Rapid screening and evaluation of flood risk reduction strategies

Exploratory study on the use of the FLORES modelling approach for World Bank projects

E.C. van Berchum

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Cover photo*: Life continues in flooded communities*. Beira, Mozambique.
By: E.C. van Berchum (April 12, 2018)

Summary

Coastal cities and settlements in many countries around the world are under pressure from compound flooding events, originating from storm surge, high river discharges or extreme rainfall events. These events directly impact existing assets and livelihoods, and impede socio-economic development. Rising sea-levels, mounting hydrological and meteorological extremes, growing population and investments will increase these risks in the decades to come, especially in countries that are generally already more vulnerable. Launched in September 2006, The Global Facility for Disaster Reduction and Recovery (GFDRR) provides technical and financial assistance to help disaster-prone countries decrease their vulnerability and adapt to climate change. GFDRR is a partnership of the World Bank, United Nations, major donors and recipient countries under the International Strategy for Disaster Reduction (ISDR) system to support the implementation of the Hyogo Framework for Action (HFA).

Under the uncertain extent and impact of climate change and socio-economic development flood risk management programs necessarily include the development of future robust flood risk management strategies. Throughout the planning process, from risk identification to implementation, computer models are used to support the decision making. A crucial part of this process is the identification of robust flood risk management strategies in the early phases of the planning process when data, knowledge and resources are often still limited and uncertainty is high. In these processes, a need exists for modeling tools that allow for the screening of multiple flood risk management strategies under many future climate and socio-economic scenarios and tools that require limited resources and have limited data requirements. These modeling tools are currently not available.

This report introduces a flood risk screening model that fills this niche with a flood risk screening model, called the Flood risk Reduction Evaluation and Screening (FLORES)-model. FLORES is specifically aimed at providing useful input early in the decision-making process by quickly screening multiple flood risk management measures and their combinations under uncertainty and identify promising combinations of measures and develop them into robust strategies for flood risk management.

The FLORES model

The FLORES–model evaluates the capacity of numerous flood risk reduction strategies to reduce the impact of climate change and sea level rise scenarios for flood-prone coastal cities. Basic formulas are used instead of more complex hydraulic modelling software, to reduce computation time, and to allow the model to run on a personal computer. To maximize its usefulness in real world situations, the FLORES-model has been built with five characteristics in mind. The model (1) simulates the effects of storm surge and pluvial flooding and the combination (compound flooding), (2) simulates flood risk management strategies consisting of both structural and non-structural measures, (3) evaluates flood risk management strategies on multiple performance metrics, (4) uses low-resolution data, e.g. global open data, to facilitate its application in data scares, and 5) consists of generic modules that makes it easy to transfer the model to other cities.

The structure of FLORES is depicted in Figure 1. The core of the FLORES-model is the simulation of a single event provided by a specific storm scenario and a specific flood risk management strategy. In a single simulation the impact of a specific flood and flood risk management strategy on the number of affected people, the damage to assets, and the costs of implementing the strategy are calculated. The event simulation is run numerous times for numerous combinations of floods and management strategies, typically 10.000 - 100.000 times, which is possible because of the short computation time for a single event (e.g. tens of seconds). Re-running the events for many different storm scenarios makes it possible to include uncertainty in the analysis and assess the

robustness of the flood risk management strategies under future change. The extensive datasets created by the FLORES-model are analyzed using the open source Exploratory Modelling and Analysis (EMA) Workbench

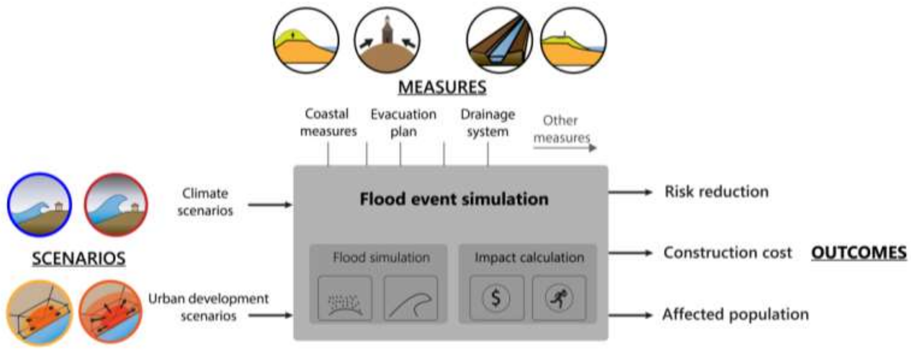


Figure 1 – The connection between the different parts of the FLORES-model simulation. The outcome of the simulation depends on factors that we can change (the 'Options' or flood risk reduction measures), and factors that are uncertain (the 'Scenarios'). The flood risk reduction strategies can be compared based on multiple parameters.

(Kwakkel, 2017b). The EMA-Workbench uses advanced data analytic algorithms to identify promising strategies for future robust flood risk management.

Within the FLORES-model, a city is schematized by dividing the surface into drainage basins, which are defined as areas within the city with the same drainage point. A rainfall flood event is simulated by calculating the hydrological volume balance for each of the drainage basins. These are subject to inflow from rain and outflow through infiltration into the soil or drainage into the sewers or drainage system. When a city is also threatened by storm surge, lines of defense (e.g. coastline, riverbank) are defined and the water flowing across such a line of defense is modelled as inflow for the affected drainage basins. When the water level rises above the border level with neighboring drainage basins, water starts flowing between basins. This process ensures a fast, but relatively realistic representation of urban surface impacted by the compounded effect of rainfall and coastal storm surge. The results of the flood simulation are used to calculate the impact of the flood situations.

FLORES offers ample flexibility to include alternative structural and non-structural flood risk management strategies like dikes and levees, urban drainage, pumping stations, spatial re-arrangement, retreat, flood proofing assets, evacuation plans, and a wide range of storms surge and rainfall scenarios. This makes the FLORES model very flexible and applicable in many current and future situation.

Case study: Beira

As a case study, the model has been implemented on the city of Beira, in Mozambique. This coastal harbor city, with nearly 600,000 inhabitants, is regularly hit by heavy rains, flooding the lower parts of the city on a yearly basis. This was shown as recent as January 2019, when heavy rains affected nearly 50,000 people. In 2000, the city was hit particularly hard by a cyclone, causing flooding through coastal storm surge. Using the FLORES-model, the current flood risk of Beira was estimated. Subsequently, a range of flood risk reduction measures was proposed and compared. Besides their ability to reduce the flood risk, they were compared based on construction costs and the ability to reduce the amount of people affected.

The case study has revealed that the FLORES flood risk screening model was able to evaluate many different events and flood risk reduction strategies based on limited and mostly public data. A comparison of the flood simulation from the FLORES-model with a more detailed flood simulation shows good agreement. The evaluation of different risk reduction strategies provides insight in what courses of action may be most interesting for further exploration.

For example, the FLORES-model results suggest that on the short term, the city would benefit most from the expansion of the drainage system and the enhancement of emergency measures. These measures focus mostly on the threat of extreme rainfall, which is shown to contribute to the risk the most, especially for the common storms. The model output shows that these measures have a large influence on the risk reduction and the exposed population, respectively. Without any measures, the lower parts of the city floods almost yearly, and the higher parts are threatened by a 1-in-10 year rainfall event. Especially for these events, a better drainage system and emergency measures can make a significant difference. Secondly, the coastal system is currently able to withstand a minor storm surge (up to a 1-in-5 year storm surge), and heightening the system of dunes and flood walls may not be the best short term choice due to the high costs and the uncertainty of future developments. However, the coastal structures are expected to play a crucial role in flood management of Beira in the future, due to coastal erosion and the expected rise in mean sea level and storm intensity. The importance of the coastal system is expected to grow with more extreme climate scenarios. The analysis has shown a clear change in priorities as a result of different future climate scenarios, which advocates further climate monitoring and adaptive measures on the short term.

For further steps regarding the flood management in Beira, it is advised to increase monitoring of hydraulic processes, like the trend in rainfall intensity, mean sea level and storm surge. Also, the effectiveness of the drainage system may decrease significantly during high tide in the Indian Ocean, and more so due to storm surge and sea level rise. This interplay between the urban and coastal system requires more attention, and the option of increasing the effectiveness with pumps or a large-scale retention need to be considered as a future option.

Recommendations

The FLORES model is still under development and several future steps are needed to develop it into a viable flood risk screening model for cities. As a part of this research, the connection with global open data sources was made for the first time. In order to test whether this yields reliable results consistently, more sensitivity analysis is needed. A future case study, focusing on a city where also detailed data is available, would enable to compare results between data sources.

Also, the distribution and application of the model requires further development of a clear overview of the model and a complete workflow. This report includes a first version, which still needs to be tested in a future research study. Finally, a future project needs more emphasis on (developing methods for) communicating the model results to end users and project stakeholders. Although the FLORES model is still work in progress, it is a promising model for flood risk screening, capable of comparing many available options to support flood risk management in increasingly complex cities and under uncertain future conditions.

Glossary

CD	:	Chart Datum. The reference elevation in the model. For the case study, this is equal to the lowest astronomical tide.
Contour	:	Subdivision of a drainage basin, denoting all areas inside the drainage basin within a particular range of elevation.
DEM	:	Digital Elevation Model. GIS-based representation of terrain elevation.
EMA-workbench	:	Exploratory Modelling and Analysis (EMA)-Workbench. This is a Python-based modelling tool, capable of performing experiments and analyzing the results of other models. Developed by (Kwakkel, 2017b).
Emergency measure	:	Measures that reduce the risk of flooding, specifically by reducing the consequences in case the flood occurs.
Feature Scoring	:	Analysis method used in the EMA-workbench which shows the dependency of an output parameter on the intervention choices or uncertainty of input parameters.
Flood defense	:	Structural flood risk reduction measure, specifically meant to stop or reduce the storm surge. This includes levees, walls, storm surge barriers and dunes.
(Flood) event simulation	:	Core of the FLORES-model. Consists of a flood simulation and an impact calculation.
Flood simulation	:	Part of the flood event simulation model. Calculates the flood extent in an urban area due to flood hazard.
Flood risk reduction measures	:	All potential structures, actions or policies that can be implemented in a flood-prone region to mitigate the effects of a flood. This includes structural barriers, but also non-structural measures like Nature-based solutions or policy measures.
Flood risk reduction strategy	:	A chosen combination of flood risk reduction measures.
FLORES	:	*Flood risk Reduction Evaluation and Screening.* This refers to the tool explained in this research, which simulates and evaluates flood risk reduction strategies to reduce the effects from flooding in a flood-prone region.
Fragility curve	:	Visualization of the strength of a flood defense. It shows the probability of failure, depending on the load, often in the form of water level.
GIS	:	Geographic Information System. Software system used to analyze, combine and manipulate geographic data.
Hydraulic boundary conditions	:	The set of initial conditions which are acting upon the modelled region. In this model, this refers to the influence of tide, storm surge, wave height, and rainfall.

Impact calculation		Part of the Flood event simulation. Uses inundation levels throughout the city to calculate impact in terms of economic damage, construction cost and amount of people affected.
MSL	:	Mean Sea Level.
Nature-based solutions	:	Measures that aim to reduce the flood risk, while at the same time enhancing natural ecosystems. They are designed to address environmental challenges as well as economic benefits. Examples are reefs, wetlands and nourishments.
Evaluation Model	:	Part of the FLORES-model. This is a Python-based tool, based on the EMA-workbench, capable of analyzing the data from the Simulation model and running analysis techniques on the results.
PRIM	:	*Patient Rule Induction Method*. Algorithm used in the EMA-workbench which finds input ranges that meet a set of performance thresholds.
Drainage basin	:	Subdivision of the city which drains to one specific outlet.
Region lay-out	:	The description of the modelled area. It acts as a base layer, upon which a combination of flood risk reduction measures can be placed. It is defined by land use, land elevation and position relative to the potential measures.
Risk	:	Set of all possible scenario outcomes, defined by their probability multiplied by the consequence of each scenario.
Situation outcome	:	A certain outcome of a surge event. If a flood defense can fail or not, there are two possible scenarios.
Verification	:	The process of confirming that the model generates acceptable results with respect to other models.

Contents

1. Introduction

1.1. Disaster risk management within the World Bank Group

In many places around the world, human activity has developed in areas vulnerable to natural hazards. Currently, floods are the leading cause of natural disaster fatalities worldwide. In the face of the current developments, where both urbanization and extreme weather events are rapidly increasing, it is no surprise human vulnerability to natural hazards is increasing as well (Doocy et al., 2013). This rise is mostly attributed to the increased urbanization of less developed regions in Asia and Africa, where high concentrations of human activity is taking place in vulnerable areas without adequate disaster risk management policy in place.

The World Bank supports developing countries in their efforts to limit the risk to natural hazards. By providing loans and technical assistance, the World Bank interacts with vulnerable regions to increase resilience of livelihoods of people, for example by financing projects that improving urban drainage system to reduce the risk to urban flooding. In the face of the rapidly changing world, these vulnerable regions are constantly challenged to make impactful decisions based on limited data.

The global principles concerning disaster risk management are based on the Sendai Framework for Disaster Risk Reduction. This UN-endorsed agreement seeks to limit disaster impact by providing a framework for the coming 15 years. It revolves around four main priorities, as explained in (UNISDR, 2015):[1]

Sendai Framework for Disaster Risk Reduction

1. **Understanding disaster risk**
   "Disaster risk management needs to be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment."

2. **Strengthening disaster risk governance to manage disaster risk**
   "Disaster risk governance at the national, regional and global levels is vital to prevention, mitigation, preparedness, response, recovery, and rehabilitation. It incentivizes the public and private sectors to take action and address disaster risk."

3. **Investing in disaster risk reduction for resilience**
   "Public and private investment in disaster risk prevention and reduction through structural and non-structural measures are essential to enhance the economic, social, health and cultural resilience of persons, communities, countries and their assets, as well as the environment."

4. **Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction**
   "The growth of disaster risk means there is a need to strengthen disaster preparedness for response, take action in anticipation of events, and ensure capacities are in place for effective response and recovery at all levels. The recovery, rehabilitation and reconstruction phase is a critical opportunity to build back better, including through integrating disaster risk reduction into development measures"

[1] *Quotes taken from www.unisdr.org/ (accessed on 06-06-2018)*

The World Bank focuses to contribute to the achievement of the Sustainable Development Goals (United Nations, 2017) and the Paris Agreement (UNFCCC, 2015). World Bank projects therefore always strive to increase the general livelihood of people and to limit the environmental impact of their actions to maximize resilience to climate change.

1.2. The Africa Disaster Risk Financing (ADRF) Initiative

The World Bank/GFDRR is the implementing partner of the Africa Disaster Risk Financing (ADRF) Initiative, which aims to support the development of multi-risk financing strategies on different scales, improve financial response capacity, and mitigate the socio-economic, fiscal and financial impacts of disasters in African countries.[2] As a part of this initiative, multiple-hazard country risk profiles have been developed for nine African countries - Cape Verde, Ethiopia, Kenya, Mali, Mozambique, Malawi, Niger, Senegal, and Uganda.

During the development of these risk profiles, various methods were used and developed to generate datasets on hazards, exposure and risk. The goal is to strengthen the African governments' capacity to design and implement disaster risk management strategies and help these governments to make informed decisions. The datasets provide useful insights into the hazards which these countries face and what regions are vulnerable to the highest risks. This is an important step towards identifying and implementing measures for reducing those risks. To assist that process further, the ADRF Initiative also facilitates and reviews financial instruments in the form of contingency funds, loans, and grands. This can be useful for enhancing the countries efforts of providing a strong society, capable of quick response in case of disaster shocks.

1.3. Knowledge gaps and objectives

A crucial step from risk assessments towards implementation of measures is the identification of promising strategies for reducing risk. To support this decision-making, computer-based risk models can be used to assess risks and compare strategies for risk reduction. When it comes to flooding, models commonly used in this context are highly advanced simulation models. These are time and labor-intensive, and depend on availability of detailed data sources. Due to this, simulating many situations and flood risk reduction strategies is time-consuming and expensive. Alternatively, analytical models exist which provide strong insight and also analytical solutions for optimized strategies best fitted for a resilient or adaptive flood risk reduction strategy. However, these models are often very simplified and focused on a single hazard (e.g. storm surge). These models do not capture the specific details and complexity of a real-life situation (e.g. combination of rainfall and storm surge). For examples of analytical optimization models, please refer to USACE (1996), Lund (2002), Voortman (2003) or Dupuits et al. (2017a).

Despite the large array of available models to quantify the consequences of flooding (e.g. HAZUS), capturing the needs of decision makers in these preliminary stages of decision making has proven to be challenging. For some specific cases, flood risk screening models have been developed. However, the application is often limited to one region and mostly one type of flooding is considered. For example, reference is made to a flood risk screening model for only storm surge (Gouldby et al., 2008; Aerts et al., 2014). There is a need for risk models that combine simple, fast, and widely applicable simulation with real-life decision-making.

This report presents the Flood risk Reduction Evaluation and Screening (FLORES)-model as a viable model for the evaluation of flood risk reduction strategies in vulnerable cities. FLORES is a fast risk-based model that simulates and evaluates the impact of many alternative flood risk reduction strategies, each consisting

[2] The ADRF Initiative is part of the ACP-EU Program Building Disaster Resilience in Sub-Saharan Africa, funded by the European Union (EU)

of a combination of measures. The computation time is reduced, as basic (hydraulic) formulas are used for flood and impact simulation, which allows for many strategies to be compared.

The main characteristics of the model include the ability to (1) consider both pluvial and coastal flooding, (2) consider both structural and non-structural measures, (3) allow for economic and non-economic performance indicators and (4) have a generic setup, which is easily adapted to other flood-prone regions around the world. The model is currently focusing on cities in relatively flat (delta-)regions.

1.4. Project scope

This report builds on the methodology described in earlier research (van Berchum et al., 2018) to further develop the model, focusing on areas which have the special interest of the World Bank. Therefore, subjects already mentioned earlier (e.g. the storm surge modelling and the evaluation techniques) will be explained shortly and new developments will be explained in more detail. The focus in this report is the following:

- Developing the model up to the point where it can simulate urban rainfall, surface flow, and urban drainage, besides the already developed Storm Surge-simulation.
- Enhancing the use of Open Data sources.
- Enhancing the generic setup of FLORES-model and exploring the possibilities to use it in other areas, in particular developing countries.

The application of the model will be demonstrated by applying the FLORES-model to a case study in Beira, Mozambique.

1.5. Report outline

First, chapter 2 describes the field of flood risk screening models and how the FLORES model fits among other models and methods. Subsequently, it explains the main methodology and key drivers of the development of the FLORES model, as well as the main structure of the model. Chapter 2.4 elaborates on the connection with other models and datasets that the FLORES model uses as input.

Chapter 3 presents a technical background of the FLORES-model. Here, the main schematizations are discussed, providing a more in-depth view of how the flood simulation works (Chapter 3.1) and which evaluation techniques can be used (Chapter 3.3). Chapter 4 shows a case study, based on the city of Beira, Mozambique, as an example of how the model can be used to provide useful information and data to support decision making in the process of developing a suitable flood risk reduction strategy for Beira.

Finally, Chapter 5 discusses the potential application to other cities. Besides explaining how flood risk screening can aid the local flood risk reduction efforts, it also provides insight into what type of cities are currently best fit for the model. As a final note, the Appendices provide additional information for those who seek more in-depth information on the model. This includes a full step-for-step workflow for the use of the model and more mathematical background on the hydraulic calculations used in the flood simulation.

