metrics - which basically signify the performance - for a flood risk reduction strategy cannot be calculated through one single flood event simulation alone. Thus, a risk profile is built for each individual strategy from 24 total simulations. These simulate the expected impact for every combination of a 0-,5-,10-,50-, and a 100-year storm surge event and rainfall event. The construction cost includes all investment cost of flood risk reduction measures mentioned in Table 5-2. As most of the measures are only designed conceptually, these figures are often based on expert judgement and reference projects.

Relationships in System (R)

The Flood Risk Reduction Evaluation and Screening (FLORES) model is used for the simulations (van Berchum et al., 2020). The urban area of Beira was schematized by dividing it up into drainage basins as the base unit of the simulation and exploration. The model requires data mostly for the simulation model. For much of the required data in this phase of the planning process, only global open data are available. The FLORES model is intended to run using limited data. In earlier research, the use of low-resolution data sources, especially focusing on global open DEMs, was found to have little effect on screening results for early conceptual design (van Berchum, 2019a). The input data for the FLORES simulation model is identical to the data used in earlier research (van Berchum et al., 2020), and is listed in Table 5-3.

Table 5-3: Data sources for the FLORES simulation model in Beira, from van Berchum et al. (2020).

Required input	Source	Reference	Data type [resolution]
Elevation	LiDAR DEM		Local data [2 m]
Structural exposure	ADFR - Building exposure	Eguchi et al. (2016	Satellite measurements [450 m]
Population exposure	ADFR - population exposure	Eguchi et al. (2016)	Satellite measurements [450 m]
Damage curves	Global flood depth-damage functions	Huizinga et al. (2017)	Global open data [-]
Surge data	GAR15 storm surge	(Cardona et al., 2014)	Global open data [-]
Rain data	Beira adaption to climate change study	(CES and Lackner, 2013)	Local data [-]
Wind data	GAR15 cyclonic wind	(Cardona et al., 2014)	Global open data [-]

5.3.2 Development of risk profiles

With the FLORES model, we were able to run the model for a set of 50 different strategies, over eight levels for each of the three external parameters (SLR, Rainfall intensity, and Development), where the risk profile of a single strategy is the result of 24 separate storm simulations. To limit calculation time, only scenarios of a single level were used for one, two or all three of the external parameters. For example, the scenario where SLR and rainfall both increase is calculated for every level, but the combination where, for example, the SLR increases to level 3 and rainfall increases to level 8 is not. Still, because of the multiple dimensions, the total computation time amounts to several hours on a single computer, even though a single flood event simulation is only a few seconds. The effect of the chosen simplifications to limit computational load is discussed further in Chapter 5. The data from the model runs are stored by the workbench and accessible for further analysis, results are presented in Chapter 4.

5.4 Planning and designing the Beira flood risk management system

Risk profiles of the current and future situations, combined with flood simulations show the necessity of a city-wide and future-proof flood risk management plan. Simulations of rainfall occurring every two years showed large scale flooding, especially in the high-populated lower-lying areas in and around Chota, a neighbourhood east of the city centre. At the same time, simulations of different severities of storm surge showed that events with a return period of 10 years would already lead to large-scale flooding in the coastal areas, including the city centre. Previous chapters include a more extensive analysis of the current flood risk, including simulations of future scenarios, underlining the need for a clear and effective flood risk management plan.
Following the step- wise approach presented in Chapter 5.2.4, we structured the FRM situation, in the form of the case study in Beira, according to the XLRM framework. Also, we described how the FLORES model was used to explore the design space by creating risk profiles for a number of different strategies. In this chapter, we show the model results with the aim to develop a clear and dynamically robust flood risk management plan. Corresponding to the last three steps of the outlined methodology, we screen for promising strategies, construct relevant robustness zones, and finally develop a dynamically robust plan.

5.4.1 Screen for promising strategies: Feature Scoring

Figure 5-4 shows the results of a feature scoring analysis for the current rainfall intensity, sea level, and development level. Here, first we analyse the system for current conditions. Next, repeating the analysis for different types of future conditions can

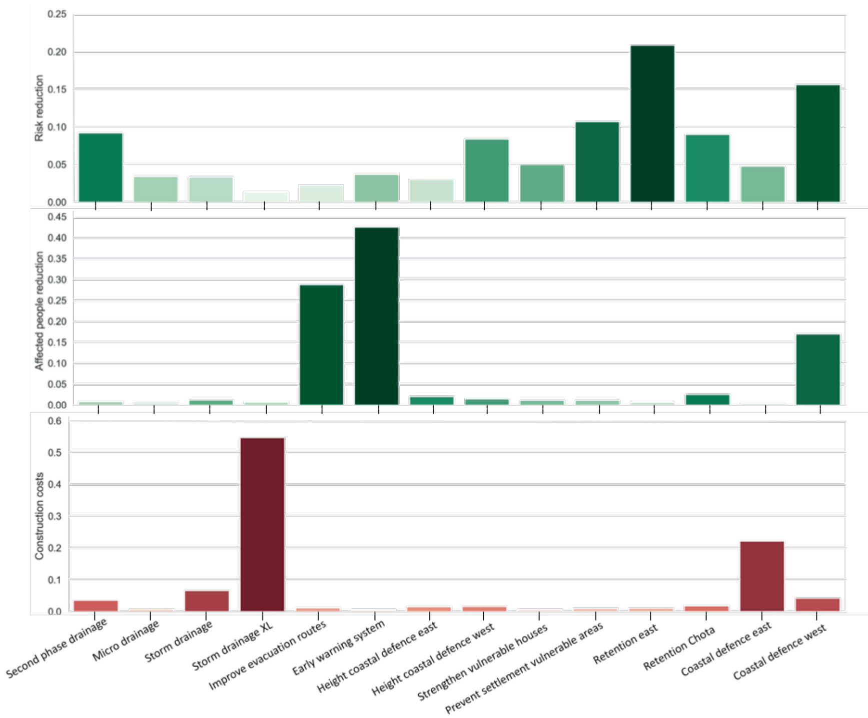


Figure 5-4: Feature scoring results in current conditions. Shown is the relative impact of flood risk reduction measures on the three performance metrics

help to show which measures scale well for more extreme circumstances. On the x-axis, all measures are listed. The scores show the relative impact of that particular flood risk reduction measure on each output metric - Risk reduction, reduction in people affected, and construction cost.

The results confirm that the retention measures, and especially the eastern retention option, are effective in reducing flood risk. Other strong influences are the western coastal defence, preventing settlement in vulnerable areas and the second phase of the drainage system. The other metrics show much more distinct outliers. The amount of people affected by flooding mostly depends on emergency measures, such as the evacuation routes and the early-warning system.

Focussing on risk reduction, Figure 5-4 shows the results for different future scenarios, where either the rainfall intensity, sea level rise, or overall development of the area is increased to level 8 according to Table 5-1. These can also be compared with the current conditions (see Figure 5-3). In the top graph of Figure 5-4, showing the Feature Scoring results for maximum increased rainfall, preventing settlements in vulnerable areas is clearly shown to be the most effective measure. This indicates that many of the vulnerable areas are mostly threatened by rainfall events. Preventing residential development in these areas, and instead use the area for retention could be beneficial in several ways, as unbuilt areas also generate less run-off.

As can be expected, a significant rise in sea level shifts the focus from rainfall to coastal storm surge as the main contributor of flood risk, making the western coastal defence - protecting the city centre – a clear priority when it comes to flood risk reduction. Similar comparisons are possible for the other performance metrics (amount of people affected or construction cost). Another possibility would be to compare feature scoring results for different levels of one external factor, e.g., comparing the results for risk reduction in the current scenario with a scenario where rainfall in increased to level 4 or level 8, according to Table 5-1. Feature Scoring is a useful first step towards an effective and robust flood risk management plan. By comparing different situations and reviewing the sensitivity of the outcomes to the different measures, the user gets a quick first impression of the impact of individual measures on the risk profile of the city. For Beira, it showed that for the current situation, the most effective measures are mostly focused on managing extreme rainfall, although future conditions can quickly shift the focus towards coastal measures in case of high sea level rise. Please

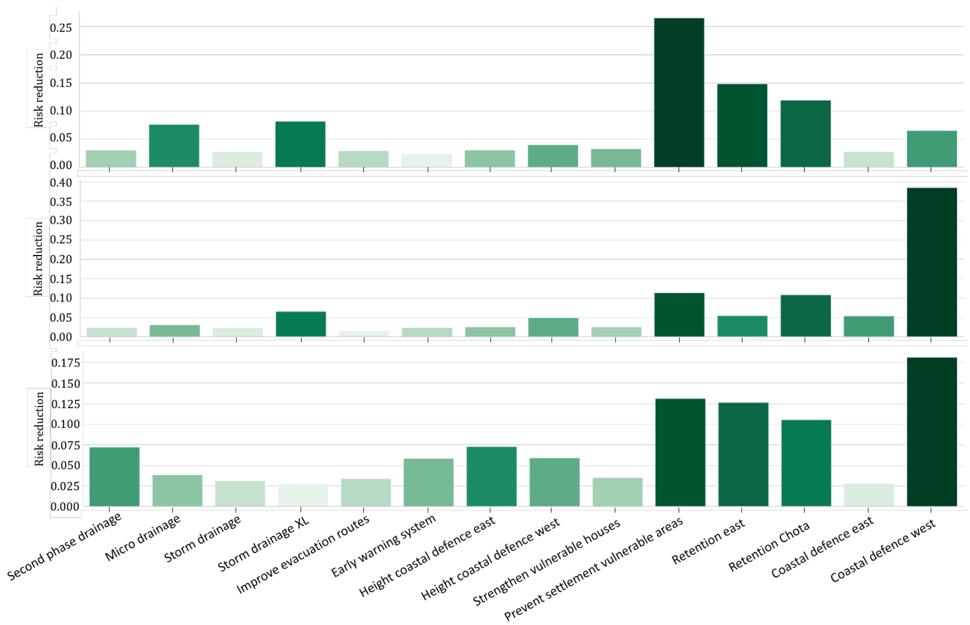


Figure 5-5: Feature scoring results for risk reduction under different scenarios. Shown are (top) an increase in rainfall intensity, (middle) an increase in sea level rise, and (bottom) an increase in urban development. Each is increased to level 8 according to Table 5-1, which is the maximum level.

note that this analysis varies the external factors individually. In practice, sea level rise and increased rainfall intensity are probably correlated, as they are both influenced by climate change. This can have a large effect on which measures to choose for a long-term strategy.

5.4.2 Construct robustness zones

In this step, we will look at the robustness zones for promising flood risk reduction measures. The nine most cost-effective strategies are compared, where cost-effective relates to the lowest total cost of expected annual damage and investment cost combined. Since no maintenance costs are implemented in the model, the yearly costs of a measure are the costs of implementation divided by an expected lifetime. In this case study, the lifetime is estimated to be 40 years for the flood risk reduction measures. The goal is to select strategies that perform well for multiple future situations to optimize robustness. This comparison can be repeated for other combinations of external factors. Through this analysis, combined with the results