2. The FLORES-model concept

2.1. Rationale for flood risk reduction screening models

There are many ways in which modern cities can be affected by natural hazards. Due to the uncertainty in how these hazards cause damage, as well as the lack of information, making the right decisions to reduce these risks is complicated. The process of decision-making can be informed and supported by performing risk analysis. This can be used to quantify the risk to natural hazards and inform decision-makers in understanding where the most significant risks lie and how to best manage them (Sayers et al., 2013).

For flood risk management, quantitative flood risk analysis is particularly challenging because of its great complexity. Traditionally, research mostly focused on the engineering challenges and their economic implications (Vrijling, 1993; USACE, 1996; Van Dantzig, 1956). Due to the relatively narrow focus (single, structural measures), analytical optimization was possible. Since then, research developed towards increasingly complicated optimization techniques (Eijgenraam, 2006; Bischiniotis et al., 2014), up to the point where the optimization could take into account intangible damages (Kind, 2014), nature-based flood protection (Vuik et al., 2016) or multiple lines of defense within the same flood protection system (Dupuits et al., 2017b). These sophisticated evaluation and optimization techniques were possible because of the very conceptual schematization of the vulnerable area. This simplicity in schematization and focus on analysis meant that effects of uncertainty (e.g. due to economic development, climate change, lack of data) can be evaluated and optimized for conceptual case studies.

Simultaneously, numerical flood modelling has developed quickly in the past decades, powered by growing computational power and the use of Geographic Information Systems (GIS)-based tools (Kovar and Nachtnebel, 1993; Djordjević et al., 1999). Over the years, a number of models have been developed, capable of high end, spatial flood simulation (e.g. Delft3D, SWMM, MIKE). The use of these models has become common practice for any large flood management design project, due to their relatively accurate simulations, even for large, spatially complex cities or regions. However, these models are complicated, labor-intensive and therefore expensive to set up. Moreover, the high accuracy demands lots of input data and computational power. It is therefore mostly used to review one or two flood management strategies, but it is challenging when many simulations are required in a fast design process environment. This type of models is therefore not very practical for different types of analyses (e.g. uncertainty analysis, investment strategy analysis) when many simulations are involved.

This contrast between conceptual risk optimization models and detailed simulation models leaves a gap, which is the field of application for flood risk screening models (see Figure 2). For these type of models, all options for flood management strategies are still open, but local spatial circumstances must be taken into account. This warrants a flood simulation which is accurate enough to simulate local effects, but fast enough to allow quantitative risk and uncertainty analysis with many simulations. Over the past decade, this has been done several times, where the models were mostly specialized for particular case studies (Aerts et al., 2014; Gouldby et al., 2008).

On the downside, flood management screening models are too complicated to allow for analytical optimization. Also, these models lack the modeling accuracy to be used for detailed design. This type of models should therefore not be viewed as replacements for conceptual risk optimization models and detailed simulation models, but rather as a complimentary tool, useful at an earlier moment in the design process and with the purpose of screening instead of simulating strategies.

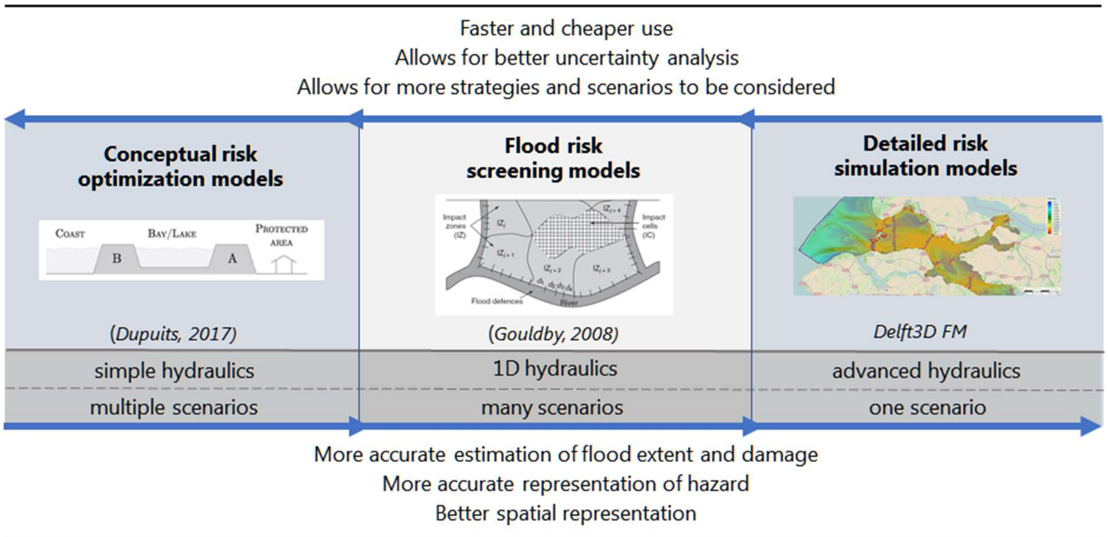


Figure 2 - Different types of flood models used in flood risk management.

Flood management screening models

Quantitative risk analysis on a city scale has been described in earlier research (Moser, 1996; Woodward et al., 2013; Gouldby et al., 2008; Aerts et al., 2014). The schematization mostly depends on the type of flooding, which can differ between coastal surge, fluvial, and pluvial flooding. Flood risk screening models that focus on coastal surge and fluvial flooding generally simplify the flood inundation model, as the most important processes take place on the border between water and land. For example, Gouldby et al. (2008) combined a simplified flood inundation method with flood damage estimation to simulate flood extent and damage due to fluvial or coastal flooding. Although they managed to gain satisfactory results for systems with multiple defenses placed adjacent, this approach is not applicable to systems with multiple lines of defense. Similarly, Aerts et al. (2014) was able to simulate hundreds of synthetic hurricanes to compare different flood risk reduction strategies for the New York region, combining a detailed storm surge model, flood damage model and elevation data with a simplified flood extent calculation to estimate expected annual damage.

When the focus is more towards pluvial flooding, connections are often made to simplified versions of the detailed flood simulation models (Leandro et al., 2009; Löwe et al., 2017). This is necessary because the local urban rainfall run-off is affected by small-scale effects. Also, the urban water management system runs both above and underground, which is often schematized with two separate, but connected models. Thorough evaluation and optimization of urban pluvial flood risk is more complicated, time-consuming and therefore less common than risk evaluation of fluvial or coastal flooding.

For coastal cities, flood can be caused by both storm surge and extreme rainfall. Assessing the flood risk in such cities requires models that can capture the interaction between these hazards and simulate an event where both are occurring. Currently, no commonly available flood risk screening model is able to simulate a combined storm surge and pluvial flood event.

Bridging the gap between engineers and policy-makers

The complexity of the advanced hydraulic models provides a challenge in the communication of the results and the discussions between engineers and policy makers. Flood risk screening models - in particular those taking urban pluvial flooding into account - can play a central role to assist in communication between engineers and policy-makers. Such a modeling approach which can be understood by a large audience of both technical and non-technical people may bridge this gap and can help to understand the entire range of choices, uncertainties, complications and consequences.

The goals of flood risk screening models are very much aligned with aspects related to many World Bank programs and projects. This type of model teaches how the possible choices affect the risk profile, which supports the local understanding of flood risk and its key drivers. The screening allows for multi-objective evaluation for many situations and futures. Together with the ability to simulate many different 'what-if'-scenarios, flood risk screening can be used to maximize flood preparedness in all thinkable scenarios. These aspects highlight the relevance for investigating flood risk screening models further. The next section will discuss in more depth such a model.

2.2. The FLORES-model characteristics

The 'Flood risk Reduction Evaluation and Screening' (FLORES)-model is a flood risk screening model for assessing the flood risk in data-scarce areas. This model aims to bridge the gap between academic risk models and advanced risk models by simulating based on basic hydraulic processes with simplified region-specific information. It has been developed at the Delft University of Technology with the goal to explore and evaluate the impact of many different flood risk reduction strategies within a flood-prone area. The FLORES-model has been developed with several characteristics in mind, mainly based on goals and purposes of flood risk screening models. These main characteristics are:

- **Low computational load**
  The model should be able to assess the (reduction in) impact due to the implementation of a flood risk reduction strategy in seconds, which allows for many strategies and scenarios to be considered.
- **Wide range of measures and scenarios**
  The risk of flooding can be reduced in many different way, including structural solutions, policy-based measures, disaster management and nature-based solutions. Moreover, these strategies will have to perform in an area subjected to changes in (urban) environment and climate. Realistic strategies will often be a combination of these categories, tested for different scenarios.
- **Different performance metrics**
  Different considerations may be leading in a design process, ranging from economic considerations to number of affected people. Different performance metrics can provide new insights and trigger useful discussions.
- **Multi-purpose evaluation techniques**
  There are many stages of the design process in which a comparison of many simulations can be useful. The model should be able to support the generation of alternatives by showing trade-offs between measures and optimize based on case-specific goals. For supporting stakeholder discussions, it should be able to assess the impact of local choices, taking uncertainties and future scenarios into account.
- **Limited data requirements (compatible with Open data)**
  One of the key aspects of this modeling approach is that it can be applied based on open data sources. Many flood-prone regions around the world are coping with a lack of data and funds to develop or buy expensive data sets. Because this model focuses on the conceptual design phase, detailed data sets, although preferred, are not required.
- **Generic setup**
  The model is being developed in a generic way, allowing for relatively fast assessment of different regions. The goal is to provide a model that only requires processing of the local characteristics beforehand, using GIS tools. By not requiring any alterations to the model itself, working with the model will be faster and easier. This way, the workflow can be streamlined for organizations like the World Bank, that require many, quick assessments.

2.3. Structure of the FLORES model

The FLORES model is centered around flood event simulation, which is repeated numerous times for different storms, flood risk reduction strategies and future scenarios, see Figure 3. This repetition is possible because the simulation especially focusses on computational speed[3]. In a later stage, the results can be used to explore the design space in order to learn how the city's risk profile reacts to different situations and design choices. The in-depth technical specifications of the model are described in Chapter 3.

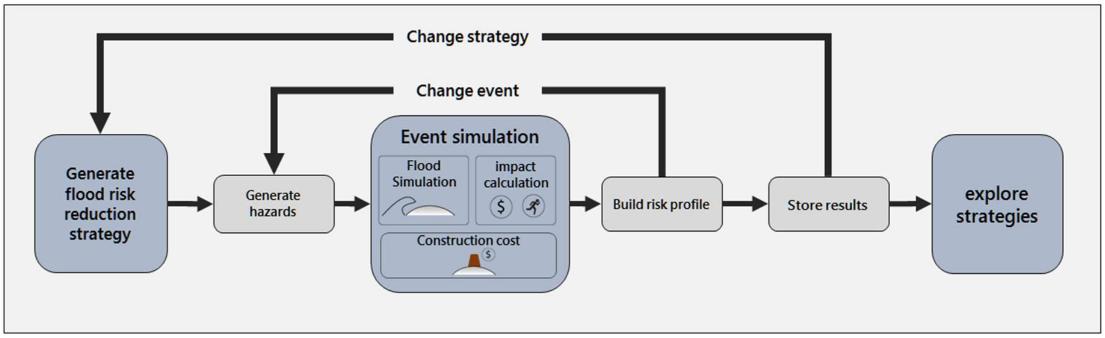


Figure 3- Flowchart of the Flood risk Reduction Evaluation and Screening (FLORES)-model. Calculations of the event simulation are repeated for different events, after which the results are combined to build a risk profile of that strategy. This information is stored for later analysis and comparison.

Simulating hazards and hydraulic processes

At the core of the FLORES model is a rapid flood event simulation. This calculates the effect of both rainfall and storm surge by simulating several hydraulic processes. The urban flooding is schematized by an urban inundation model, connected with a drainage system model, which accounts for retention as well. Urban inundation can also result from storm surge, which overtops or overflows (one or more) flood defenses. In case of a more complicated coastal situation - with an estuary or inner bay -, the interaction between the water bodies inside and outside of the coastal zone is considered.

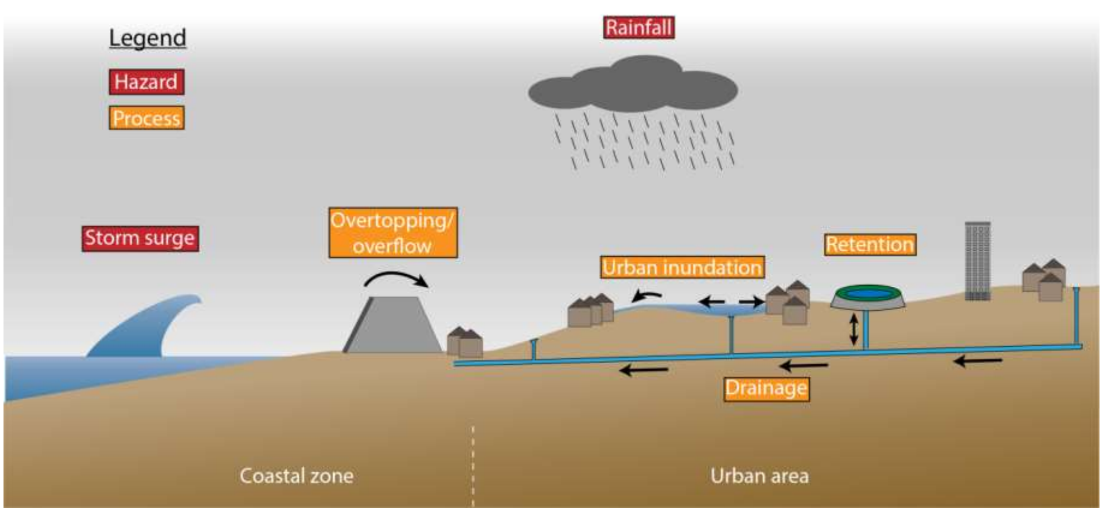


Figure 4 - Hazards and hydraulic processes considered in the model

[3] *To illustrate, one simulation executes in roughly 5 seconds on a single computer. For the case study – further explained in Chapter 4 -, an evaluation of 200 flood risk reduction strategies, with 25 event simulations per strategy, for 4 future scenarios results in a total runtime of 28 hours.*

Assembling a risk profile

The flood simulation results in the multiple output metrics that indicate the impact of the flood event: expected value of damage, expected amount of affected population, and cost of construction and repair. However, one flood simulation is not a complete representation of the city's flood risk. Therefore, the risk is defined as a combination of all possible events, each of which has a probability of occurrence and a potential negative consequence (Kaplan and Garrick, 1981).

When modelling, it is impossible to simulate all scenarios, which is why a number of simulations are used to represent the entire risk profile. The number of simulations is ideally as low as possible, in order to limit computation time. In an earlier case study which focused solely on storm surge, 5 events were used to assemble a risk curve, which shows the change in expected damage with more extreme events. However, the current case considers both flooding through coastal storm surge and extreme rainfall. If we would like to consider the compound effect of both hazards, this would mean that 25 events are required to get a satisfactory idea of the risk profile. This is visualized in Figure 5, which shows the expected damage depends on the return period of the separate events. When the total expected value of damage is calculated from this multi-hazard risk curve, it is important to take the interdependence into account (see also Chapter 3.2).

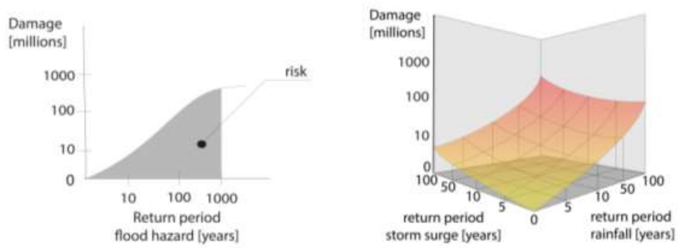


Figure 5 – risk profile for 1 flood hazard (left) and for 2 (right). The compound risk profile is built from 25 flood event simulations. The total risk is computed by integrating over both axes.

The return period in this case is the inverse of the yearly probability of exceedance. Please note that the use of 5 flood events per hazard has been chosen arbitrarily. Sensitivity analysis should clarify the optimal amount of flood events that describes the risk profile sufficiently accurate with the least amount of events. This might vary from case to case. The last step is to compare this risk figure with the risk figure of the null-scenario (doing nothing), which results in the risk reduction because of the flood risk reduction strategy. This can be compared between strategies.

Comparing strategies and exploring the design space

Due to the computational speed, it is possible to repeat the process shown above for many different flood risk reduction strategies and for different scenarios (future scenarios or assumptions for unknown variables). After, we can analyze the results. Through the tools provided by the EMA-workbench (Kwakkel, 2017a), we can explore the results in order to inform on:

- Which (combinations of) measures are effective in reducing risk.
- What type of strategies are especially effective compared to their cost.
- Which strategies are robust for future changes in hazards or urban layout.
- Which uncertainties in design or modelling greatly affect the preferred choice of strategy.

This information, combined with flood maps of individual events and strategies, teaches designers and stakeholders about the range and effect of their choices. The possibilities are evaluated and compared systematically, with the aim to steer the design towards the most promising direction. Later in the process, feedback from events and implemented measures can be used to check whether the flood risk reduction strategy performs as expected.

2.4. Data requirements

The FLORES-model combines (and therefore requires) data on three main topics: The *Region layout*, the *Flood risk reduction strategy* and the *Hydraulic boundary conditions*. The Region layout mostly describes the current situation in the area, the flood risk reduction strategy represents all the possible measures that can be implemented and the hydraulic boundary conditions represent the hazards and the flood events. Looking in more detail to the individual layers, the minimal data requirements can be listed as follows:

Table 1 – Indication of required input data for the FLORES-model. This list is the minimal requirement to run all parts of the model. Less data can still lead to valuable information, although some analyses or evaluations cannot be done. More detailed data can be used for more precise results.

Layer	Required input	Description
Region Layout	Elevation	Absolute height of the area above a specific datum
	Land cover	Type and/or value of land (e.g. residential/ business/other purposes)
	Vulnerability	Scale of potential impact(e.g. Number of inhabitants, land value)
	Damage curves	Relation between inundation level and percentage of value damaged
	Development	Population growth, urban development
Flood risk reduction strategy	Structural measures	Types of measures, construction costs, location, efficiency
	Non-structural measures	Type of measures, implementation cost, expected impact
Hydraulic boundary conditions	Surge data	Time series of water levels during a storm for different return periods
	Rain data	Time series of rain intensity for different return periods
	Wind data	Main wind direction and wind speed during different storms
	Future changes	Change in hazard intensity

Developing countries often lack detailed datasets or reliable historic records. The goal is therefore to develop a tool that is useful with the minimal amount of local data required. A practical first step is to build the model from open-source material. Later, when deemed sufficiently interesting, the choice can be made to increase the level of detail with locally gathered data. Table 2 shows an overview of what types of open-source material could be used and what would be preferred when other sources are also available.

Table 2 – Overview of possible input sources for the data required for the FLORES-model.

Required input	Open source	Reference	Resolution	Remarks
Region layout				
Elevation	Shuttle Radar Topography Mission (SRTM)	Farr et al. (2007)	30 m	Paid services available (e.g. Airbus WorldDEM, 12m)
Land cover	GlobeLand30	Chen et al. (2017)	30 m	Preferred: Land use data
Exposure	Global Human Settlement Layer (GHSL) – Built Up	Smith (2017)	38 m	Can also be based on economic value of land
Damage curves	Global flood depth-damage functions	Huizinga et al. (2017)		Very limited number of land use types
Flood risk reduction measures				
Measures	Reference projects	*Various*[1]		local feasibility studies preferred
Hydraulic Boundary conditions				
Surge data	GAR2015	(Cardona et al., 2014)		Preferred: time series based on local historic analysis
Rain data	*Various*[2]			
Wind data	GAR2015	(Cardona et al., 2014)		
Future changes	Global scenario reports	IPCC (2014)		Preferred: National scenarios

[1] *For structural measures, some general cost information is available. Construction cost of storm surge barriers can be based on (Mooyaart and Jonkman, 2017). Costs can also be based on reference projects, e.g. (GCCPRD, 2015).*

[2] *There are several sources that obtain precipitation data on a global scale. Which should be preferred depends on the area and the requested time scale. An comparison between models can be found in (Sun et al., 2018).*

3. FLORES technical specifications

This chapter describes the model in more detail. The subchapters are divided into the three main actions of the model: Simulating a flood event, assembling a risk curve and exploring the model results.