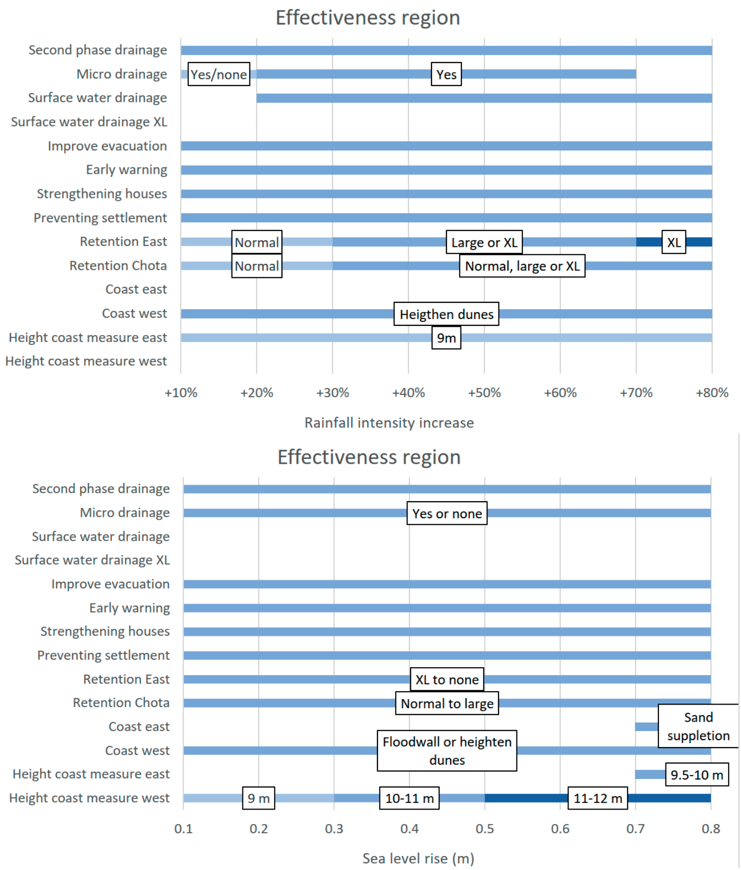


Figure 5-6: Robustness zones for measures in the Beira case study indicating for which sets of future conditions the measures are effective. Shown: (top) robustness to increase in rainfall intensity, and (bottom) robustness to increase in sea level rise. For measures that have multiple options (sizes or crest heights), different colours are used to differentiate.

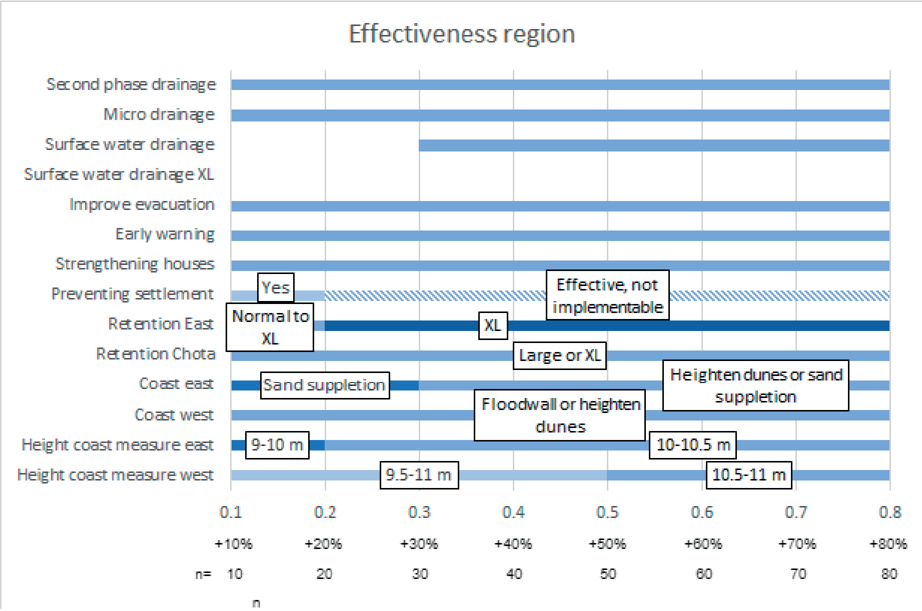


Figure 5-7: Robustness zones for the situation where rainfall intensity, sea level rise, and city development all increase.

of other analyses like feature scoring and PRIM analysis, these flood risk reduction strategies can be broken down into their individual measures, where the aim is to find the measure that are more effective and robust for any given situation.
Practically, this comes down to comparing the measures that are part of the most cost-effective strategies, with a preference for the measures that are part of multiple effective strategies and measures that perform well for other performance metrics as well. When repeated for each future scenario, the result for each measure is a list of scenarios for it is highly effective. This can be visualized in the form of robustness zones, see Figure 5-6. Shown here are the robustness zones for each measure in the case of an increase in rainfall intensity (top) or sea level rise (bottom). The robustness zone (shade blue bar) shows the range of conditions – in terms of external factors - in which the measure is part of an effective flood risk reduction strategy. In some cases, measures can be built – and upgraded – to different sizes or heights. In this case, the optimal size or height is shown in the graph. As shown in the figure, several measures are effective for any increase in rainfall intensity or sea level rise. Others are only cost-effective after a certain increase, or transition into upgraded versions.
Similar robustness zones can be made for other performance metrics or combinations thereof when these are deemed relevant for the design. It can be especially useful to analyse the effects of multiple uncertainties and the challenge these pose for measures included in a robust plan. To illustrate, Figure 5-7 shows the robustness zone for the situation where all performance metrics – rainfall intensity, sea level rise and city development – increase. For the coastal measures, this shows the growing contribution to flood safety of measures on the eastern coast for more extreme

futures. This stepwise and potentially interactive analysis, using robustness zones, can be very helpful in building a robust flood risk reduction strategy.
An overall conclusion that can be drawn from the robustness zones shown for different future scenarios above is that there are a number of measures that are effective in the current scenario, as well as more extreme future scenarios, e.g., developing the second phase of the drainage system, improving evacuation, or implementing early-warning systems. Other measures are only effective for a specific subset of scenarios, and might need expansion to stay effective, or cannot be implemented at some scenarios, such as measures at the eastern coast or preventing settlements in flood-prone areas.

5.4.3 Develop a dynamically robust plan

The feature scoring analysis provides a broad understanding of the sensitivity of the performance towards the different measures. Robustness zones show, in a clear and accessible way, what measures are effective flood risk reduction strategies under different scenarios. Here, we will design a dynamically robust FRM plan for Beira for the short term, medium term, and long term. Important to note here is that we do not make assumptions on the timing of changes in external factors, such as the expected sea level rise in 50 years. Instead, a dynamically robust plan takes all these time horizons into account and adapts the timing of their implementation depending on how the future unfolds. This does require a contingent monitoring plan to support the timing of investment decisions.
On the short term, several measures have been identified that should be taken right away: development of the second phase of the drainage system, improvement of the evacuation routes, implementation of an early-warning system, building retention capacity in Chota, and preventing settlements in highly flood-prone areas. This follows from the robustness zones in Chapter 5.4.2, as these measures have a particularly large range of applicability – including the current situation - and are therefore relatively robust. This mostly entails measures that focus on reducing the impact of extreme rainfall, as that is currently the greatest influence on the flood risk. Also, these measures do not block the construction of other measures in the future, maximizing the adaptive capacity of the strategy.
When considering the medium-term horizon (10-30 years), based on developments in external factors, a new set of measures can be made for potential future scenarios, where the chosen measures depend on the data from the robustness zones and other analyses. For example, an increase in rainfall intensity would suggest focusing on retention capacity in the east side of the city, a slight increase in the coastal defences in the urban western part of the city and flood proofing houses. In another example, an overall increase in external factors would require an additional focus on drainage capacity, retention capacity in the central part of the city and some improvements to the eastern coast. The exact choices of measures should be the result of stakeholder discussion, where robustness graphs can help as background data.
Looking at the long term (>30 years) horizon of the FRM plan, large changes in the local situation and external factors are expected. Therefore, likely a number of

additional measures, on top of those mentioned earlier, will be needed to keep the flood risk sufficiently low. This underlines the need for measures that either are effective in more extreme future scenarios, or that can be adapted. For the case of Beira, some measures were mentioned to be implemented right away, because these were effective in the current scenario, as well as in most future scenarios, see Figure 5-5. For other locations, the choice is less clear and depends on how the situation develops. For example, the right type (e.g., dune, floodwall) and height of the measure on either the eastern or the western coast can change over time. This should be considered when designing, as heightening a flood wall is significantly more complicated than heightening coastal dunes. Another potential choice in this context is to build a measure, such as a retention basin, knowing future expanding might be necessary if the situation develops further. Similar considerations can be applied for different parts of the drainage system or retention throughout the city.
By taking these different time horizons into account early, we explicitly aim for measures that combine well with other measures and do not block the option of using additional measures in the future. Here, the design team can be supported greatly by the robustness zones. These clearly show which types and stages of measures fit different situations, giving the design team the tools to efficiently discuss the options, combinations, and which risks it wishes to take or avoid. Through development of the dynamically robust FRM plan, and especially using the robustness zones, there is also increased insight into the data required to make these future decisions. In the case of Beira, short term decisions are mostly dependent on developments in rainfall intensity, meaning that adequate and regular monitoring of rainfall is necessary or should be set up to ensure that an increase in future risk or a moment of necessary action is recognized in time.

5.5 Discussion

The aim of this chapter is to demonstrate a new approach to planning for robustness in flood risk management. Also, it shows the application and potential of robustness zones for flood risk management in complex and highly uncertain flood risk management environments. The case study in Beira provided a realistic example, with a lack of data, multiple flood hazards, and several uncertain external factors that influence the future performance of the FRM system. With the use of the analyses demonstrated in this research, we were able to develop a dynamically robust plan while explicitly taking this complexity and uncertainty into account. However, some limitations should be kept in mind.
First, a flood risk screening model, FLORES, is used in which the physical processes of the flood simulation are significantly simplified in comparison to common high-detail flood simulation software. This is necessary because of the many simulations required for the exploratory modelling approach used to construct the robustness zones. The use of the FLORES rapid screening model brings with it a set of conceptual simplifications. These simplifications are apparent for example in the city schematization, and result in a minimum scale and limited options in location

and layout of flood risk reduction measures. For example, when the urban area is schematized on the scale of neighbourhoods, a measure focussing on a single street will not show correctly. This affects measures for pluvial flooding more often than measures for coastal flooding. These schematizations – kept basic for the sake of limiting computational load - influence the uncertainty accuracy of the simulation results. van Berchum et al. (2020) describe these limitations of the FLORES in more detail.

The schematization of the urban area and the simulation of flood events is relatively detailed and computationally heavy compared to models commonly used in exploratory modelling, leading to a relatively low number of simulations. In total, 50 different strategies were evaluated over 8 levels in three dimensions. This is an especially large limitation compared to a full factorial analysis of future situation (basically analysing all possible combinations of future situations). To execute such an extensive analysis within a workable time (several hours), would greatly exceed the capacity of a single computer. Because this research is mainly aiming to demonstrate the application, the number of simulations is limited. When applied in actual design of dynamically robust flood risk management plans, it is recommended to use computers / clusters with much higher computational power to analyse more strategies in more situations. Using smart optimizations, such as an early search for promising strategies to limit the number of strategies to assess, can greatly reduce this computation load.

Second, there is great uncertainty in the yearly cost of individual measures. This is mostly due to the conceptual design of the measures, and accompanying lack of information of material cost, construction methodology, and operation and maintenance. Estimated investment costs are evenly spread over the lifetime of the individual measures. Consequently, there is less differentiation between various types of measures. Where measures that are already proven technology or require little maintenance should normally be favoured from a risk perspective, this does not show when the investment cost is evenly spread over the lifetime. More data on the measures and how they will be implemented can improve the parameters and therefore make it possible to differentiate on these qualities.

Third, with the current methodology, three variables were considered, where the ‘development’-variable is used to signify both economic and population growth. Decision-making among policymakers and planners is a task that takes much more variables into account. However, scaling for more variables will take an exponentially larger toll computationally. In practice, instead of fully following the model results, it should therefore be clear that only the most important variables are considered, and they merely support the decision-making process. The model provides useful information of the consequences of different choices, which should be input for a larger conversation of the design team and stakeholders.