3.1. Flood event simulation

3.2.1 *Schematization of a flood event in a coastal city*

The Flood simulation uses simplified hydraulic calculations to calculate inundation levels throughout a flood-prone city as a result of a combination of coastal storm surge and heavy rainfall. Subsequently, it estimates the impact in terms of expected damage, construction costs and affected population, see Figure 6.

The simulation can roughly be divided in two parts: Hydraulic calculations and the Impact calculations. In

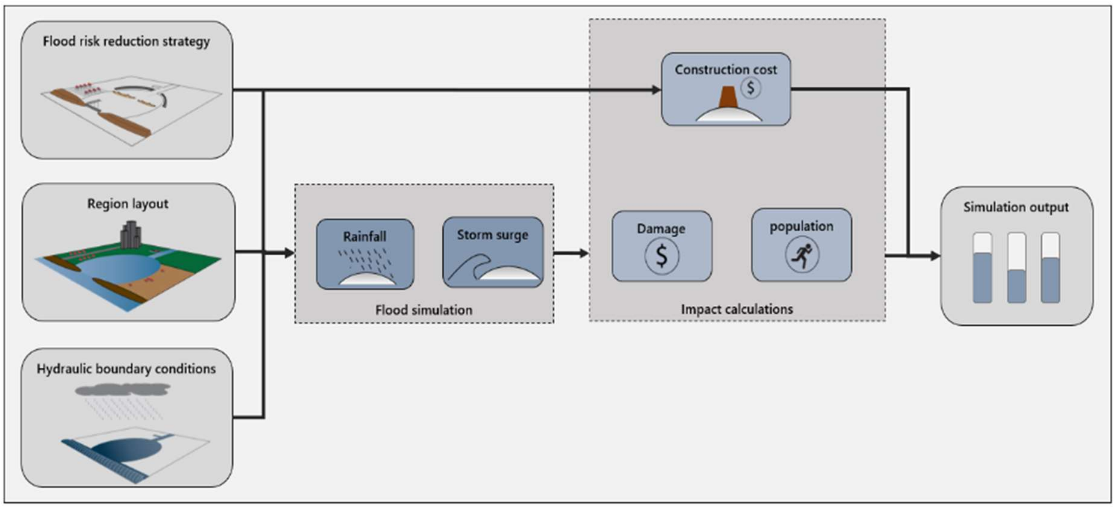


Figure 6 – Schematization of the flood event simulation

the following sections, these parts will be explained further. Especially the new additional module to the FLORES-model will be explained in more detail. Background information on previously developed parts (simulation of storm surge and the probabilistic analysis of flood defenses and scenarios) can be found in earlier reports by Van Berchum and Mobley (2017).

Within FLORES, the city is schematized as a number of drainage basins. A drainage basin is defined as the area where the water drains towards the same location, i.e. the lowest point in that specific area. In this way, the local topography of a flood-prone city with local depressions is accounted for. The hydraulic simulation of a storm and/or rainfall event revolves around the (connected) volume balances of these drainage basins. This type of simulation has many similarities with other Rapid Flood Inundation Models (RFIM) as proposed by Shen et al. (2016), Liu and Pender (2010) and Lhomme et al. (2008). In the FLORES Flood simulation, this volume balance is expanded by taking into account rainfall, infiltration, drainage, retention and surface flow between drainage basins. Moreover, when a city is also threatened by storm surge, lines of defense (e.g. coastline, riverbank) are also defined and the water flowing across such a line of defense is modelled as inflow for the affected drainage basins. This volume balance will be repeated for each basin and for every timestep throughout the flood event.

3.1.1. Model Preparation

The simulation needs several steps of preparation, mostly within a GIS environment. This preparation and the steps of the hydraulic calculation during the simulation is explained further below. More information on code can be found in *Appendix A*.

Region layout: GIS data extraction

When setting up the model, data on the regional layout must be adapted for the simulation. This implies that GIS-based information needs to be converted into easily accessible databases. Using GIS software for every simulation is too intensive computationally, which is why the information on the region is converted to a table structured format (CSV).

All preparation can be done with the use of standard tools of GIS software packages (QGIS or ArcGIS).First, the city is divided into drainage basins, see Figure 7. These basins are defined as parts of the region that drain in the same point. Next, these basins are divided into height contours, areas within a range of elevation (e.g. 4 – 4.25 m + CD). With this information, a Volume-Depth curve can be constructed. This will act as the backbone of the volume balance calculation throughout the simulation.

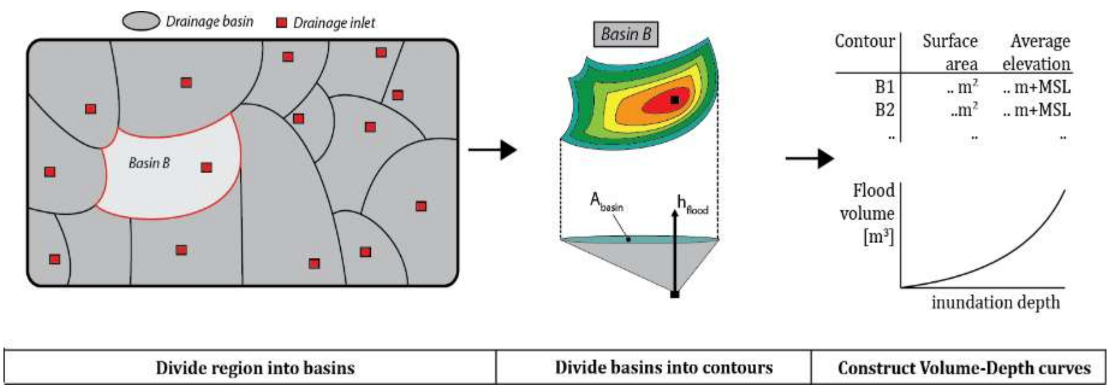


Figure 7 – Schematization of the city from GIS data into input data for the FLORES model. Based on the DEM, the region is divided into basins and contours, leading to a Volume-Depth Curve of every basin.

Several steps are required to make the data fit for the FLORES-model. The exact workflow is explained further in Appendix A. For each drainage basin, the following information should be gathered:

- Elevation of contours and corresponding Volume-Depth curve
- Surface area
- Elevation of borders with adjacent drainage basins
- (if applicable) retention capacity
- (if applicable) drainage capacity
- (if applicable) length of basin bordering Line of Defense along open coast or flood defense

Hydraulic boundary conditions

The hydraulic calculations simulate the effects of one flood event, consisting of coastal storm surge, extreme rainfall or a combination of both. Using tidal data, maximum storm surge, rainfall intensity, storm duration and wind characteristics, these conditions are prescribed as inputs in the model. For the coastal storm surge, a time series at the coast is used as input, calculated as the summation of tide and storm surge, see Figure 8. Usually, entire time series of storm surge above normal tide are not available. In most cases, only maximum surge levels for different probabilities of exceedance are available. The tidal maximum is assumed to coincide with the maximum surge level, halfway through the storm (which is a conservative choice). The noticeable part of the storm surge is often relatively short compared to the total storm duration. As default, a n-power of sine is applied for the shape of the storm surge in time. If local data is available, a more tailormade shape of the storm surge can be applied. Besides tide and storm surge, the time series of water level at the coast can also shift due to sea level rise. For the storm visualized below, a characteristic time period of 24 hours is used, based on information on the storm surge (this particular information is related to the case study of Chapter 4). Other time periods are also possible.

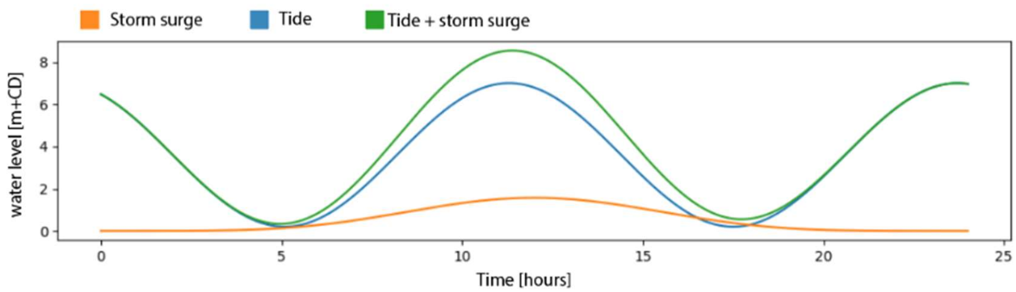


Figure 8- (green) water level at the coast during a storm surge event in Beira (see chapter 4). This consists out of a tidal component (blue), and a storm surge component (orange). Not depected is sea level rise applied. When applied, this would shift the entire series upward.

For each timestep of the flood simulation, the water level at the coast is determined and used as main load on the coastal zone. In the coastal zone, this is used for the calculation of discharge across the coastal defenses through overtopping or overflow. The water level is also used to calculate the probability of failure of the coastal defenses through the fragility curve. The calculations in the coastal zone (defined in the model as a Line of Defense) are explained further in earlier work described by van Berchum et al. (2018).

The wave height also plays a significant role in the fragility calculation and the calculation of discharge across a Line of Defense. The significant wave heights for different return periods are input in the model. For locations around the world, the wave height can often be found for deep sea conditions (e.g. through NOAA open data). The significant wave height near the coast is estimated by taking shoaling and refraction into account. However, the coastal situation usually leads to breaking before a land barrier is reached, limiting the maximum wave height. This is different when an inlet is present. For inlets, the water depth is often not limiting the wave height, which affects the forces on any potential storm surge barrier placed in the inlet. The wave height is calculated with:

$$H_s = \min\left(H_{s,c}, 0.5 \cdot \left(h_{surge} - h_c\right)\right) \qquad [1]$$

Where,

H_s	: Significant wave height [m]
$H_{s,c}$	: Significant wave height in the coastal zone [m]
h_{surge}	: Elevation of coastal surge [m+CD]
h_c	: Bed elevation of the coast (for land barriers) or river bed (for inlets) [m+CD]

Information on rainfall intensity can often be found in the form of intensity-duration-frequency (IDF) curves. Examples of these curves are depicted in Figure 9. For the model, the intensity for different return periods is used for a duration of 24, 48 and 72 hours. In the model, the duration can be changed to see its effect. When the risk is mostly based on compound flooding, a flood event duration is used which is characteristic for compound events in that region. Unlike storm surge, real time series of rainfall are usually random, and solely defined by an average rain intensity. In the model, the rainfall is assumed to be equal to the average rain intensity for every time step in the default setting. Although this is not realistic, it is assumed sufficient as long as no other information is available.

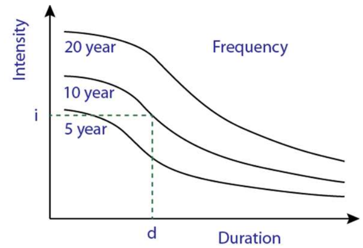


Figure 9 - conceptual depiction of an IDF Curve. It shows for every combination of average rain intensity and event duration, the frequency of that type of event. For example, a rainfall event of duration d with intensity i occurs once every 10 years. (source: reviewcivilpe.com)

The wind characteristics (wind speed and direction) are only considered when a large inland waterbody (e.g. lake, lagoon, bay) is present to calculate wind set-up, because the effect of wind on the coast is already taken into account in the storm surge. More information on modelling the effect of wind on large water bodies through wind set-up is explained by Van Berchum and Mobley (2017).

Input of the boundary conditions is required for different return periods, which is the inverse of the probability of exceedance (1-in-100 year storm is equal to a storm with a yearly exceedance probability of 0.01). This is the case for characteristics of the storm surge, waves, rainfall intensity and wind. For most scenarios, an event simulates the compound effects of both coastal storm surge and extreme rainfall. This requires information on the correlation of both hazards, which is often not available. Therefore, we will assume a correlation based on worldwide references. During the flood simulation, the probability of the event is calculated based on the return periods of the coastal storm surge and the rainfall, and the correlation. This is input for the risk curve. The calculation of risk (reduction) is explained in Chapter 3.2.

Flood risk reduction measures

A flood risk reduction strategy consists of a combination of potential measures. In order to represent the full array of options for flood risk management, many different types of measures are included. Measures can affect different parts of the model. Therefore, they are divided into four different categories as shown in Table 3.

Table 3 – 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 defenses	Levee Storm surge barrier Sand nourishment	Between hazard and vulnerable area	Flow into drainage basin
Drainage	Drainage system Pumps	Between drainage basins	Maximum discharge between basins
Retention	Retention basin flood routing	Drainage basin	Volume of water stored in drainage basin before damage occurs
Emergency measures	Improve evacuation early warning system	Drainage basins	People in vulnerable areas
Flood proofing measures	House reinforcements Raising houses	Drainage basins	Property value damage curves

The calculations related to these measures are explained in Chapter 3.1.2.

- Flood defenses are a central part of the storm surge simulation, explained in more detail in (Van Berchum and Mobley, 2017). These structures are placed on Lines of Defense, which are often located on the border between the source of the hazard (e.g. sea, lake, river) and vulnerable drainage basins. They affect the overflow/overtopping discharge by storm surge into the drainage basins behind the Line of Defense. For this calculation, the use of new flood defenses leads to a new structure height and slope (compared to the null-scenario). Also, these structures are modelled to have a failure probability, which leads to two different flood outcome scenarios.

- Drainage measures improve the maximum discharge between basins. During the flood simulation, the flow towards a downstream basin is calculated. This flow is limited when the water level is close to the water level of the downstream basin. The discharge is unaffected when the difference is 1 meter or more. A drainage measure is input as a maximum drainage discharge per basin. This represents the maximum amount of water that can be discharged out of the basin through drainage. This discharge is based on design discharges or channel dimensions.
- Retention measures increase the amount of water a drainage basin can store before it starts to flood. Most basins have some ability to store water (pond, lake, riverbed, canal) before flooding starts. A retention measure is defined as an additional volume. Retention measures are input for the model as entire projects, instead of the ability to freely add retention to basins with variable costs. The cost of retention projects are based on reference projects. Which are local references where possible or more general costs per m^3 retention.
- Emergency measures are assumed to only affect the exposure. Measures like early warning systems or enhancing evacuation routes limit the amount of people that can be exposed to flooding. In the model, this is chosen on the scale of drainage basins, where normally basins are chosen that are well connected and close to higher ground. The measures affect the exposed population as a limiting factor, which is multiplied with the original population:

$$P_e = f_e \cdot P_o$$

Where P_e is the new exposed population, f_e is the factor as a result of the emergency measure, and P_o is the original population.

Multiple external scenarios

Data collection can significantly lag the urban development, especially in fast-growing cities in developing countries. By the time the flood risk reduction strategy is implemented, the situation has most likely changed significantly from the situation when this strategy was selected. This difference will only grow during the expected lifetime of the implemented measures. Therefore, it can be useful to include various scenarios to see how the strategy performs under different future scenarios (states of the world). These futures can be categorized on the future change in hazards (e.g. climate scenarios) or change in exposure (e.g. urban development scenarios).

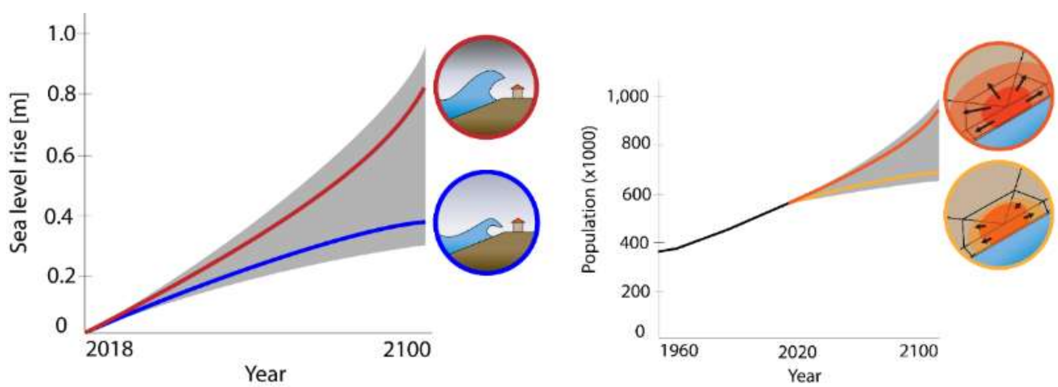


Figure 10 – (left) Climate change will likely lead to higher sea levels and more extreme storms, wind speeds and wave heights. This can be considered through a low (blue) and high (red) climate scenario. (right) Urban development is mostly unpredictable. Many African cities grow quickly. Based on many factors (including flood risk), the future can be taken into account through an increasing (dark orange) or a more gradual (light orange) growth in population and urban development.

Multi-objective robust evaluation

The preparation phase provides all case-specific information needed to run a simulation, as well as information on all the input variables that can be adjusted. These variables can be divided into two groups:

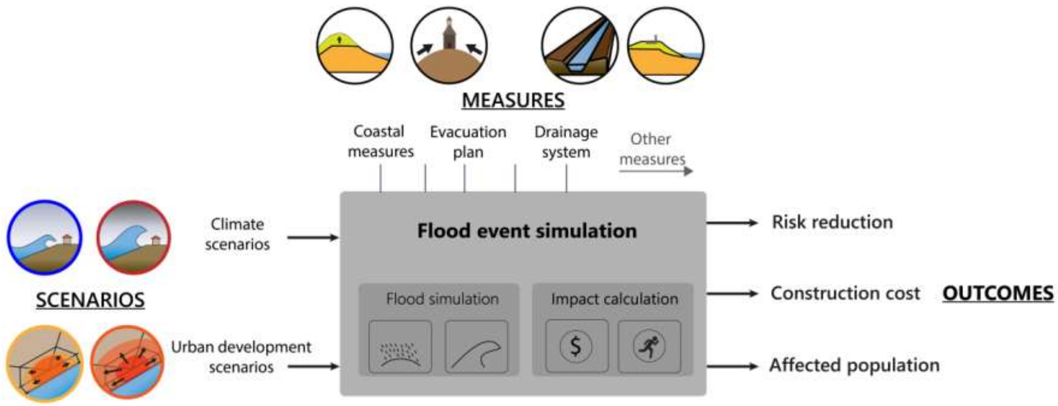


Figure 11 – The connection between the different parts of the FLORES-model simulation. The outcome of the simulation depends on factors that we can change (the 'Options' or flood risk reduction measures), and factors that are uncertain (the 'Scenarios'). The simulation will run hydraulic calculations, taking rain and storm surge into account, and impact calculations. It will result in three performance metrics, the 'outcomes', that can be compared later.

Options and Future scenarios. Options are the levers that are part of the flood risk reduction strategy, meaning that the modelers and decision-makers can choose whether or not to implement certain measures. Future scenarios are states of the world, which are uncertain at the moment of modeling. These are out of the control of decision-makers. Because of the large uncertainty of the future, no probabilistic distribution is connected to these states of the world. This can be used for robust design, which is defined as a design that performs satisfactory for all considered future states of the world.