Finally, the robustness zones are an easy-to-use and comprehensible visualisation tool to show which measures are effective elements of a robust flood risk reduction strategy. This includes several assumptions on what qualifies as an effective strategy. Also, to improve simplicity, no differentiation is made between measures that are more effective than others. This type of visualization is most useful when working with larger teams where not everyone is familiar with the inner workings of robust FRM design

analysis.
The development of robust plans can be very complicated work. It is especially challenging to define which specific measurable parameter should be monitored and at which values of those parameters choices should be made. A design team should be clear on which parameters and values are used, as well as the arguments these choices are based on. This information combined with the results of the analyses such as the robustness zones provides a complete package of background information built to inform decision-makers as effectively as possible, even with limited information.
As the high level of complexity is a common argument against the use and development of dynamically robust FRM strategies, it is advised to continue development of (visualisation) tools that support and simplify steps towards such a plan. Robustness zones are easy to understand and use, but can be expanded and enhanced by adding, for example, visual aids on where measures hinder each other. Also, similar visualisations can be constructed per scenario (instead of per measure), basically showing which measures are effective for each scenario. Finally, the approach towards developing dynamically robust FRM strategies would be helped by a clear methodology on how to combine short, medium, and long-term horizons.
In future research, it is recommended to use this methodology for different case studies using locations with better input data. Such a case study could act as a benchmark on what type of information can be obtained from such an analysis. It could also be an example for the application and as such be the next step towards wider application.

5.6 Conclusions

This chapter introduces a new approach of introducing dynamic robustness in a flood risk management setting. The combination of simple schematization of the influencing factors and rapid flood risk screening made it possible to compare many flood risk reduction strategies. The results were analysed using robustness zones, which showed the range of external parameters under which a measure would perform satisfactorily. This led to insights into the applicability and robustness of measures. Subsequently, these were used to develop a dynamically robust flood risk management plan for flood-prone coastal cities, taking into account the uncertainties of changing flood hazards – consisting of both coastal storm surge and extreme rainfall – and a growing city.
With this approach, we were able to (1) structure the FRM challenge with the XLRM framework, (2) develop risk profiles for many strategies with the FLORES model, (3) screen for effective strategies through feature scoring, (4) construct relevant robustness zones for each measure, and (5) develop a dynamically robust FRM plan that explicitly takes uncertainties and potential future changes into account. This allows us to support decision-making by providing information on which measures provide robust flood risk reduction, while keeping options open to adapt, and adjust course based on new information.
The approach was used in a case study in Beira, Mozambique. This large and rapidly

growing city on the coast of the Indian Ocean is threatened by both extreme rainfall and storm surge. For the schematization with the XLRM framework, three main external factors were identified that influence the future flood risk, namely rainfall intensity, sea level rise and city development (a combination of economic development and population growth). Several flood risk reduction measures, focusing on the effects of storm surge, extreme rainfall or both were identified as design choices or policy levers. As performance metrics, several flood risk reduction strategies, consisting of a combination of measures, were compared on their ability to limit economic flood risk, amount of people affected and total construction cost. Development of the risk profiles was carried out with the FLORES model.

The model results were analysed to provide useful information for planning the robust FRM strategy. Through feature scoring, it was identified that the current situation is mostly benefitted by adding (the infrastructure for) retention capacity in the eastern part of the city, as well as preventing further settlement in highly vulnerable areas, above other measures. These measures mostly focus on flooding through excessive rainfall, which is the main contributor to current flood risk. Robustness zones were developed for each flood risk reduction measure. This showed a few measures that are highly effective in the current situation and do not block future choices or expansions, and therefore are a robust design choice. Other measures, such as more extensive drainage, and coastal defences on the eastern part of the city depend on future developments in flood hazards and city development. The choice to construct these measures should be made at a later moment, while regularly monitoring representative variables. The variables to monitor – as well as the precise content of these choices – should be discussed and decided in close collaboration with local stakeholders, in particular the local government.

Like Beira, many cities around the world struggle to develop a future-proof flood risk reduction strategy, as limited data and a limited budget greatly complicate design choices. The approach presented in this chapter can assist engineers, support discussions with stakeholders and motivate design choices for decision makers. The ultimate goal of the approach presented is to assist engineers and planners navigate the growing uncertainty and complexity of flood risk management planning.

Appendix A: Model input

Table 5-4: Flood risk reduction measures used for the Beira case study. L: Length, V: Volume. Sources: (Arcadis, 1999; CES & Lackner, 2013; Deltares et al., 2015; Deltares et al., 2013; E. C. van Berchum et al., 2020)

Name	Type	Dimensions	Constant costs ($)	Variable costs ($)
Heighten dunes - east Sand supplements	Structural	L:9500 m L:9500 m	3M /km 2M /km	1.5M /km/m 0.5M /km/m
Heighten dunes - west Floodwall	Structural	L:4800 m L:4800 m	4M /km 5M / km	1.5M /km/m 1M /km/m
Second phase drainage	Drainage		12M	
Micro drainage	Drainage		8M	
Surface water drainage system Surface water drainae sys. XL	Drainage Drainage		40M 80M	
Retention East Retention large Retention extra large	Retention	V:1.5*10^{6}m^3 V:3.0*10^{6}m^3 V:6.0*10^{6}m^3	5M 10M 20M	
Retention Chota Retention large Retention extra large	Retention	V:1.0*10^{6}m^3 V:2.0*10^{6}m^3 V:4.0*10^{6}m^3	2M 4M 10M	
Improve evacuation	Emergency		1.5M	
Early warning system	Emergency		0.4M	
Strengthening houses	Flood proving		1M	
Prevent settlement vulnerable areas	Urban planning		4M	

Chapter 6

Conclusions and recommendations

6.1
Conclusion

This dissertation explored the fundamental challenges of flood risk screening. Developing and applying the Flood Risk Reduction Evaluation and Screening (FLORES) model in real-life case studies proved it possible to support the early phases of strategic planning of flood risk management in complex urban regions with compound flood risks, many alternative measures, limited data availability and considerable uncertainties on future operating conditions.
This chapter answers the research questions identified in the introduction of this dissertation.

i. *What are the main characteristics of an effective flood risk screening model?*

The main goal of a flood risk screening model is to provide useful information in the early phases of the planning process. This requires a balance between simulation accuracy and computational speed. This is especially true for screening models, which often have to operate with limited input data, time, and resources. Combined with the wide range of possible measures – such as coastal structures, drainage, evacuation, urban planning – it is complicated to make a clear and fair comparison between different flood risk reduction strategies.

An effective flood risk screening model has been developed which (1) can simulate the effects of a flood risk reduction strategy on a complex, flood-prone region, (2) takes into account many different types of flood risk reduction measures, (3) evaluates the results of different strategies based on economic and non-economic performance metrics, and (4) has a generic setup and is easily adaptable to different regions around the world. These characteristics mainly focus on the versatility needed to run simulations a wide range of situations and many different types of measures. A practical application, where computation time matters greatly, requires simplified hydraulics to allow fast simulation.

In this research, the FLORES model used rapid flood simulation to assess the effects of a flood risk reduction strategy probabilistically. Keeping the flood simulation fully probabilistic made it possible to include the risk calculation as a central part of the model, leading to the risk profile, a crucial statistic for comparing flood risk reduction strategies. The risk profile shows the expected damages over events with different characteristics and return periods.

However, some factors cannot easily be described probabilistically. These were included by surrounding the probabilistic simulation with a shell that allows for comparison between non-probabilistic external factors. This shell adds the capabilities to include external factors such as sea level rise and urban expansion, and evaluate the effectiveness of measures and strategies for different scenarios, thus increasing the applicability of the model. In this research, the model was used in the Houston-Galveston Bay area, where it showed that the effectiveness of flood risk reduction strategies mainly depends on the choice for the coastal land barrier. Also, the effectiveness of Nature-based Solutions depends greatly on other measures in the chosen strategy.

ii. *How can the parameters of compound flood events be modelled both rapidly and accurately enough for use in flood risk screening?*

A significant part of the research focused on the rapid simulation of the compounded effects of multiple flood hazards. Although in many cases, an extreme event will result from either storm surge, heavy rainfall or high river water levels, some events may simultaneously lead to multiple hazards. For example, a coastal region threatened by a hurricane may endure coastal storm surge and heavy rainfall. The effects thereof can compound, leading to more damage than an analysis of separate flood hazards may conclude. So far, this has not been included in flood risk screening models.

Considering multiple interacting flood hazards results in a substantial increase in the number of simulations required to form a risk profile for one flood risk reduction strategy. Also, the calculation of expected annual risk is more complicated, because it needs to account for the correlation between the multiple hazards. More than in single-hazards simulations, it is crucial that the flood event simulation is based on physical processes instead of empirical formulas. The latter are often fitted on earlier research or events, which are rarely applicable to multi-hazard events. This added layer of complexity leaves only numerical models as a possibility to simulate flood events, even though the computation time can increase significantly.

This research found a solution by using drainage basins, areas where water flows towards one point. Basins replace grids of cells with set dimensions commonly used in numerical modelling and geographic information systems. FLORES simplifies the relationships between cells (basins) by bringing every impact back to its core: a volume of water transferring from one area to another. Rainfall becomes a surface area-dependent inflow, and storm surge becomes inflow from an infinite basin (the sea/ocean), possibly restricted by a barrier or levee. This modelling approach takes compounding effects into account easily within one simulation. Implementing these translations at the beginning of each time step also limits the simulation time to a minimum. As a result, simulating a flood with multiple hazards has only little additional computational load and the added strain on the total modelling time mostly comes from the many more simulations needed to construct one flood risk profile. Finding the minimum number of simulations giving a sufficiently accurate idea of the flood risk and how it depends on its variables – i.e., the flood hazards – is therefore the best way to keep the simulation time within workable limits. The model runtime is very sensitive to using multiple flood hazards and numerous future scenarios. Even though one simulation takes only a few seconds, comparing 500 strategies under many future scenarios meant multiprocessing was necessary to keep the total model runtime within a day.

This research applied flood risk screening of compound flooding in Beira, Mozambique. This analysis includes both storm surge, rainfall flooding and their co-occurrence due to cyclones. In Beira, the FLORES model provided insight into prioritizing measures and long-term effects. The simulations identified the drainage system and coastal protection as crucial elements of an effective flood risk management strategy. In cases where coastal storm surge and extreme rainfall occurred, the storm surge significantly restricted the city's ability to drain rainwater, leading to additional flooding and damage. In the short term, the city is aided most through expansion of the drainage system, as the damages resulting from extreme rainfall are the main contributor to the current flood risk. However, in the longer term, where more sea level rise is expected, the increase in coastal storm surge – as well as the effects on the drainage capacity – the coastal system is expected to become the dominant factor in the flood risk management of Beira.

iii. *How can free global DEMs be used within flood risk management and flood risk screening in particular?*

Especially in areas with limited available data, there is a lot of potential added value for a first conceptual analysis of the risk profile that flood risk screening can provide. It can be very costly and time-consuming for such areas to produce data necessary for more traditional flood risk management tools. The local topography, which is generally required as a Digital Elevation Model (DEM, map that shows the area's elevation), is the most critical input data for flood risk management. Some versions of DEMs are available for free and have (near-)global coverage but are yet not on a level of detail to be useful for detailed flood simulation of urban areas.

The FLORES model was used and adjusted in Beira to show the application of flood risk screening using a free global DEM. First, several DEMs were compared for their suitability for use in flood risk screening. Compared to the SRTM and ALOS World 3D, the TanDEM-X WorldDEM came first. The performance of WorldDEM is remarkable given that the spatial resolution of the WorldDEM (~90m) is less than the spatial resolution of the latest versions of the SRTM and ALOS World 3D (~30m). The strength of the WorldDEM can be attributed to its vertical resolution. WorldDEM is not only much more accurate, but also more consistent.