3.1.2. FLORES hydraulic calculations

Hydraulic simulation steps

The hydraulic calculation can be considered as a connected bathtub model on a drainage basin scale. For each time step and for each basin, all incoming and outgoing volumes are calculated and balanced. The total hydraulic simulation is shown in pseudocode in Table 4.

Table 4 - Code and steps for the hydraulic simulation in the FLORES-model

```
For every time step:
        For every basin:
                For every scenario:
                        Calculate inflow rain                                   (Step 1)
                        Calculate outflow infiltration                          (Step 2)
                        If basin is located directly behind line of defense:
                                Calculate inflow storm surge                    (Step 3)
                        Add incoming surface flow from other basins             (Step 4)
                        Calculate outflow into retention                        (Step 5)
                        Calculate outflow drainage [eq 2,3]                     (Step 6)
                        If water level > elevation drainage basin border:
                                Calculate flow between basins                   (Step 7)
                        Calculate new water level                               (Step 8)
For every basin:
        Calculate maximum water level                                           (Step 9)
```

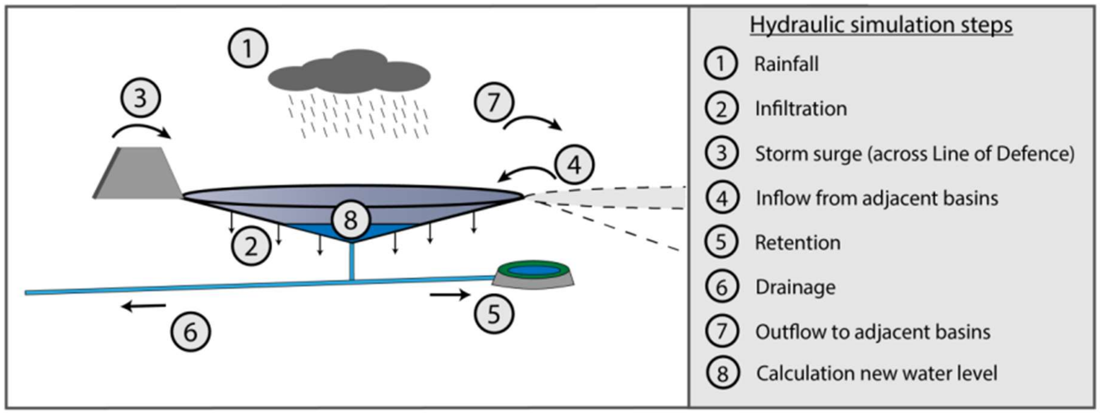


Figure 12 – Steps involved in the hydraulic simulation of the FLORES model. The numbers relate to the steps mentioned in Table 4. The steps are explained further below.

Step 1: The rain volume is calculated through the rainfall intensity and the drainage basin surface area. See equation 1. The rainfall intensity is assumed constant for the entire flood event by default but this can be refined if local data is available.

Step 2: The amount of outflow through infiltration into the soil depends on the surface area which is inundated. See equation 2. To reduce computation time, the surface area at a given inundation depth is estimated by linearizing between the surface area at the minimum inundation and at the maximum basin elevation.

Step 3: The model checks if the drainage basin is located behind a Line of Defense. If so, the inflowing volume for the basin is calculated (see Figure 13).

Step 4: This step calculates the inflow from adjacent basins through surface flow. When the water level in other basins rises past the elevation of the border between basins, a volume is transferred to the other basin, which acts as inflow during the next time step. See step 7 for more information.

Step 5: For every basin, there is the option to add retention capacity. This is volume that can be stored in the basin before flooding occurs. This can be a pond, a river branch/drainage system or a retention basin. The amount of retention used is constantly tracked. Water in retention will also flow downstream when a flooding disappears.

Step 6: If a basin is connected to a system that transports the water away from the basin, the amount of volume passing to the next downstream basin is calculated. This transportation can be through natural river streams or man-made drainage systems. See equation 3 and 4.

Step 7: If the water level rises above the elevation of the lowest border with a neighboring basin, surface flow is simulated by transferring an estimated volume of water to that basin. If after deduction of the volume, the water level is still higher than another basin, this is repeated (See Table 5 for more information).

Step 8: Using the Volume-Depth curve, the new water level is updated after every time step.

Step 9: The simulation results in time series of water levels in every drainage basin. This step takes the maximum water levels, which are used for the impact calculation.

Equation [1]:

$$Q_{r,b} = A_b \cdot I_r \cdot t \qquad [1]$$

Where,

$Q_{r,b}$: Volume inflow due to rain $[m^3]$
A_b : Surface area of the drainage basin $[m^2]$
I_r : Rain intensity [*m/hour*]
t : length of timestep [*hours*]

Equation [2]:

$$Q_{i,b} = q_i \cdot A_b(h_b) \cdot t \qquad [2]$$

Where,

$Q_{i,b}$: Volume outflow due to infiltration $[m^3]$
q_i : infiltration rate $[m/hour]$
$A_b(h_b)$: Surface area of the drainage basin at elevation of water level (linearized) $[m^2]$

Equation [3,4]:

$$Q_{drain} = q_{max} \cdot t \cdot DF \qquad [3]$$

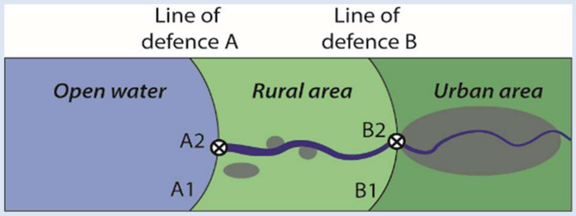
$$DF = \min(h_{diff}, 1) \qquad [4]$$

Where:

Q_{drain} : Volume drained out of basin during one time step $[m^3]$
q_{max} : Discharge capacity of the drainage system in the basin $[m^3/s]$
t : Length of the time step [s]
DF : Drain factor, which limits the drainage volume when the water level is close to the downstream water level [-]
h_{diff} : difference in water level between basin and downstream basin [m]

Hydraulic schematization of storm surge

The impact of a storm is simulated by schematizing the area as a series of Lines of Defense and Protected areas. During the hydraulic calculation, the model checks whether a basin is located behind such a Line of Defense and calculates the volume of water that enters the basin per time step.



A Line of Defense can consist out of multiple flood defenses. The volume of water entering the basin depends on whether the flood defenses hold or fail (and which). This is included by simulating all possible outcomes. The discharge into the next layer is simulated with the use of a – combination of – hydraulic formula(s). Many different combinations can be applicable (e.g. flood defenses on land or water, flood defenses that hold or fail). The situations and used formulas are further explained in (Van Berchum, 2017).

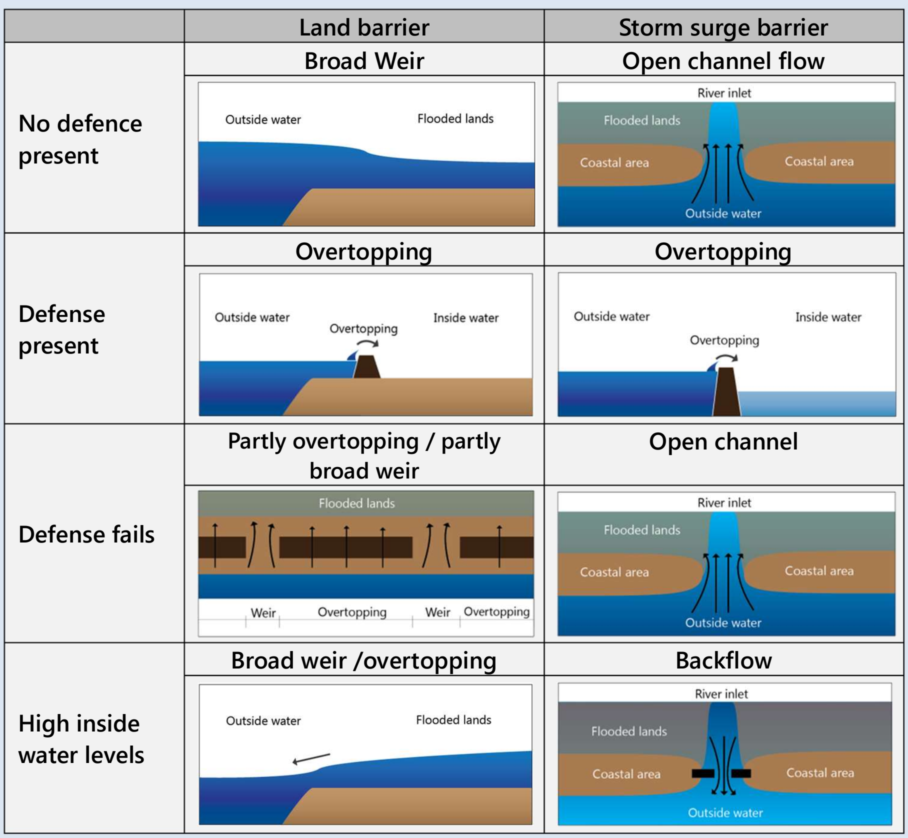


Figure 13 – Simple hydraulic relations are used and combined to simulate the many different forms of discharge past a line of defense.

Table 5 - Code for the calculation of potential flow between basins. This type of schematization through drainage basins and flow between them has been modelled before, see Figure 14.

For adjacent basins:
    threshold = max(water level in adjacent basin, border elevation)
Sort adjacent basins on threshold elevation (low-high)
For adjacent basins (lowest threshold first):
    If water level source basin > threshold
        Area factor = (surface area source basin) / (surface area receiving basin)
        Calculate new water level [eq. 5]
        Calculate volume through volume-depth curve
    Else:
        Break calculation

The goal of equation 5 is to estimate the new water level in both basins, without having realtime information of the receiving basin. It estimates the new shared water level, based on the ratio of the surface areas of the basins. For example, when the receiving basin is twice as large, f_A equals 2. With equation 5, the new water level in the source basin (h_{new}) becomes $h_{threshold} + \frac{1}{3}\left(h_{receiving} - h_{threshold}\right)$.

Equation [5]:

$$h_{new} = \frac{h_{receiving} * f_A + h_{threshold}}{1 + f_A} \qquad [5]$$

Where:

h_{new}	: New water level in the source basin [m+CD]
h_{source}	: Old water level in the receiving basin [m+CD]
f_A	: Area factor, ratio between the surface area of source and receiving basin [-]
$h_{threshold}$	: elevation of the threshold, which is the highest of either the water level or the border between the basins [m+CD]

Figure 14 – Similar modelling in earlier work: (Left) Schematization of a drainage basin as a cone(upper left), and how inundation above border elevation is schematized (Shen et al., 2016), and (right) description of the different spilling/merging steps between basins (Lhomme et al., 2008).

Probabilistic calculation within the FLORES simulation

The expected impact of one storm depends on whether the implemented flood risk reduction interventions will hold or fail. The probability of failure of these structures is measured through their fragility curve. This curve characterizes the strength of the structure and shows the relation between failure probability and the load. Here, only one type of loading can be included, which currently is the outside water level. Wave height also affects the failure probability by changing the location and standard deviation of the fragility curve. But this effect is neglected for the time being. For more information on this calculation, please refer to (Van Berchum and Mobley, 2017).

This calculation is repeated for every structural flood defense. Given a few flood risk reduction measures, scenario outcomes can differ significantly within the same strategy. This is considered by simulating all scenarios.

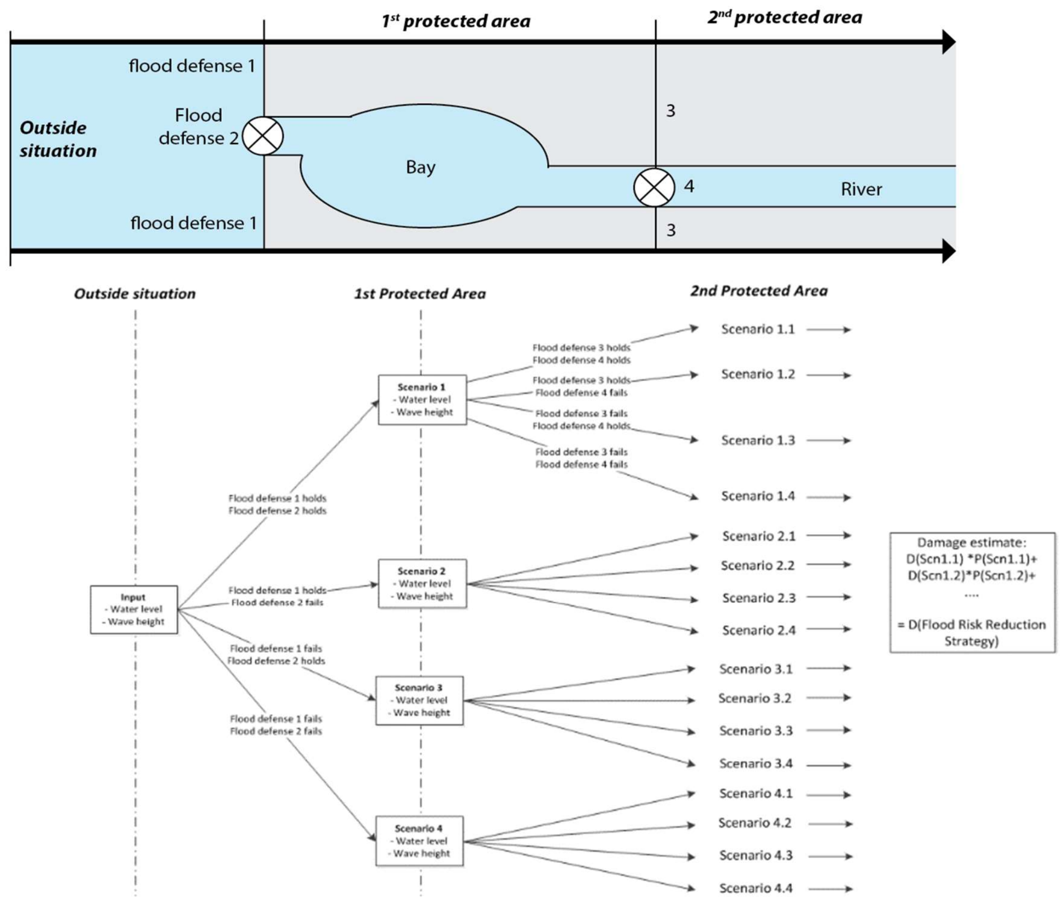


Figure 15 – schematization of storm surge scenarios. In the example (up), the region includes two lines of defense with both two flood defense types, each of which can hold or fail. The chart (down) shows how the expected value of damage can be calculated from the different possible outcome scenarios.

Because of this schematization, the amount of calculations quickly adds up when the amount of lines of defense and the amount of flood defense structures in the lines of defense grows.

3.1.3. Impact calculation

At this point, the scenario outcomes and the maximum inundation for each drainage basin can be used to determine the flood impact. This can be clarified through different metrics: The expected value of damage, the cost of construction and repair, and the estimated amount of people affected.

Damage calculation [from (Van Berchum and Mobley, 2017)]

Damages are calculated by finding the inundation level which is 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. 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): [4]

$$D_s = \sum_{l=1}^{s}\left[\sum_{k=1}^{m}\left(\sum_{j=1}^{n}\sum_{i=1}^{u} D_{T,ijkl}\right)\cdot P_{s,l}\right] \quad [6]$$

$$D_{T,ijkl} = V_{st,ijkl}\cdot p_{st,ijkl} + V_{ct,ijkl}\cdot p_{ct,ijkl}\left(h_{f,j}\right) \quad [7]$$

$$h_{f,j} = h_{m,kl} - h_{cr,j} \quad [8]$$

Where,

D_s	= expected damage for one flood risk reduction strategy [$]
D_T	= expected damage for one land use type [$]
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_w	= maximum flood height in watershed [m+CD]
h_{cr}	= elevation of contour [m+CD]

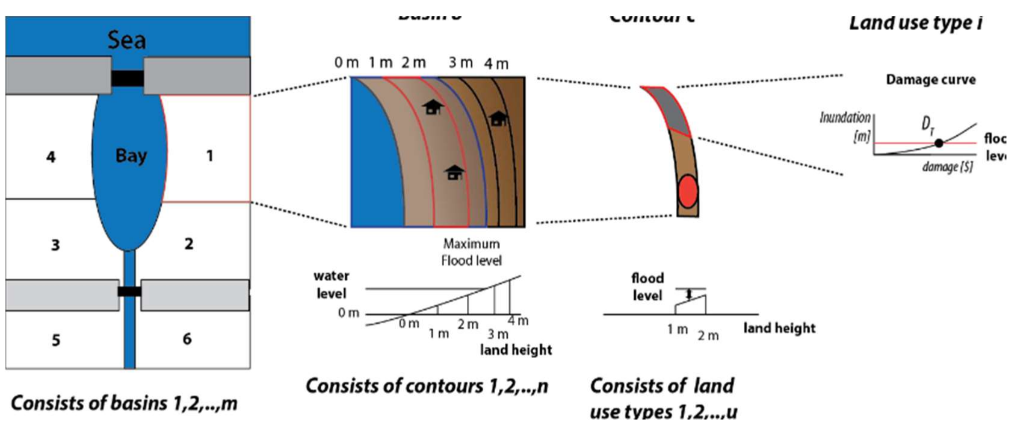


Figure 16 - Process of calculating damages for a given flood level. Every basin is divided into height contours. Subtracting the elevation from the water level gives the maximum flood level. This is input for the damage curves, which estimates damage for one land use.

Cost of construction and repair

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 (e.g. material, manpower), which are taken into account as 'variable costs'. When a flood defense fails, also repair cost is taken into account. The repair cost is defined as the cost needed to clear structural damage and replace up until old value. Maintenance cost is not taken into account.

$$C_{fd} = \left(C_{con} + C_{var}\cdot \left(h_{str} - h_0\right)\right)\cdot l_{str} \quad [9]$$

[4] *Portion of structure/content damaged at a given inundation depends on the land use type. This model uses seven land use types, which each have their own damage curve.*

In which:

C_{fd}	: Construction cost of flood defense [$]
C_{con}	: Constant construct cost of flood defense [$/m(length)]
C_{var}	: Variable construction cost of flood defense [$/m(length)/ m(height)]
h_{str}	: elevation of structure crest [m+CD]
h_0	: elevation of location of structure [m+CD]
l_{str}	: length of structure [m]

$$C_{r,fd} = RF_{fd} \cdot C_{fd} \cdot BF_{fd} \quad [10]$$

Where:

C_r	: Repair cost of the flood defense [$]
RF	: Replacement factor, total relative cost of both clearing the area and replacing the structure [-]
BF	: Breach factor, portion of the structure that is assumed to fail [-]

Estimated amount of people affected

Like the damage calculation, the amount of affected people can be estimated from the inundation depth. From input data, the number of inhabitants per basin and contour can be estimated. Based on the land use, the percentage of people affected at a certain inundation depth can be determined.

$$N_s = \sum_{l=1}^{s}\left[\sum_{k=1}^{m}\left(\sum_{j=1}^{n}\sum_{i=1}^{u} N_{T,ijkl}(h_{f,j})\right)\cdot P_{s,l}\right] \quad [11]$$

Where:

N_s	= expected amount of people affected
$N_T(h_{f,j})$	= expected amount of people for one land use type
h_f	= flood inundation in contour [m] (see equation [...])
$P_{s,l}$	= probability of scenario outcome for this strategy [-]

3.2. Risk curve assembly

The ability to reduce risk is the main performance metric for the FLORES model. One simulation is not enough to capture the full performance of the measures. Therefore, multiple simulations are combined to approximate the risk curve. This curve represents the expected damage as a function of the probability of exceedance of the main hazards. For the FLORES model, an extreme event can consist of a combination of two hazards: extreme rainfall and coastal storm surge.