Next, the Tandem-X WorldDEM was used as the basis of a flood risk screening analysis and compared with the original research, which was based on a far more detailed LiDAR dataset. This comparison was mad on four levels: the flood simulation, flood impact, flood risk, and the effectiveness of measures and strategies.

The comparison of the WorldDEM-based screening showed differences on the scale of a single flood simulation but showed similar patterns on how strategies affect the flood risk of a city. Although the differences fall within the uncertainty range, the flood simulation showed a small skewedness towards flooding in lower-lying areas and higher average water depths. The effectiveness of measures and strategies led to mostly similar insights into which measures to prioritize. For the results based on the WorldDEM and the LiDAR datasets, a short-term prioritization for increasing drainage capacity was vital. For more extreme future climate conditions, strengthening the western coastal flood defences was crucial for any effective flood risk reduction strategy.

iv. How can the rapid flood risk screening approaches be used to facilitate more advanced policy analysis techniques, such as robust decision-making?

Recently developed policy analysis methods for decision making under deep uncertainty rely on exploratory modelling. Exploratory modelling requires extensive datasets in the form of numerous realizations of a predictive model. There is a gap in the required computation speed for these applications and current hydraulic models, which can be bridged with flood risk screening models.

This research introduces an approach to use a flood risk screening model to develop a dynamically robust flood risk management plan. The FLORES model was especially fit for this purpose, as it was developed according to the XLRM-framework, that divides a model into external factors (X), levers that can be changed (L), the modelling relationships (R), and the performance metrics (M). As a result, it is compatible with many methodologies for supporting decision making under deep uncertainty that follow a similar philosophy, such as robust decision making and adaptive pathways (Walker, 2013).

The approach uses the following steps: (1) structure the FRM challenge with the XLRM framework, (2) develop risk profiles for many strategies with the FLORES model, (3) screen for effective strategies through feature scoring, (4) construct relevant robustness zones for each measure, and (5) develop a dynamically robust FRM plan that explicitly takes uncertainties and potential future changes into account. This allows us to support decision-making by providing information on which measures provide robust flood risk reduction, while keeping options open to adapt, and adjust course based on new information.

The approach was used in a case study in Beira. As external factors, a potential rise in sea level rise, rainfall intensity, and city development (growth of population and economic value) was used. The FLORES model simulated and compared many different strategies. In turn, the results were used for feature scoring and to create robustness regions (ranges of potential futures where a measure is expected to be effective). These showed several highly effective measures in the current situation that did not block future choices or expansions, and therefore are a robust design choice. It also showed other measures that depend on developments of external factors to become effective. In short, these results and analyses were used as a base of a dynamically adaptive flood risk management plan for the city of Beira.

The use of flood risk screening for these applications is the next step towards explicitly modelling adaptive or robust management plans. Even though some recent examples show that explicitly designing towards robustness and adaptivity is possible (e.g., Bloemen et al. (2019)), in many cases this is still a qualitative comparison, supported by a few simulations. The combination of exploratory modelling – which entails running quantitative analyses based on a many simulations – and rapid flood risk simulation allows us to research the value and impact of adaptive designs and the uncertainties that drive them.

General findings: Advancing Flood Risk Screening

Concluding, this research introduced and demonstrates methods for using flood risk screening to support effective flood risk management. The growing design space, consisting of a wide range of flood risk reduction measures, leads to a more complicated decision-making process for flood risk management. Also, the focal point of flood risk management activities, where the largest challenges are expected, shifts further towards countries where only limited data is available. Flood risk screening can add information and insights at the early phases of planning and design, where it is most needed.

The development of the FLORES model demonstrated how fast flood simulations can be used at the core of a versatile, full-probabilistic analysis of a flood risk reduction strategy. The rapid simulation, based on simplified hydraulic formulas, allowed for many strategies and measures to be compared and thus an exploration of a large design space.

6.2 Recommendations

6.2.1 Technical recommendations

This dissertation describes the research on advancing flood risk screening as a useful addition to the flood risk manager's toolbox. Parallel to the presented topics, the research also focused on the continued development of the FLORES model towards a viable example of a flood risk screening model. Here, various suggestions are given for further research and development for FLORES and flood risk screening as a whole. This includes recommendations on how to implement flood risk screening models within the currently common framework for planning flood risk management systems and more in-depth views on how to deal with the trade-off between model accuracy and computation time.

The next step in the development of flood risk screening models is to further demonstrate its added value in the toolbox of a flood risk management expert. To improve the integration of the flood risk screening models in planning flood risk management systems, it is recommended to apply it to other flood-prone cities and regions. By building a library of case studies, this can demonstrate the range of application and act as a guide for future projects. The cases should also show the standardized workflow and include manuals for incorporating the model and model results in the standard way of planning of major clients (e.g., the World Bank). These case studies can be carried out similar to the research presented in this dissertation, where the entire analysis revolves around the FLORES model. However, due to the relative novelty of using models like this, it may be hard to convince stakeholders, especially when extra budget for development is needed. Another option is to integrate specific parts of the flood risk screening model (e.g., rapid flood simulation, damage estimation, or multiple future scenarios) within the current practice, to expand the portfolio of case studies, and further develop the capabilities and usability of the model this way.

This library of case studies should focus on areas where the flood risk screening approach will be most useful. At the moment, these areas are locations with a complicated flood risk management challenge – in terms of hazards and the range of potential measures – and limited available data. The strength of flood risk screening stems from its ability to systematically analyse the most complex flood-prone cities and provide useful information in a moment in design where most other models would need much more data, budget, and time. This gap in the design process is currently filled through expert judgement and the formulation of a limited number of promising strategies. The main challenge now is to demonstrate how these same experts, now supported with a screening model, can present their results faster, more completely, better supported through simulations, and on a wider variety of relevant topics. For example, the FLORES model has been developed with easy implementation in mind. This means that a single expert can screen the flood risk situation and compare possible strategies for a new location in a matter of weeks, including the gathering of available (open source) data and information on the considered measures.