In total, 25 simulations are run to approximate the damage for events with a different probability of occurrence. For both hazards – coastal storm surge and extreme rainfall – 5 probabilities of exceedance are considered (5, 10, 50 and 100 year^{-1}, as well as the ordinary situation). The expected value is calculated by numerically integrating the damage over the probability of occurrence. This needs to be done carefully, because of the relatively small number of realizations (25) on which the entire risk curve is based.

A double numerical integration is used, based on the Simpson integration method. To apply this, the standard Simpson numerical integration method for the different steps in probability. The integration method is included in the Python SciPy package:

$$\boldsymbol{p_r} = [0, 0.01, 0.02, 0.1, 0.2, 1]$$
$$\boldsymbol{p_s} = [0, 0.01, 0.02, 0.1, 0.2, 1]$$
$$D(p_i, p_j) = \begin{bmatrix} d_{0,0} & \cdots & d_{0,1} \\ \vdots & \ddots & \vdots \\ d_{1,0} & \cdots & d_{1,1} \end{bmatrix}$$

$$E_{d,r}(D) = \left(simps\left(simps\left(D\left(p_i, p_j\right), \boldsymbol{p_r}\right), \boldsymbol{p_s}\right)\right)$$

$$r_{d,r} = \frac{E_{d,0} - E_{d,r}(D)}{E_{d,0}}$$

Where:

$\boldsymbol{p_r}$	= probability of exceedance for the rainfall event. For the points in this vector, the damage is known [1/year]
$\boldsymbol{p_s}$	= probability of exceedance for the storm surge event. For the points in this vector, the damage is known [1/year].
$D(p_i, p_j)$	= Matrix of all (36) realization of the risk curve for which the damage is expected to be known. This includes 25 runs of the model. For cases more extreme than 1/100 year rainfall or storm surge event - where probability of exceedance is less than 0.01 -, the damage is assumed to be equal to the 1/100 year rainfall event. Also the regular situation ($d_{1,1}$) is assumed to cause no damage [$]
$E_{d,r}(D)$	= Expected value of damage [$ / year]
$r_{d,r}$	= Risk reduction. The relative reduction of expected value of damage as a result of implementing a flood risk reduction strategy [-]
$E_{d,0}$	= Expected value of damage of the null-scenario, where no flood risk reduction strategy is implemented. Is calculated beforehand [$/year]

This process can be visualized through a risk curve, see Figure 17. Here, the damage is shown, based on the probability of exceedance of the two hazards mentioned above (storm surge and rainfall). The calculation of the reduction in affected population is done in the same way. Here, the expected number of people affected, $E_{p,r}(P)$, is compared with the expected number of people affected in scenario where no flood risk reduction strategy is implemented, $E_{p,0}$, to calculate the reduction in people affected, $r_{p,r}$.

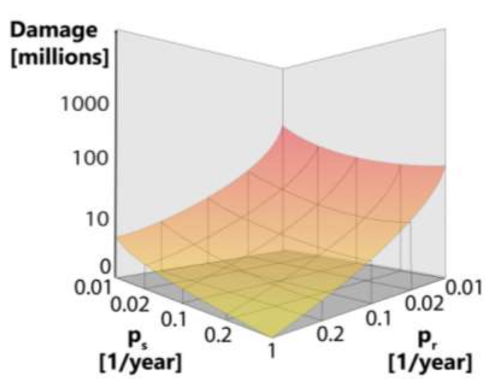


Figure 17 – Multi-hazard risk curve, showing the damage based on probability of exceedance of two potential threats: storm surge (p_s) and rainfall (p_r)

Dependency between hazards

Some cities are threatened by more than one type of flood hazards. When two or more hazards are relevant, the dependency between them can have a large effect on the risk profile. The probability of extreme compound events will differ greatly when the hazards can be considered independent or dependent. The dependence affects the joint probability of each of the simulations (shifting the 'weight' of the individual simulations). For example, when storm surge and rainfall are independent, the probability of a 1-in-100 year storm surge events occurring during a 1-in-100 year rainfall event is $1/100 \cdot 1/100 = 1/10{,}000\ per\ year$. However, when dependency between storm surge and rainfall grows, the joint probability of this event rises significantly, up to $1/100\ per\ year$ when fully dependent.

As a conceptual example of a risk curve, we assume damage to be a function of both the return periods: $D(s,r) = 1/p_{s,r} \cdot 2$ in millions, where s and r are the return periods of the storm surge and rainfall, respectively, and $p_{s,r}$ is the joint probability of the event. If 25 scenarios are considered (0, 5, 10, 50, 100 year events for both hazards), the fully independent case sums all scenarios:

$$E_d = \frac{D(0{,}0) + D(0{,}5) + D(5{,}5) + \cdots + D(50{,}100) + D(100{,}100)}{25} = 2.2\ billion$$

However, in a fully dependent case, many scenarios are not possible, so only 5 scenarios are given a higher probability.

$$E_d = \frac{D(0{,}0) + D(5{,}5) + D(10{,}10) + D(50{,}50) + D(100{,}100)}{5} = 5.1\ billion$$

This is an increase of 130% in expected annual damage. In reality, these hazards are neither dependent or independent, so the error will not be this extreme. However, it does show that wrong assumptions at this part of the risk calculation can have a large impact on the total expected damage.

3.3. 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. This part of the model consists of two steps: the assembling of the risk profile and the evaluation of strategies.

3.3.1. Open exploration with the EMA workbench

The analyses of the results of the many simulations 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 the context of the FLORES model, it generates potential flood risk reduction strategies and *states of the nature* (future scenarios in climate and urban development), 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.

The first goal of the use of the EMA workbench within the FLORES research is to inform stakeholders. Running the flood simulation model numerous times has led to huge amounts of data on how different strategies and future scenarios result in differences in risk reduction, implementation cost and affected population. The first step is therefore to visualize this data to show interesting trade-offs and trends. At this point, we still look at all options. Common techniques include Pair Wise Plotting, Feature Scoring, and Scenario Discovery (Bryant and Lempert, 2010; Kwakkel and Jaxa-Rozen, 2016). These have been used in an earlier case study involving the Houston-Galveston Bay area. Many other analysis techniques are included within the workbench for different purposes. For example, interactive visualization can be used to complement stakeholder discussions in real-time and regional sensitivity analysis can be used to quantify uncertainties.

Pair wise plotting

This first visualization quickly shows how different output types compare to each other. As an example, Figure 18 shows how 500 different strategies to protect the Houston-Galveston bay lead to differences in outcome (no future scenarios were applied). Although this does not show the effect of individual measures yet, it does show overall trends and trade-offs between outcomes. Also, when applied to different states of the world, it shows how the effects of the strategies are affected.

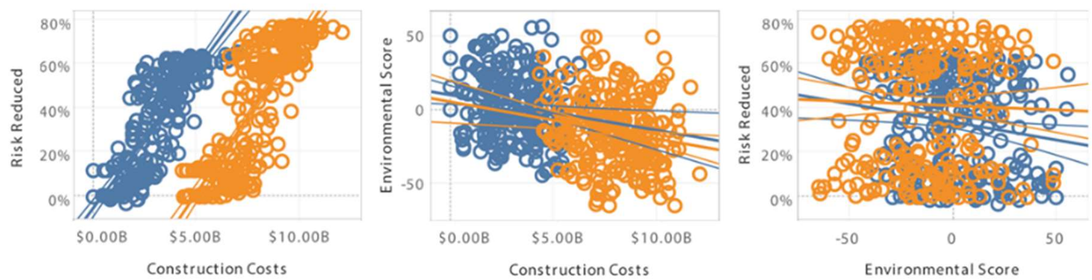


Figure 18 - Pair Wise Plot for the FLORES-model for the Houston-Galveston Bay area. Blue indicates strategies with a coastal storm surge barrier implemented, while orange indicates no barrier in the inlet. Two trend lines can be distinguished when comparing construction costs with risk reduction. Also, Environmental impact has a low correlation with both construction costs and risk reduction.

Feature scoring

The second technique requires more advanced analysis. Feature scoring is a family of techniques popular in machine learning to identify the most relevant features. The method used in the FLORES-model is called

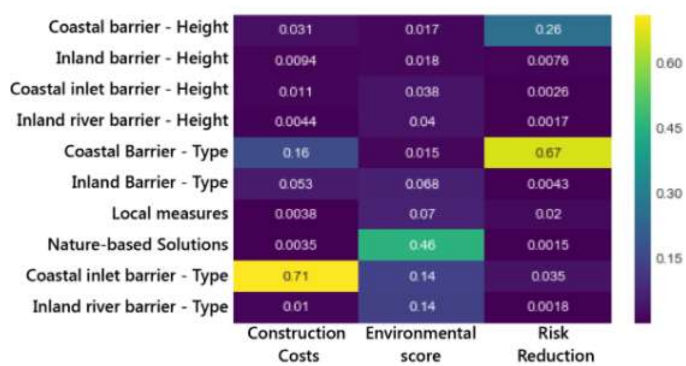


Figure 19 – Feature Scoring table for the FLORES-model for the Houston-Galveston Bay area. Higher numbers imply higher impacts. For example, the most important factors that drive risk reduction are the type of coastal barrier, the height of the coastal barrier and the type of coastal inlet barrier. The number indicates its relative importance.

Extra Trees (Geurts et al., 2006) and is included in the EMA workbench. An example based on the Houston-Galveston Bay case study is shown in Figure 19. It shows how the different outcomes are affected relatively by input choices. Higher numbers imply higher impacts.

Scenario discovery

The third technique is scenario discovery and is mainly used herein. Scenario discovery is a relatively recent approach for identifying subspaces within the model input space that have a high concentration of results which fulfill certain goals (e.g. good cost-benefit ratio). For example, it could look at flood risk reduction strategies that reach a set goal in terms of risk reduction (e.g. a risk reduction of more than 60%), and show that most of these successful strategies include a particular combination of drainage and retention measures. This would imply that these measures are effective for reaching the mentioned goal.

A dominant machine learning algorithm for Scenario Discovery is the Patent Rule Induction Method (PRIM, see Friedman and Fisher (1999)). In the context of the FLORES model, it can find flood risk reduction measures that comply with a particular group of demands. Through the algorithm, it is able to limit the design space. If we look at the first example in Table 6, it starts with the full design space. Here 50 out of 500 considered strategies comply with the goals set under 'Goals'. The algorithm finds the design choice that (1) limits the design space as much as possible, while (2) trying to limit the loss of interesting strategies along the way. In the example, it was able to make 3 design choices. Without further changes, the design space is limited to a subset where 40 out of 49 strategies comply with the goals.

Table 6 - Example of PRIM results. Explanation: 'Goals' are the strategy outputs we want to achieve, 'Start' indicates how many strategies comply with the goals initially, 'Results' show which design choices are made to narrow down on the interesting strategies, 'Final box' indicates how many strategies are still within the new design space and how many comply with the goals.

Goals	**Start** Strategies of interest	**Results** Design choices (priority from top down)	**Final box** Strategies of interest
Focus on risk reduction			
For climate scenario 1: $risk\ reduction > 0.6$ $construction\ cost < 100M\$$	**50** out of 500	1. Most effective design choice 2. Second design choice 3. Third design choice	**40** out of **49**
For climate scenario 2: $risk\ reduction > 0.45$ *Construction cost* < 95 M$	**86** out of 500	1. Most effective design choice 2. Second design choice 3. Third design choice 4. Fourth design choice	**60** out of **82**

3.3.2. Directed search with the EMA workbench

The second goal of using the EMA workbench is to directly support decision making by identifying the best flood risk reduction measures, based on multiple demands and (deep) uncertainties. The included algorithms mostly focused on robust decision making and multi-objective optimization (Herman et al., 2015; Kasprzyk et al., 2013). With techniques included within the workbench, adaptive planning schemes can be set up to support ongoing investment schemes during the lifetime of the flood risk reduction project, in order to optimize risk reduction, while minimizing investment risk. Directed search techniques have not been used in the context of the FLORES model yet.

3.4. Model possibilities and limitations

As a flood risk screening model, the FLORES-model actively seeks the balance between computation speed and simulation accuracy. It is important to keep in mind which simplifications are made and what their impact on the uncertainty is. On the other hand, the simplicity of the model adds the possibility to quickly include new simulation or analysis types. Currently, the model is still under development and can easily be tailored for special situations. Some of the potential expansions will be mentioned here.

Limitations

There are several points that limit the current applicability of the FLORES model, which should be taken into account when using the model in future case studies or assessing the results. Here, the limitations will be divided between FLORES model limitations and non-FLORES model limitations.

The limitations of the model itself are mostly related to the assumptions made in the simulation and the current state of development of the model:

1. Many physical processes in the model are simplified. The flood simulation is simplified by dividing the city into drainage basins and checking the hydrological volume balance for each basin (see Chapter 3):
    - When there is a net inflow of water into a drainage basin, this immediately adds to the flooding on the scale of the drainage basin. Solutions that slow down the water flow on a smaller scale than these basins cannot be considered at this moment.
    - Storm surge is modelled as boundary condition, leading to inflow (in the form of overtopping/overflow) for chosen combination of basins. In scenarios where a barrier fails, the moment of failure is set. The portion of the barrier that actually fails is set as well. Sensitivity of this design choice has not been tested yet.
    - The drainage is simplified in comparison to common 1D-2D dual drainage models. Drained water does flow to - and is limited by - the downstream basin. However, because only the downstream basin is considered, water is not capable of draining upstream, in case the water level is higher than the upstream basin(s).

2. The model is still in development. This means some of the main characteristics still must be tested or validated.
    - The storm surge simulation has shown in an earlier case study to have acceptable accuracy (<20% error in calculating maximum inundation levels on a watershed level). However, the rain event simulation (with the surface-runoff model and the drainage model) is only scarcely validated, because of the lack of flood simulations with more detailed software.
    - Other processes are not a part of more detailed software packages and can therefore not be validated. Examples are: Simulating how failure of a portion of the flood defenses affect the flood simulation and simulating how the flood reducing impact of Nature-based solutions affects/ is affected by nearby structural measures.
    - Currently, a timestep of 6 minutes is used for the event simulation, as this was proven to correctly the flow of water in an earlier case study. The best timestep is a trade-off between computational load and accuracy. Sensitivity of the simulation to differences in timestep has not been tested yet. It is expected that the optimal timestep will depend on the complexity of the city and data.
    - Similar sensitivity analysis is needed for other variables, like the step in elevation for the contours (which is 0.25 m for the case study). Another variable is the return period of the storm surge and rainfall. Currently, 5 simulation runs per hazard (25 in total) are used to approximate the risk curve.

- When multi-hazard flood risk is considered, the model can consider interdependency between these hazards. As proven in Chapter 3.2, the difference between dependent and independent hazards can be very significant. Cities in developing countries often lack enough data to make good estimates about the interdependency. Future case studies and comparable research can be used to make well-educated estimates, when local data is not available.

Non-FLORES model limitations relate to reasons outside the model itself that might limit the application of the model:

- Most data sources have very limited resolution, as they are based on global models. These global data layers are often based on satellite data (e.g. Elevation, land cover, exposure) or on reference projects in different countries (e.g. Structural measures, damage curves).
- Although the sensitivity of the model to different resolutions of input data has not been tested yet, the expectations is that the resolution of the Digital Elevation Model (DEM) is most crucial for accurate simulation. The city is schematized according to the DEM and other attributes are connected to areas connected to the DEM (see Chapter 3.1)
- Many vulnerable cities consist of rapidly developing urban areas. Data can therefore be outdated quickly.
- A crucial part of an effective flood management strategy is the ability of local (governmental) organizations to correctly use, maintain and develop the implemented flood risk reduction measures. Foreseen problems with capacity building or maintenance of infrastructure can have a strong influence on the decision making, but is not included within the model.
- Much input can best be collected through local interaction (e.g. finding high-risk areas, considered measures, current response system). This information can be crucial for a useful and realistic representation of the (problems in the) city. However, this information is often not available in a format compatible to the FLORES-model (e.g. drawn maps, very limited data). This should be assessed by experts in urban flooding and used to improve or validate the input data.

4. Case study: Beira, Mozambique

4.1. Introduction

As a demonstration of the model implementation and capabilities, FLORES is applied to simulate and evaluate the flood management in Beira, Mozambique. Over the past few decades, severe rainfall events have regularly flooded large parts of the city. As vulnerable low-lying parts of the city are becoming increasingly urbanized, the people of Beira are experiencing flooding on an almost yearly basis. Moreover, the major floods of 2000 showed that the region is also subject to tropical cyclones, pushing coastal storm surge past the protective dunes and destroying parts of the city that already have been hit by the hard winds and heavy rains.

Figure 20 – Overview of the Beira area. The city is located on the point where the Pungwe River meets the Indian Ocean.

The FLORES flood risk screening model will be used to show what the impact of (a combination of) extreme rainfall and coastal storm surge on Beira can be, and how this can affected through the implementation of flood risk reduction strategies. First, a brief description of Beira and possible strategies to reduce flood risk is provided. Next, the required input of the model is given (4.2), the validation of water levels (4.3) and the results (4.4).

4.1.1. Towards a flood safe Beira

Beira is one of the largest economic centers in Mozambique, which is currently undergoing rapid urban expansion. The city is located at the coast and at the mouth of the river Pungwe and houses the most important harbor of the country. The old city is built on the high dune ridges and in the north, near the airport which is built higher up. However, recent urban development has led to increased housing development in lower lying areas in between the old city and the airport. The regular floods are having an enormous impact on the quality of life of the inhabitants of Beira. Besides the direct inflicted damage from the flood event and the damage due to inundation, many are also indirectly affected by the interruption of business activity and higher maintenance costs. The heavily overgrown drainage system is incapable of draining the low-lying areas, even weeks after heavy rains occur, causing major health risks through malaria and dengue.

Whereas Beira once was a large touristic attraction with beautiful beaches and large hotels, decades of civil war and disasters destroyed the businesses, infrastructure and reputation. Although the war ended in 1992, the many floods – most notably the 2000 Mozambique flood – have kept the city in a constant state of recovery. Despite the many problems that Beira is facing, a number of local governmental and non-governmental organizations, backed up with international support, is dedicated to increase the quality of living in Beira and manage the risks it faces. Most notably:

- **Conselho Municipal da Beira** (CMB, the municipality of Beira). As the main local government in the city of Beira, the CMB plays a central role in management and maintenance of flood risk reduction efforts and financing thereof.
- **Instituto Nacional de Gestão de Calamidades** (INGC, the national disasters management institute). Responsible for monitoring, assessment and response of disasters, like floods, droughts and cyclones. Operates on a local, regional and national scale.
- **Administração Regional de Aguas-Centro** (ARA-Centro, the central-Mozambican water board). Responsible for the operational water resources management at a regional level.
- **Instituto Nacional de Meteorologia** (INAM, the national meteorological institute). Responsible for monitoring and prediction of meteorological events (precipitation, tide, surge, cyclones) and climate predictions.

Supported by international organizations, most notably the World Bank, these organizations have managed to assess and implement several measures to reduce flood impact. Some notable recent developments:

Year	Development
2012	Implementation of *flood early warning system*, by INGC and German government (GIZ). Local committees throughout Beira were educated and trained to facilitate evacuation and recognize safe zones.
2014	*Beira Masterplan 2035* published, commissioned by Dutch government (NWP). Includes an integrated assessment and outlook.
2016	*Green Urban Infrastructure Project Beira*, supported financially by the German government (through the KfW). Restoration of the short urban river Rio Chiveve, to improve local drainage and enhance green areas in the city.
2018	Large *drainage rehabilitation project*, financed by the Mozambique government through the IDA. Restores and enlarges parts of an old drainage system, including several control stations.

Also, some smaller initiatives are taking place. For example: law enforcement to halt sand mining, private initiatives to biologically protect coastal dunes or development of comprehensive street-level hazard maps for evacuation. Although hopeful, the city is still highly vulnerable and the risk due to flooding is only growing, because of the rapid urban expansion and growing natural hazard. Because of the scale, complexity, and impact of flooding in the city, an integrated, city-scale flood risk reduction strategy is required to adequately support the people of Beira up to a point where the city can focus on development instead of recovery.

Finding the right flood risk reduction strategy for the city of Beira can be complicated for various reasons. Namely, (1) there are many possibilities of measures which also impact each other and each other's effectiveness, (2) there is little data available, (3) there are several unknowns (climate change, urban development, political development) that greatly affect the strategy's effectiveness, and (4) the choice for the best flood risk reduction strategy also depends on non-economic metrics, like local impact and support, ability to reduce amount of people exposed, shortening inundation times and environmental impact.

4.2. Model setup

4.2.1. Data input

Good and reliable data on Beira is scarce. Although some earlier research has been done, reliable data on hazards and flood damages is not available. The exception is the topography, where recently a LiDAR-based Digital Elevation Model (DEM) was made. For many of the other required data, open data sources will be used. Information on structural and non-structural measures is based on earlier conceptual studies (Deltares et al., 2013)

Table 7 – Data input used for the FLORES-model in Beira

Required input	Source	Reference	Data type [resolution]
Elevation	LiDAR Digital elevation model (DEM)		Local data [2 m]
Exposure- structural	ADFR (R5) – Building exposure	Eguchi et al. (2016)	Satellite measurements [450 m]
Exposure - population	ADFR (R5) – population exposure	Eguchi et al. (2016)	Satellite measurements [450 m]
Damage curves	Global flood depth-damage functions	Huizinga et al. (2017)	Global open data [-]
Flood risk reduction measures	Expert mission report, earlier research		Local / global open data
Surge data	GAR15 storm surge[1]	(Cardona et al., 2014)	Global open data [-]
Rain data	Adaption to climate change Feasibility study	(CES and Lackner, 2013)	Local data [-]
Wind data	GAR15 cyclonic wind	(Cardona et al., 2014)	Global open data [-]
Future changes	Global scenario reports	IPCC (2014)	Global open data [-]

[1]The time series of a storm surge also requires tidal data, which was provided by CES and Lackner (2013)

4.2.2. Hydraulic boundary conditions

The simulation takes coastal storm surge and extreme rainfall into account. This requires data for different return periods of event intensity. For storm surge, this is based on global data by Cardona et al. (2014), which provided storm surge runup for different return periods as a result of tropical cyclones. rainfall data is based on analysis part of the research by CES and Lackner (2013). The used hydraulic boundary conditions can be found below. The storm surge and rainfall is assumed to be independent, based on a first analysis using ERA-interim (Dee et al., 2011). Whether this assumption is valid should be examined in future analysis.

Table 8 - Hydraulic boundary conditions for the Beira case study. Please note that the surge is additional surge caused by a cyclone. In the model, this is added to the 3.6 meters difference between the CD and the Mean Sea Level, plus the 3.4 meter tidal amplitude. The model will use a storm duration of 24 hours.

Return period [years]	Maximum surge [m]	Maximum surge level [m+CD]	Rain intensity (24h) [mm/hour]	Rain intensity (48h) [mm/hour]	Rain intensity (72h) [mm/hour]
2	0.2	7.2	7	4	3
5	0.3	7.3	9	6	4
10	0.5	7.5	11	7	5
50	1.6	8.6	14	9	7
100	2.2	9.2	16	10	8

The combination of mean sea level, tide and storm surge is shown in Figure 21.

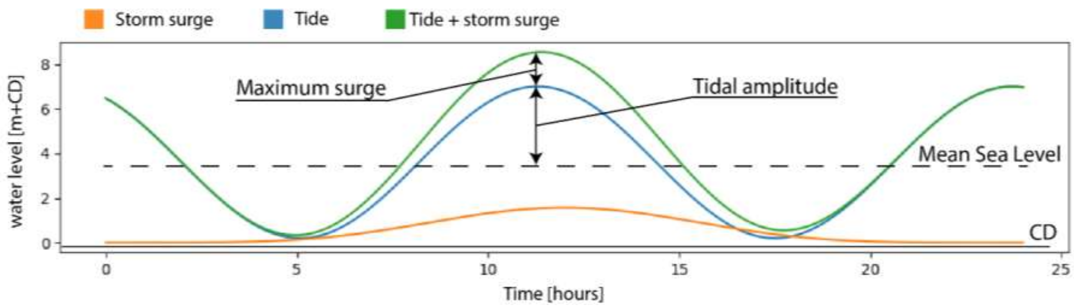


Figure 21 – exemplary time series of coastal water levels. (green) total water level as a result of mean sea level, tide and surge, (blue) standard tidal variation and (orange) run up due to storm surge.

A number of studies have analyzed the region and listed measures to reduce the risk of flooding in and around the city of Beira (Arcadis, 1999; Deltares et al., 2013; Deltares et al., 2015). In April 2018, a short scoping mission was undertaken to gather information on the current flood recovery policy and prevention efforts, as well as potential other flood risk reduction measures.[5] The following measures are considered:

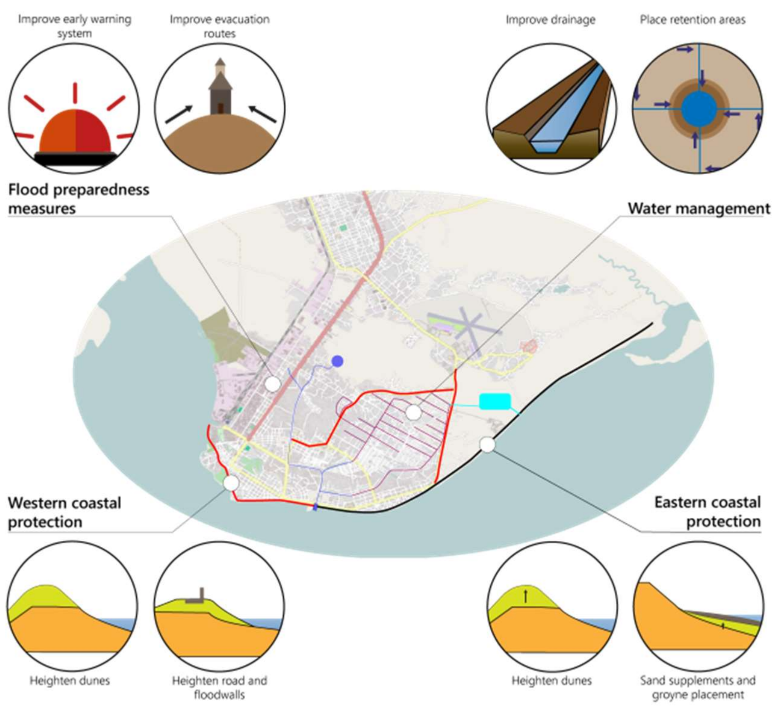


Figure 22 – city of Beira with a number of potential flood risk reduction measures

[5] Scoping mission commissioned by Dutch government. Findings by Deltares and HKV Consultants. Results were presented at Second Beira Investors Conference (May 31, 2018).

Table 9 – Flood risk reduction measures considered in the FLORES-model

Measure type	Location	Description	Information source[1]
Flood defenses	Eastern coast	Heighten dunes	[1],[2]
		Sand supplements	[1],[2]
	Western Coast	Heighten dunes	[1],[2]
		Place floodwall	[1]
	Inland Road	Heighten road	Reference projects[2]
Impact reducing measures	Urban area	Improve drainage system	(CES and Lackner, 2013)
		Provide additional retention	(Deltares et al., 2015; CES and Lackner, 2013)
	Low-lying areas	Improve evacuation routes	[2]
		Early warning system	[2]

[1] Used local reports: [1] (Arcadis, 1999), [2] (Letitre et al., 2018), [3] (CES and Lackner, 2013), [4] (Deltares et al., 2015). [2]When no reports are available focusing on the situation in Beira, reference projects in other cities are used to estimate the cost of construction and expected impact. This has also been used to substantiate the other measures when provided reports were incomplete. i.e. (Jonkman et al., 2015; GCCPRD, 2016)

The costs of flood risk reduction measures are mostly based on reference projects. Input for the model allows for a distinction between constant cost and variable cost. Variable cost is how much the construction cost will change with a change in size (e.g. levee height or retention capacity). For the current case study, this option is only applied to the structural coastal measures. Other measures are mostly input in a single option, and therefore do not need the division between constant and variable cost.

When reference projects are available, only the total cost is provided. This does not inform us on the portion of the cost that depends on the size of the structure. Currently, this division is estimated based on reference projects with different sizes. In future, it would be preferred to provide guidelines on what part of the total construction costs are constant (e.g. costs through ground clearance, engineering, design) or variable (e.g. material, manhours). For the Beira case study, the following costs are used:

Table 10 - Cost estimates for the Beira case study.

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 area
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 $		
Microdrainage	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 $		

4.2.3. External scenarios

Initially, four scenarios were considered: Two future climate change scenarios and two urban development scenarios. Climate change scenarios were included as a shift of mean sea level and a more severe rainfall intensity. Urban development was included by multiplying the land value and population of different land use types with different factors. Data is based on findings by CES and Lackner (2013).

Table 11 - Adjustments to the input data, based on external scenarios.

Category	Scenario	Variables		
Climate change		**Sea level rise**	**Unit**	**Increase rainfall int. factor**
	Low	0.3	m	1.3
	High	0.8	m	1.6
Urban development		**Residential factor**	**Commercial factor**	**Industrial factor**
	Low	1.2	1.4	1.3
	High	1.3	1.6	1.7

After initial running of the model with these four scenarios, it became clear that the choice of urban development scenario hardly affected the risk reduction or the reduction of amount of people affected. This is due to the way these outcomes are calculated. Urban development affects both the risk calculation of the strategy in question and the original situation without any measures. The relative reduction therefore changes only slightly. Although the urban development does affect different land use types differently, this difference is too small to significantly lead to changes in percentages of reduction in risk or people affected. Therefore, urban development scenarios will not be considered in further steps. Climate scenarios do significantly change the outcome and effectiveness of flood risk reduction strategies, and therefore these scenarios will be considered during further screening.

4.3. Validation

Lack of data also makes it challenging to prove the validity of the model. No detailed measurements have been done during previous extreme events. Moreover, only limited detailed flood modelling software have been done in Beira. Currently, only the flood extent due to rainfall can validated, as the flood map below is available, showing the flood extent for a 1-in-10 year rainfall event. This shows comparable flood extent throughout the city, although the ANUGA simulation, executed by CES and Lackner (2013), predicts higher flood levels in low-lying areas with a particular steep slope (close to higher grounds).

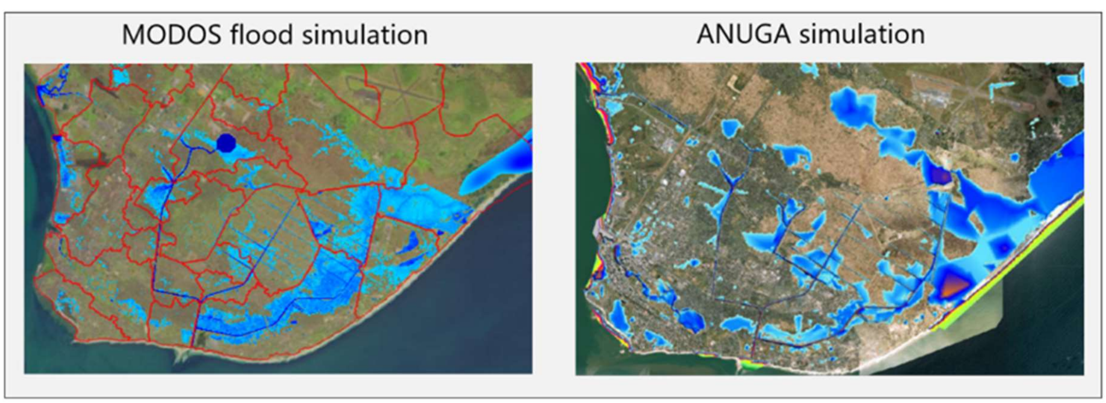


Figure 23 - flood extent resulting from a 1-in-10 year rainfall event for the FLORES-model (left) and an ANUGA simulation, which was part of the Rio Chiveve feasibility study

4.4. Results

The goal of the use of the FLORES model in the Beira case study is to provide useful information in the discussion aimed at finding the most suitable strategy for flood risk reduction. The results will be presented in several steps that will be undertaken: The initial screening, analysis of most promising strategies, and evaluation of promising strategies.

4.4.1. Current risk profile of Beira

The strategies will be compared based on their ability to reduce the risk of flooding throughout all possible events. Currently, the flood risk can be attributed to a number of threats / phenomena's:

- The most common cause of flooding is extreme rainfall. This happens on a nearly yearly basis, depending on the part of the city. The flood maps shown below are made using the FLORES hydraulic simulation. For a rainfall event that happens on average once every two years, already the lower parts between the city center and the airport flood. The city center itself drain through the Rio Chiveve. More extreme rainfall (1-in-10 year event) leads to flooding of the lower parts of the densely inhabited areas along the coast.

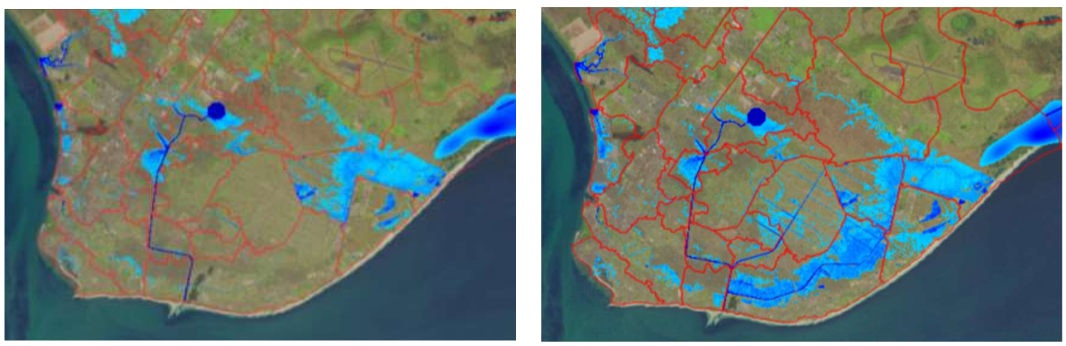


Figure 24 – (left) flood map of a 1-in-2 year rainfall event. Minor flooding occurs, mostly in the east, which is still relatively uninhabited. In the city center, there are minor floodings on a local scale. (right) flood map of a 1-in-10 year event. Here, much more area is flooded, mostly on the eastern part of the city, which is not connected to the drainage system.

- Coastal storm surge leads to flooding as well, mostly as a result of a tropical cyclone. Because cyclones don't affect Beira on a yearly basis, their effect becomes apparent for more extreme simulations (a 1-in-50 year flood event leads to 1.5 meter surge). More common storm surge events (0.3 meter surge for a 1-5 year event) are the result of smaller storms and are insignificant compared to the 3.4 meter tidal amplitude. This difference is shown in the simulations below.

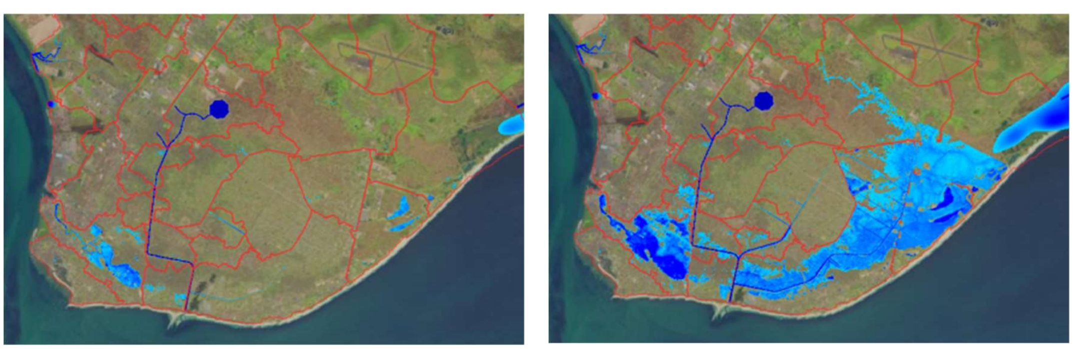


Figure 25 – (left) flood map of a 1-in-5 year storm surge. No flooding occurs, except for the banks of the Rio Chiveve, which causes no damage. (right) flood map of a 1-in-50 year storm surge. Here, clearly the eastern part of the coastal protection is overtopped. Water accumulates in the lower parts of the coastal parts of town.

- An important threat that is often overlooked is the possibility of compound flooding. Measures against pluvial flooding often rely on drainage to transport the water out of the vulnerable areas. However, no pumps are present, meaning that a drainage system cannot drain when the outside water level is above the water level in the system. In Beira, this leads to a period of time during high water when the drainage system does not work. This time period increases when a storm surge is present or through sea level rise.

For the assessment of flood risk reduction strategies, it is important to consider how it affects the hydraulic processes in the city and how these hazards are affected by it. Ultimately, the strategies need to be compared based on the entire set of possible scenarios. In order to quantify this comparison, the current risk profile of Beira is calculated as a benchmark. This risk profile cannot be determined analytically and there are an infinite number of possible scenarios, therefore a number of events are chosen to represent the entire set of possibilities. In this case, the events are characterized as the return periods of the underlying hazards, namely the coastal storm surge and extreme rainfall. For each of the hazards, five return are defined (5, 10, 50, 100 years, and the case where it doesn't occur). This adds up to 25 different possible combinations.

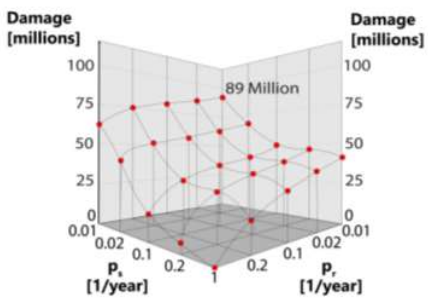


Figure 26 – Risk curve of the current situation in Beira. This shows the expected damage of a flooding with a probability of occurrence of the storm surge (P_s) and a probability of occurrence of the rainfall (P_r). The probabilities are per year. For example, the expected damage of an compound flooding event with a 1-in-100 year storm surge and a 1-in-100 year rainfall intensity is 89 million USD.

As a final step before comparing flood risk reduction strategies, the risk curve as shown in Figure 26 is reduced to a single figure, the total risk or the expected annual damage. All flood risk reduction strategies are compared on the portion of risk reduced due to the implementation of the strategy. Figure 27 below shows the risk reduction, affected population reduction and construction cost of 500 different strategies, for two different climate scenarios.