There is a good opportunity for using flood risk screening in a riverine situation. For such areas, many measures are available that not only hold back flooding or mitigate the impact but are able to completely change the course of water flow. Examples are dikes, retention basins, room for rivers, bypasses, and dams. The impacts of such measures are much harder to predict based on expert judgement, and the synergy or trade-offs with other measures even more. A first comparison of the risk profiles, provided through flood risk screening, can greatly improve the planning process for riverine flood risk management challenges.

Other than extending the field of application, developments in other fields can support the integration of flood risk screening into real-world planning. This dissertation has shown that input data on a global scale is often still very coarse but can be of added value in the flood risk screening phase. Although DEMs are crucial, developments here are regular and expected to continue. Also, exposure data on population density, fragility curves, damage curves, and hazard data can be found for almost every country in the world based on global models or country-specific analyses. It is highly recommended to develop global datasets to other types of data, such as global land use (value) maps and economic exposure. Also, global figures of costs of measures can help standardize and quicken the process of setting up flood risk screening models. Normalizing the use of global open data in flood risk management can be beneficial for both fields. This application – for example through flood risk screening - gives clear and tangible use cases for research in producing global open data and improves the standard datasets that flood risk management can use.

With respect to the continuing development of the FLORES model, several future steps are recommended:

- The FLORES model is constructed in a modular way, which allows for improvements of individual parts of the model without disrupting the overall framework. Due to the modular setup, experts from different fields can easily improve specific parts to support the continuous development of FLORES as a whole. Examples of modules where additional research is recommended to improve the range of application, modelling accuracy, or the computation speed are the simulation of the urban drainage and urban planning measures.
- Besides the development of the existing modules, also new parts can be added. By using GIS as the main data source and including water levels throughout the area for each time step, connections can be made to many areas of application that have not been a part of such large-scale models before. Examples are the inclusion of urban development planning, planning evacuation routes, salinity levels in flow, or the impact and risks of closable emergency barriers.
- The flood simulation at the heart of the FLORES model should be validated with a library of historic events or simulations with more detailed flood simulation models. This will be necessary to grow trust in the capabilities of the model to simulate the wide array of situations. Some specialized simulations will be needed to validate the production of flood risk profiles. For this, simulation of many different flood intensities will be necessary, but more importantly also simulation of many different flood scenarios (outcomes of which barriers will fail or not).
- It is recommended to explore the development of the FLORES model to include riverine flooding. So far, the FLORES model has been developed for coastal cities, focussing strongly on the strength of coastal flood risk reduction measures in the face of an oncoming storm surge event. For implementation of riverine flooding in FLORES,, and especially the large scale measures, this would probably require the integration of 1D modelling of the river.
- In the Netherlands, a lot of research is focusing on combining structural and non-structural measures and policies, for which the FLORES model is very well

suited. Here, it is recommended to apply the model first on cities along the major rivers, as this will be easier to simulate based on limited data than cities along the coast and the Rhine delta. Coastal cities, like Rotterdam, generally have a more complex, highly regulated hydrological system, which makes it harder to simulate without detailed information. Here, the FLORES model can help urban and landscape planning challenges for local governments and water boards by quickly demonstrating the effects of the many options available. Especially planning for combinations of structural flood risk reduction measures and policy measures like zoning can benefit greatly from a first screening approach.

- It is recommended to explore additional policy metrics. The model is built to provide multiple performance metrics, which are now mainly based on economic damage and costs. Discussions with decision makers would benefit from additional metrics, such as environmental or social impact.

6.2.2 Outlook on the use flood risk screening

Behind the emergence of flood risk screening is a wider movement toward using (exploratory) models to support policy decisions. Experts, previously analysing scenarios using back-of-the-envelope calculations are increasingly aided by tools and models. Methods similar to flood risk screening are used more and more in other fields to quickly calculate what the effects of different choices or additions to infrastructure would make, such as the economic effects of political decisions, the flow of traffic due to new roads, or the impact of restrictions on the spread of disease. The complexity in these fields – often resulting from the inclusion of human behaviour – forced analysts to embrace these types of conceptual models, instead of relying solely on expert judgement.

Flood risk screening is a reaction to the rising complexity in flood-prone cities. Issues and knowledge of hydraulic engineering, water management, and urban planning and governance all play a role. Exploratory modelling is well-suited to deal with this rising complexity, because of its ability to consider and analyse all scenarios and stakeholders. As more fields embrace the use of exploratory models in complex situations, its application in the flood risk management domain is probable to become more widespread, more accepted, and eventually expected.

Using computer models to support early planning and design based on limited data does come with higher uncertainty than is usual in commonly used flood simulation software. Exploratory modelling – in particular the rapid flood simulation – requires heavy simplifications on the schematization of the area and flow. The result is a higher uncertainty than the simulation models used now. The number of required simulations also rises with the number of parameters to take into account. The answer on the question how to keep the stakeholder's trust in the model results is a combination of using easy-to-understand and easily available models, thorough validation (E.g. on past events), and not ignoring the expert's judgement on where the validity of the model ends. For example, because the city is schematized within the FLORES model on the scale of drainage basins, quantifying the damage to an individual building is well outside the uncertainty range. The role of the expert user as the translator between model results and decision support is crucial.

As a final remark, this dissertation would like to emphasize the opportunity presented by flood risk screening. Urban flood risk management has increasingly developed from a mostly engineering exercise towards a multidisciplinary challenge with many different (and sometimes opposing) interests. Progress in design is optimally made through continuous discussion and collaboration between previously often divided fields of expertise. Here, flood risk screening methods as developed in this dissertation can support to get engineers and planners into the process quickly and early by providing quantitative information early-on and based on both engineering and planning measures and information. It would be fitting if this development towards multidisciplinary flood risk management is reflected in the future toolset of designers and engineers.

The model code, as well as used datasets, is available online on:
https://github.com/ErikBerch/FLORES-Beira

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List of publications

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Awards

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