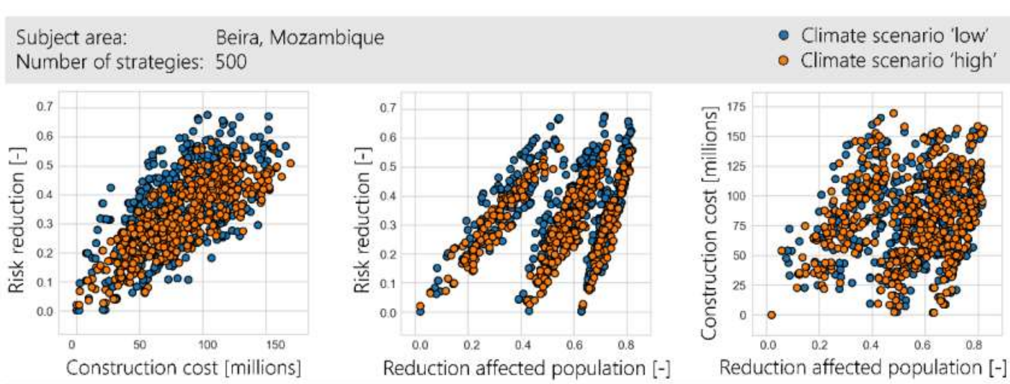


Figure 27 - Pair wise plotting graphs, which shown how the output parameters relate to each other. One dot is one flood risk reduction strategy. The colors indicate two different future climate scenarios.

4.4.2. Initial screening

The first step is to look at all the options. Figure 27 shows how the different outputs (risk reduction, construction cost, and reduction in affected population) relate to each other. Each dot is one strategy and is calculated through based on 25 simulations for different combinations of rainfall and coastal storm surge (see Chapter 3.2). The figures below compare the results of 500 randomly constructed flood risk reduction strategies. The colors show different climate scenarios, where blue shows moderate future climate change and orange depicts strong future climate change.

These graphs can be studied to find interesting trade-offs. A couple of things stand out:

- Judging from the graph comparing risk reduction to construction cost (left), there is clearly a positive correlation between risk reduction and construction cost (meaning that more effective strategies will probably be more costly). However, individual strategies can deviate from the trend significantly. By definition, this means that some relatively cheap measures are very effective and do not have a more costly substitute.
- In the range of low-cost flood risk reduction strategies, the outliers between climate scenarios are more extreme (further from the mean). This can most likely be explained by how the risk is reduced here. These strategies probably rely on inland solutions (drainage, retention) for their risk reduction, as these types of measures are relatively low-cost. However, these measures are influenced by climate through the increase in rainfall and a decrease in effectiveness (through higher mean sea levels, so less time to drain). For high-cost and high-risk reduction strategies, also more expensive coastal protection is implemented. Here, small additional investment can easily lead to safety in both climate scenarios. Therefore, the difference in risk reduction for both climate scenarios is smaller for the more complete (and expensive) strategies.
- There are clearly three separate trends for affected population/risk reduction. This is probably based on the emergency measures (enhancing emergency routes, early warning system). These measures limit the exposure to population, but do not affect structural risk.

Input-output dependency

With Feature Scoring, it is possible to show how the output metrics depend on the input choices. This is used to identify the most important inputs or uncertainties. In short, it shows which choices or scenarios (listed at the left hand side) have the largest influence on an output metric (below the table). The numbers imply the level of influence, where 0 means no influence and 1 means that the output is totally dependent on the choice for that input.

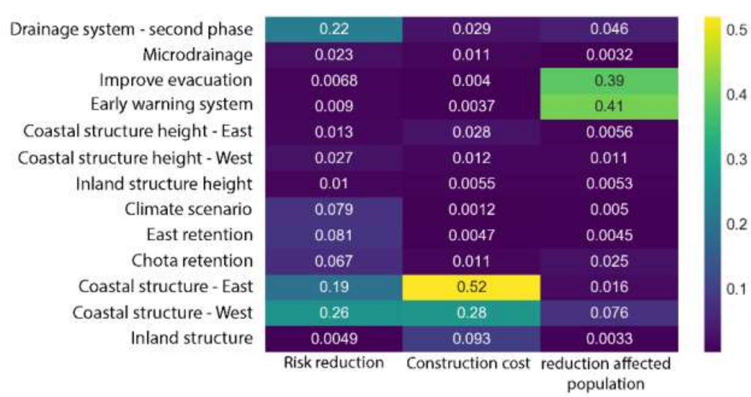


Figure 28 - Result of feature scoring analysis. The table shows the relative importance of the system choices and uncertainties (left side) to the outcomes (below). Higher number indicates higher importance.

- The height of the flood defenses has a relatively low impact on both risk reduction and amount of people affected. This can be explained by the minimum amount of heightening. The current coastline is already capable of withstanding a storm surge. Because heightening of a few centimeters is not worth the start-up cost, the defenses are heightened up to an elevation with is safe in most situations. The fact that the coastal measures are the most impactful for risk reduction, shows that the current elevation is not enough for future scenarios. Also, erosion causes weakening of the coast. In short, heightening the defenses now probably means overspending either on unnecessary height or start-up cost, and a potential more effective investment would be to wait and combine strengthening of coastal structures with efforts to counter coastal erosion.
- Both emergency measures greatly influence the affected number of people, but have no influence on structural damage. This difference is enhanced by the fact that the evacuation and early warning system focus on areas with low structural value and high human exposure.
- The effectiveness of retention quickly diminishes when a storm surge has to be accounted for. This, plus earlier mentioned effect on the drainage system, signals that more attention should be paid to the negative impact of the outside water level (and the role of climate change) on the city's ability to drain water out of the city.

4.4.3. Analysis of most promising strategies

The final part of the initial screening involves identifying promising combinations of measures. This can be done with the PRIM algorithm (for more information, see 3.3.2 or (van Berchum et al., 2018)). As a first rough optimization, we will search for strategies that optimize risk reduction and construction cost, as these measure are opposing each other more than the measures that seek to reduce the amount of people affected. Table 12 is the result of a PRIM analysis. For this algorithm, performance goals can be provided for the flood risk reduction strategies. These goals can be outputs (e.g. minimal risk reduction, maximum costs) or inputs (e.g. to check performance for 1 climate scenario). The PRIM algorithm screens all strategies and identifies the ones that meet the goals.

Subsequently, it is able to restrict the design space by discarding a choice for a flood risk reduction measure (effectively discarding all strategies that included that measure). The result of such an analysis can be read as follows: 'If you restrict the input choices (left) to the options shown in the graph, you will have a strategy that most likely reaches your goals, regardless of the choices in the rest of the system.' Also, measures mentioned first have the largest impact. Some interesting results:

- The situation in Beira clearly requires a flood management plan that deals with both coastal and pluvial flooding. For both climate scenarios, the analysis focusing on flood risk reduction includes improvements to the drainage system –which primarily counters inundation by rainfall – and coastal defenses, which aims to repel coastal storm surge. Although this was also shown in the Feature scoring, Table 12 nicely shows the distinction between climate scenarios:
    - In the lower climate scenario, the drainage system is the first priority for risk reduction, the second priority is retention. This shows that the flood risk in this climate scenario mostly results from rainfall.
    - In the higher climate scenario, the importance of the coastal system is unmistakable. This can partly be explained by the diminishing effect of the sea level rise on the effectivity of the drainage system. This advocates for (1) plans for strengthening the coastal system if the situation keeps deteriorating due to climate change, and (2) looking into measures to ensure the effectiveness of the drainage system under high water conditions (e.g. pumps).
- When relatively low-cost solutions are required, the drainage system is still crucial for risk reduction for the lower climate scenario. The higher climate scenario shows that the relative effect on risk reduction compared to construction cost is much higher for the western part of the coastal protection than the eastern part. Interestingly, first priority is even to exclude all strategies that

heighten the dunes, even though the eastern coast was shown to have a large effect on risk reduction.

- Also for the strategies that seek to balance all three goals, the combination of the drainage system and a coastal protection is featured in the design choices. It is interesting to explore a model run with these measures included in order to focus more on the effectiveness of the other measures.

Table 12 – Results from PRIM analysis. This algorithm limits the design space by making design decisions, which aims to maximize the preset goals. Explanation: 'Goals' are the strategy outputs we want to achieve, 'Start' indicates how many strategies comply with the goals initially, 'Results' show which design choices are made to narrow down on the interesting strategies, 'Final box' indicates how many strategies are still within the new design space - after filtering for the measures listed under 'results' - and how many comply with the goals.

Goals	**Start** Strategies of interest	**Results** Design choices (priority from top down)	**Final box** Strategies of interest
Focus on risk reduction			
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 east > 9.5 m 5. Height coastal structure west > 8.9 m	**60** out of **67**
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	- Coastal structure west - Height coastal structure west > 8.5 m - Coastal structure east - Improve evacuation	**50** out of **57**

4.4.4. Simulation of results

Below, we quickly view a couple of flood maps of the area, while assuming the measures above are taken.

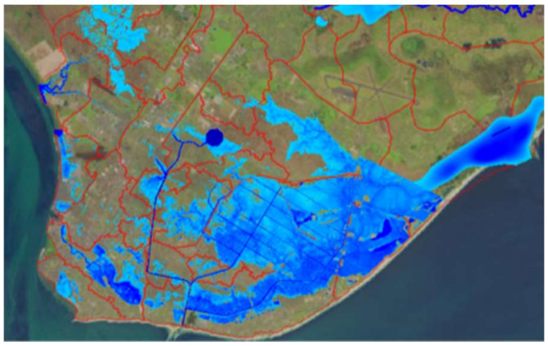
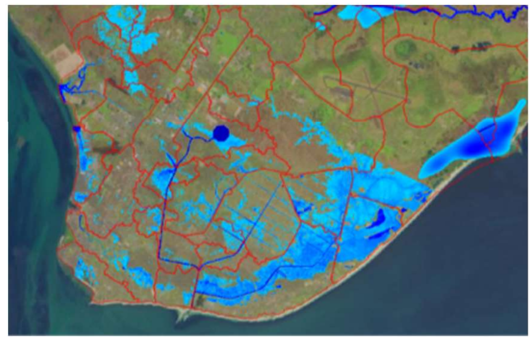
Storm surge 1/10 years Rainfall: 1 /10 years	
No flood risk reduction measures	**Second phase drainage system Eastern dunes heightened to 10.5 m+CD Western floodwall built up to 9 m+CD**
	

Figure 29 - Flood extent in Beira, Mozambique for a 1/10 year storm surge and a 1/10 year rainfall event. (left) no flood risk reduction measures in place. (right) several flood risk reduction measures implemented.

4.5. Discussion flood management in Beira

As mentioned above, Beira needs an extensive package of measures, focusing on both the hazards in order to reduce the risk of flooding. Although the model cannot - and is not meant to - provide exact parameters and designs for the measures that should be implemented, the information can be used to support decision making on the which type of measures deserve more attention, where additional measurements would be useful further in the process and where funds are most effectively spent.

In the short term, the city would probably benefit most from the expansion of the drainage system and the enhancement of emergency measures. These measures have shown to have a large influence on the risk reduction and the exposed population, respectively. These measures can be realized against a relatively low cost. Retention has no direct value without other measures in place. It should be investigated in more detail which amount of additional drainage capacity and amount of investment in emergency measures is most effective.

Secondly, planning of the heightening of coastal measures may be considered. The dunes along the coast have a large influence on the flood risk of Beira. Even more so when the situation keeps deteriorating due to climate change. Currently, the coastal system is able to withstand a minor storm surge, and heightening them right away may not be the best short term choice due to the high costs and the uncertainty of future developments. However, the coastal structures are expected to play a crucial role in flood management of Beira in the future, due to coastal erosion and the expected rise in mean sea level and possibly storm intensity. A promising way forward would be to measure coastal erosion and sea level rise locally more intensively and include heightening of the coastal flood defenses within the efforts to strengthen the coast against coastal erosion. The additional measurements can help later design efforts to find the most effective design and height of the coastal protection.

For further steps regarding the flood management in Beira, it is advised to increase monitoring of hydraulic processes, like the trend in rainfall intensity, mean sea level and surge. The analysis has shown a clear change in priorities as a result of different future climate scenarios. Also, the effectiveness of the drainage system may decrease significantly during high tide in the Indian Ocean, and more so due to storm surge and sea level rise. This interplay between the urban and coastal system requires more attention, and the option of increasing the effectiveness with pumps or a large-scale retention need to be considered as a future option.

5. Flood screening approach for World Bank projects

Although still in development, the model aims to be a generic tool that can be applied to support World Bank projects. One of the main goals of the FLORES-model is to be implemented on cities with different layouts and topographies with relative ease. Chapter 5.1 discusses how the model fits within the efforts of supporting African governments in effectively implementing disaster risk management strategies. In Chapter 5.2, the potential to use the model in other cities is explored in the cities of Abidjan in Ivory Coast and Cotonou in Benin. Finally, Chapter 5.3 explains the work flow of implementing the model in a new city through a work plan. Please note, the tools and the case study explained in this report are part of an ongoing development of the FLORES-model. This implies that: (1) some of the methods described require further research for verification and (2) many of the detailed analysis tools have not been explored and implemented yet.

5.1. Lessons learnt from the Beira case study

The first exploratory implementation of the FLORES model in Beira has led to several insights related to the use of flood risk screening within the flood management process and the possibilities of the FLORES-model.

For Beira, the model was used in a data-poor environment for the first time. This case study was developed to show the basics of all possibilities that can be considered with the use of the FLORES-model, being:

- Fast impact simulation of pluvial and coastal storm surge flooding and their compounded effects
- The ability to assess the risk reducing capabilities of combinations of flood risk reduction measures
- The ability to assess the combination of structural and non-structural measures
- The ability to vary across input parameters, granting the possibility to assess different climate scenarios, urban or economic development scenarios, and test unknowns
- The ability to compare flood risk reduction strategies based on multiple performance metrics with well-known tools within the field of policy analysis.

Most of these characteristics were already explored in an earlier case study for Houston (van Berchum et al., 2018). Besides of the additional focus on the pluvial flooding, the model in Beira also focused on:

- Improving the generic setup of the model, making it easier to transfer the model to other cities
- Developing an easy connection to open data, making it possible to use the model on areas with very limited local information.
- Improving the transparency of the model, making it easy to establish which factors and formulas govern the results.

5.2. Application potential for other cities

To further establish the FLORES model as a useful model for risk assessment and risk management exploration in data scarce regions, the model could be implemented for other cities. Consultation within the World Bank led to two cities in Western Africa that might be interesting for the model to consider: Abidjan (Côte d'Ivoire) and Cotonou (Benin). This chapter will shortly explain the context and explore the possibilities for the use of the FLORES-model in these regions.

5.2.1. Problem description

Both the cities of Abidjan and Cotonou are large coastal cities with international harbors. These cities have a large economic importance for the respective countries. For Abidjan, with almost 5 million inhabitants by far the biggest city of the two, heavy rainfall has led to damages, displacements of people and loss of life already on multiple occasions (Danumah et al., 2016). The situation in Abidjan is mostly complicated because of its topography, with the main urban area integrated into a large lagoon, the Ébrié Lagoon. A shipping canal connects the lagoon with the ocean. A lot of critical infrastructure, like the airport and the main evacuation routes, is in vulnerable areas.

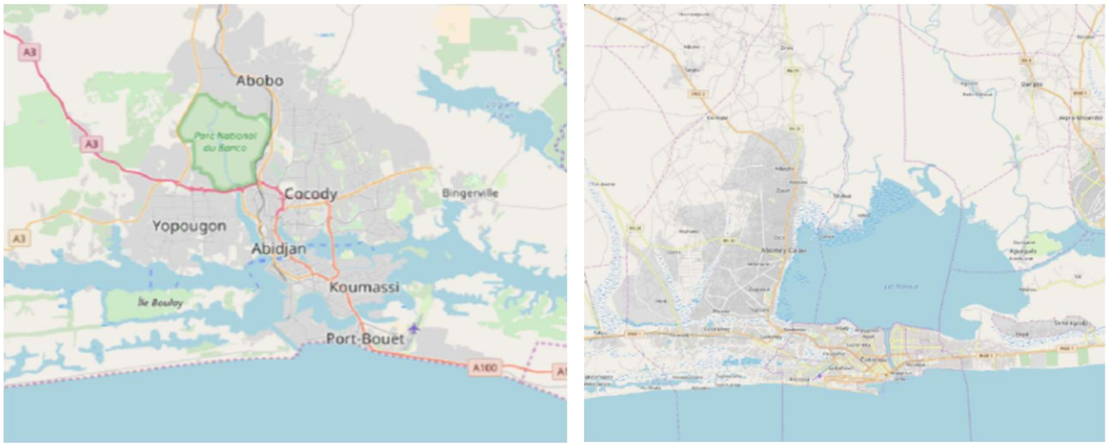


Figure 30 – Maps of Abidjan, Côte d'Ivoire (left) and Cotonou, Benin (right)

The coastal city of Cotonou is in the South-east of the Republic of Benin. Like Abidjan, Cotonou is connected to the Atlantic Ocean. After decades of rapid urban expansion, the population in the low-lying area adds up to nearly a million people, which is more than a tenfold increase in 60 years. Making a trustworthy assessment of the flood safety in Cotonou greatly depends on either carefully predicting or controlling how the inland bay behaves during extreme situations. In the case of Lac Nokoué, this behavior not only affects Cotonou, but also the city of Porto Nuovo - capital city of Benin - on the northeastern side of the bay.

5.2.2. The use of the FLORES model in Abidjan and Cotonou

Both cities are part of a complicated hydrological system. The cities are built close to the sea, but are also affected by secondary large waterbodies, connected to the ocean. The FLORES model is especially well fit for these types of urban systems, for the following reasons:

- The effect of the hazards are hard to predict, because of the numerous ways in which they (coastal storm surge, inner bay water level, and rainfall) interact. The effectiveness of implemented flood risk reduction measures is highly influenced by the positioning and strength of other measures. The interaction between measures can be captured very well with the FLORES model.
- The FLORES model has been built around a similar problem in an earlier case study, focusing on the Galveston Bay, Texas (van Berchum et al., 2018). The cities and their coastal system can be divided into several layers. The designer has the choice where to put flood defenses. Because of the fast computation time, all combinations can be assessed for different heights of the barriers.
- Both situations are subject to large uncertainties regarding the future in terms of climate change and especially urban expansion. The location and magnitude of future urban expansion will greatly affect the flood risk of the city and therefore the effectiveness of the measures protecting them. The FLORES model can be used for sensitivity analysis, in order to find a strategy for reducing flood risk that is robust for future change.
- Large part of the flood impact is related to inundation of low income areas. These areas are underrepresented when flood risk evaluation is only based on economic impact. The FLORES model

can consider both the economic damage and the impact to the population, because of its ability for multi-objective evaluation.

A crucial part of an accurate, but fast simulation of the hydrological systems in Abidjan and Cotonou is to separate the coastal zone from the inland zone. These areas interact but are subject to different processes. This is possible in the FLORES model through the use of Lines of Defense. In both cities, an outer line of defense will be defined at the coast, consisting of two parts. One part on each of the sides of the respective inlets. The second line of defense is defined between the inner water body - the Ébrié Lagoon and Lac Nokoué - and the urban area of the city. This is shown in Figure 31.

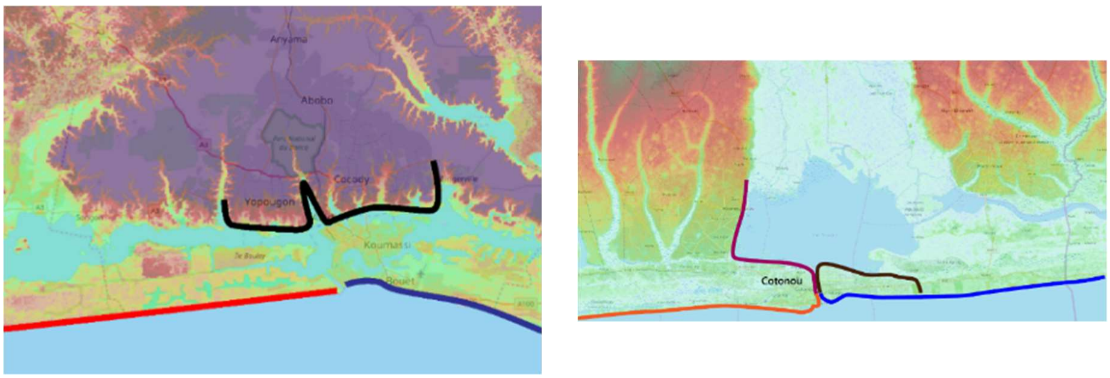


Figure 31 – Digital Elevation Model for the cities of Abidjan (left) and Cotonou (right). The colored lines show potential locations for protection from coastal storm surge. DEM is based on the SRTM dataset.

The data required for this analysis will have to be either open data or locally gathered data. Especially information about which measures are considered, what the local problems are and a map of land use throughout the area is preferably based on local information. The lack of information and the potential added value of additional data gathering can be assessed within the model. Problems that might be faced would mostly be based on processes on a scale much different than the city-scale. Abidjan is relatively steep close to the lagoon, which makes low resolution data harder work with. Also, both the Ébrié Lagoon and Lac Nokoué can be influenced by processes outside of the considered regions.

Concluding, the cities are very well fit for the FLORES model, for the FLORES model can be utilized to unravel the complexity of the flood processes in these cities and potential strategies to reduce the risk. For the development of the model, more attention needs to be paid to data collection and validation, but provided this is done with care, the FLORES model should very well be able to provide useful information for the improvement of the flood risk management planning for the cities of Abidjan and Cotonou.

5.3. Flood risk screening work plan

This chapter explains the main steps necessary to ensure the model is used optimally. This includes a clear preparation and potential uses of the results. This starts at analyzing whether the FLORES model is the best model to apply for the specific city and design phase. Secondly, the model needs to be prepared. This means that data needs to be collected and structured to fit in the model. Subsequently, the flood simulation can be tested and validated. Finally, the screening tools can be used to interpret the model results. The separate steps are explained in more details below. For a complete step-by-step walkthrough on how to build and run the model, please refer to Appendix A.

Step 1: Model application

First, the flood problem in the city and the goal of using a computer model needs to be assessed. This can show whether the FLORES model is the right model for this situation. Questions that need to be discussed:

- **What flood issues does the city face?**

Flood issues can be caused by different types of hazards. For large-scale flooding, mostly three hazard types are identified:

  - Extreme rainfall
  - Coastal storm surge
  - River flooding

The model has been used in earlier case studies to simulate coastal storm surge and extreme rainfall events. River flooding has not been modelled yet, although it is expected to be possible with minimal model adjustments.

- **Which stakeholders are involved in local flood management?**

Before working to improve the flood management, it is crucial to understand the current system in place and which organizations and groups are involved. This involves (local) government, inhabitants, and all organizations active in monitoring and responding to flood hazards.

- **At what stage is the current effort of finding an effective flood management system?**

FLORES is most useful in the initial screening or conceptual stage. Especially when all options are still open and much is still unknown, it can provide first directions and help the user get a feel for how the flood risk in the city changes because of his or her flood management choices. At a later stage in design, it can be used for sensitivity analysis, although more advanced software might be more useful at that stage (more data available, less simulations required)

- **What are the main questions that need to be answered by the model?**

The FLORES-model supports decision making by providing information on how flood risk reduction strategies affect the city. Other common subjects that are often part of flood management strategies that are not discussed are: Maintenance, investment planning, coastal zone management, capacity building/requirements

- **What metrics can help decide what the best type of flood management would be?**

The strategies are compared quantitatively, which means that only measurable metrics can be taken into account accurately. Other results, often also important, are harder to compare: local preference, impact in landscape, political impact. This model should be used to compare strategies based on for example expected damage, inundation, affected number of people and construction costs.

When the analysis shows the need for a flood risk screening model, there should be a clear view on the type of information that can be useful for decision making. This can help decide on which measures to take into account and which screening tools should be used.

Step 2: Model preparation

This step includes the information gathering and the schematization of the city, flood risk reduction measures and the flood hazards. In data-scarce regions on the world, gathering data can be especially challenging. Therefore, one of the future goals is the ability to run the model fully reliant on global datasets. Where available, better (local) information can be used to substitute parts of the model. The following types of data is needed:

Table 13 – Data types of information sources for the FLORES model

Layer	Required input	Format
Region Layout	Digital Elevation Model	GIS
	Exposure - structural	GIS
	Exposure - population	GIS
	Damage curves	Excel/csv
Flood risk reduction strategy	Structural measures	Local reports / reference projects
	Non-structural measures	Local reports / reference projects
Hydraulic boundary conditions	Surge data (if applicable)	GIS/Excel/csv
	Rain data (if applicable)	GIS/Excel/csv
	Wind data (if applicable)	GIS/Excel/csv
	Future changes	Climate change reports

NOTE: *more detailed data is preferred, but if no local or national information in available, it is possible to use global open data sources. See the additional information* in Appendix A.

The bulk of the schematization is executed in a GIS environment. In the latest version, QGIS was used. The city's DEM can be used to schematize the drainage basins and contours. Also, other necessary traits can be assigned to the contours. If applicable, the city should also be schematized into different Lines of Defense, which is based on expert judgement. The modeler needs to identify useful and characteristic locations for flood defenses and Lines of Defense.

When detailed data sources are not available, datasets will often have to be processed before the data can be used in the model. In order to make the input data as realistic as possible, information gathered through reports, earlier research or stakeholder conversations should be considered during processing. As end result, the GIS schematization and processing results in a number of .csv files, which act as input for the FLORES model.

Step 3: Flood simulation tests

The model runs in Python. By making choices for the type of flood hazard and flood risk reduction measures, the model calculates the construction cost, the amount of flooding and the resulting impact. Before large numbers of simulations are run for evaluation, the model simulation should be tested for realistic results. The model can be verified in different ways, based on available information:

- The model simulations can be verified by simulating historic events. The flood extent can be compared with aerial / satellite imagery. In the case these images are not available, inhabitant can indicate local inundation for historic events.
- When earlier research has already simulated flooding in the project area, the results can be used for verification.
- For other situations, or when no verification is available, simulation results of relatively common situations can be mapped and judged by local organizations.

Python scripts are available to build flood maps from the simulation results.

Step 4: Exploration

When the simulation has shown reliable results, the EMA workbench evaluation runner can be used to run numerous simulations throughout the entire design space. When finished, this is saved in a single library, holding all information on the simulations and the results. These results can be explored with the wide range of exploration tools available in the EMA workbench. Jupyter Notebooks are available for both the evaluation runner and the exploration tools.

The result analysis can be used for a broad exploration or for a focused optimization. A broader exploration can help to show which type of measures are most effective and which situations (uncertainties) have the most impact on the model outcomes. This can be combined with optimization algorithms, in order to find the best flood risk reduction strategies for certain assumptions or expected futures.

Step 5: Evaluation

The total package of simulating individual flood risk reduction strategies, exploring different designs and scenarios, and optimizing to find the best strategy can be repeated multiple times, which will teach how the city's risk profile reacts to the available design choices. Based on the initial questions, different useful results can be provided:

- Advice on which (type of) measures is most effective in reducing flooding or any of the metrics, also taking uncertainty of future scenarios (and other predefined uncertainties) into account.
- Strategies that are optimized for predefined demands. For example, it is possible to show the 5 most effective flood risk reduction strategies that minimize flood damage, provided a limited budget. Individual simulations can be used to show the differences between these strategies and compare the effectiveness of measures.
- The results can be used to support further conversations with local groups or future design teams. Interactive exploration tools can show the effect of assumptions or choices in real time, which allows the model results to be used as a learning tool.

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Appendix A : Model workflow

This chapter explains the workflow required to run the FLORES-model for a new city. The model is still in its development phase, which means that some programming-related preparation is required. Also, some minimal customization is required for the model to work. The final goal for the model is to make the model fully input-dependent, meaning that no changes or additions to the code itself needs to be made for the model to work.

Step 1: Coding preparation

FLORES is a Python-based model and uses several constantly-developing Python libraries, including the EMA workbench. Without proper version control and preparation of the code, this will quickly lead to a chaotic model that will become unusable shortly after first use, because of changes in the libraries. This can be prevented with clear control of versions and folders.

1.1. Open a new main folder, named after the city. (used here: <CITY>)
1.2. In this folder, copy all files from the central FLORES repository folder 'FLORES Startup'.
1.3. Setup Jupyter Notebook within the virtual environment. Use interpreter:
'<CITY> /venv/Scripts/python.exe'

Step 2: Model preparation

The input data needs to be formatted into several .csv files in order to connect to the FLORES Simulation model. The bulk of the schematization happens in a GIS environment. In the latest version, QGIS was used.

Data gathering

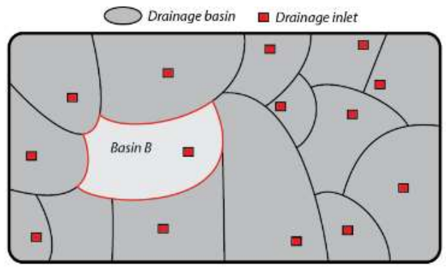
When no detailed, local data is available, data from global data sources can be used. These mostly consist of satellite-based GIS maps and global reports. The following global open data sources have been found and used before:

Required input	Source	Reference
Region layout		
Elevation	Shuttle Radar Topography Mission (SRTM)	Farr et al. (2007)
Exposure - land cover	GlobeLand30	Chen et al. (2017)
Exposure - population	Global Human Settlement Layer (GHSL)	Smith (2017)
Damage curves	Global flood depth-damage functions	Huizinga et al. (2017)
Flood risk reduction measures		
Measures	Reference projects	*Various*[1]
Hydraulic Boundary conditions		
Surge data	GAR2015	(Cardona et al., 2014)
Rain data	*Various*[2]	
Wind data	GAR2015	(Cardona et al., 2014)
Future changes	Global scenario reports	IPCC (2014)

[1] For structural measures, some general cost information is available. Construction cost of storm surge barriers can be based on (Mooyaart and Jonkman, 2017). When general overviews are not available, costs can be based on reference projects, like (GCCPRD, 2015).
[2]There are several sources that obtain precipitation data on a global scale. Which should be preferred depends on the area and the requested time scale. An comparison between models can be found in (Sun et al., 2018).

Schematization of the city, measures and hazards

2.1 divide the city up into drainage basins.



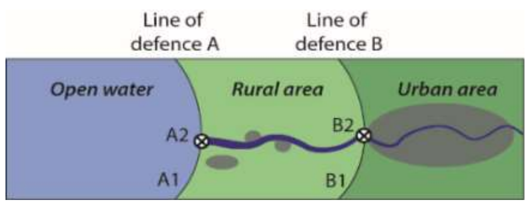
The main schematization of the city will involve the division into drainage basins. These are parts of the city where all the water will flow towards the same point. Using QGIS, this was done with the '**r.watershed'** tool in the build in GRASS environment.

NOTE: often, this data needs to be cleaned up, to get rid of unnecessarily small basins or other errors. A reasonably workable number is to divide the city in 30-50 basins. A useful tool for this is '**v.clean.rmarea'**, from the GRASS environment, which removes smaller than threshold areas and adds them to neighboring areas according to a rule specified by the user.

NOTE: Depending on the local geometry and available data, preprocessing of the data might be necessary for '**r.watershed'** to produce accurate results. '**r.watershed'** can produce additional maps such as a flow accumulation map, which can be used to check the results of the basin delineation.

2.2 formulate Lines of Defense (if applicable)

- *This step is only necessary if structural flood defenses are considered against coastal storm surge or river flooding.*



Structural flood defenses form a central part of the simulation of surge flow (either from coastal storm surge or river flooding). The flow is simulated as a sequence of lines of defense and protected areas. Based on the city layout, the digital elevation model, and the location of proposed measures, these lines of defense can be formulated. Often, these lines of defense are situated along the water (coast, river, bay) or major infrastructure. Per line of defense, divide (if necessary) into characteristic pieces.

NOTE1: More lines of defense and defenses per line significantly increase computation time. For reasonable times, limit both to max 2-3.
NOTE2: Should one of the Lines of Defense cut through a drainage basin, divide the basin in two according to the location of the Line of Defense.

2.3 Divide the city into height contours

With the **'r.mapcalc'** tool (QGIS, GRASS), the DEM can be divided into separate raster files, according to their elevation, which can then be transformed into one shapefile. In previous case studies, a step size of 0.25 m was chosen. This can be changed based on DEM detail level or required detail.
is might lead to many small areas because of the DEM accuracy. This can be cleaned up slightly with the use of the **'v.clean.rmarea'** tool.

2.4 Combine contour data

	First, the shape files of drainage basins and contour should be combined, so every basin has its own list of height contours. Subsequently, data on structural and population exposure should be added to each basins height contour, the exact procedure is dependent on the form in which the information is available. Eventually, each height contour should contain the following information: • Basin number • Contour number, starting at the lowest point in the basin • Minimum elevation • Maximum elevation • Surface area • Structural value, divided per land use • Population This data can be converted to .csv file, as input for the FLORES model. To make sure no errors occur, the format should fit. Information on the contours and their characteristics should be added according to the following format: *File name*: region_layout_contours.csv *Header (case sensitive):*

Basin_ID	Contour_ID	Height_min	Height_max	Area	Population	Land_use_1_value	Land_use_..

Example row:

4	2	2.75	3	510000	34	82200	0

2.5 Basin border information

Water starts flowing between basins as soon as the water level reaches the elevation of one of the borders of the drainage basin. Using the **Profiles from lines tool** (SAGA tool available in QGIS), we need to identify the following data for each border:

- Border_ID
- Basin 1
- Basin 2
- Border-length
- Border_height

For the border height, we will use the mean of the lowest 25% of the border, to exclude the accidental lowest points. Information on the basin border should be added according to the following format:

File name: region_layout_basin_borders.csv

Header (case sensitive):

Border_ID	Basin 1	Basin 2	Border_length (m)	Border_height_mean (m)	Border_height_lowest25% (m)

Example row:

23	1	11	917.9	9.027223	8.822897

2.6 Basin hydrology

For each basin, we need information on:

- Whether a drainage system is present in the basin
- Capacity of the drainage system
- Where it drains to
- Any retention capacity

There are several points to note here. This involves the occurrence of exit points (drainage outlets, connections to outer water), which let water exit the water system of the city. Also, it is possible that a basin houses small stream or canal. This can be seen as both drainage and retention. Information on basin hydrology should be added according to the following format:

File name: region_layout_basin_hydrology.csv

Header (case sensitive):

Basin_ID	Drainage channel	channel size	other drainage	Drains to basin	Retention

Example row:

6	yes	small		20	180112

2.7 Layers input information

The next step is to insert the information on individual layers of the city. Currently, there are three types of layers: Unprotected area, protected area, and line of defense.
Unprotected areas are areas that lie outside of any protection and are directly subject to outside hydraulic conditions. Here, the basin codes that are part of the unprotected area is needed.

For Lines of defense, the following information is needed:

- Sequence number, showing in which order the layers are encountered
- Number of defenses in the line of defense
- Total length of line of defense

For each flood defense:
  - Name of location
  - length of location
  - Land elevation of location in null-scenario
  - Basins protected by flood defense
  - Length of each basin protected by defense

2.8 Hydraulic boundary conditions

The hydraulic boundary conditions are divided according to hazard type. The following data is needed on storm surge for different return periods:

- Maximum storm surge
- Normal tide amplitude
- Any differences between CD and MSL
- Maximum wave height
- Maximum wind velocity
- Storm duration
- Any climate scenarios

For extreme rainfall, the following information is needed for different return periods and different storm durations:

- Maximum rain intensity
- Any climate scenarios

2.9 Flood risk reduction measures input

The measures that can be implemented to reduce the likeliness or the impact of flooding is very case-specific in terms on which areas they affect and the costs. Discussions with (local) stakeholders should be conducted to understand what has been done so far and what measures are considered. The effects can be divided into several groups:

- Flood defenses. This type of measures requires a lot of information, including:

	Location(s), considered heights, general dimensions, used material, cost estimate • Drainage. Requires information on: expected drainage capacity, impacted area, construction cost • Retention. Requires information on: expected retention capacity, which areas drain on the retention basin. • Emergency. Requires information on: affected variable (exposure, damage curve, surface flow), impact factor, implementation cost This information can be based on reference projects when no local reports or correspondence is available. **2.10 development scenarios** These scenarios are included to take future developments into account. The scenarios can affect the hazard (e.g. climate scenarios or changes to the hydraulic conditions outside of the project area) or the exposure (e.g. urban development). Based on the type of effect, information can be taken from reference projects or high-level reports. Urban development and climate often changes similarly on a country level. • For hazard-related scenarios, information is required on the difference in height of storm surge, mean sea level, rain intensity and wind characteristics for different return periods. • For exposure-related scenarios, information is required on the expected relative growth of value and population for different land uses. **2.11 Input check** The following files should be present in the main FLORES startup folder: • **Data (empty)** • **Library** ◊ FLORES_simulation_model.py ◊ simulation_definitions.py ◊ simulation_data.py ◊ simulation_calculations.py ◊ **input_data** ♦ basins_drainage.csv ♦ flood_risk_reduction_measures.csv ♦ global_flood_depth-damage_functions_30102017.xlsx ♦ hydraulic_boundary_conditions_rain.csv ♦ hydraulic_boundary_conditions_surge.csv ♦ region_layout_basin_borders.csv ♦ region_layout_basins.csv ♦ region_layout_layers.csv ♦ urban_development_scenarios.csv • **Results (empty)** • **venv** ◊ **Include (empty)** ◊ **Lib (not empty, but not important to know)** ◊ **Scripts** ♦ python.exe ♦ pythonw.exe ♦ (other files) • FLORES [CITY] – Evaluation Model Runner.ipynb • FLORES [CITY] – Evaluation Model Analysis.ipynb • FLORES [CITY] – Simulation Model.ipynb It is advised to set up a virtual environment to ensure that the model will not stup running

	because of version issues with the used packages. Global damage curves from an open data source is included as an csv file and does not require alteration.
Step 3: Run simulation	Individual simulation can be run through the Jupyter notebook in the main folder: '/<CITY>/FLORES <CITY> - Simulation Model.ipynb' (please rename to correct city). If data is inserted according to format, the simulation should be able to run. If any problems still occur, the Simulation model can also be run through other (more analytical) IDE's like PyCharm or Spyder, by using the .py version of the simulation model in '<CITY>/Testing/FLORES Simulation_model.py'

Step 3a: Validation	The notebook mentioned in Step 4 visualizes the results of the model. It shows:
	• Hydrological balance:
	    o Water inflow through surge and rain
	    o Water outflow through drainage, infiltration
	    o Water inside the city through retention, flooding
	• Maximum water levels per basin
	• Expected damages per basin
	• Expected number of people affected per basin
	
	This can be visualized through GIS (not included in software yet), and compared with other flood modelling software for validation.

Step 4: Run evaluation	The production of the dataset for the evaluation is produced in the Jupyter Notebook '/<CITY>/FLORES <CITY> - Evaluation Model Runner.ipynb'. Here, input on the evaluation is required: • Number of runs • Repetitions required to build risk curve • Dataset name • Names of measures and scenarios Several changes have to be made to connect the evaluation model runner to the Simulation Model. Explanation is added in the Jupyter notebook.
Step 4a: Analyze	The evaluation of the dataset is done through the Jupyter Notebook '/<CITY>/ FLORES <CITY> - Evaluation Model Analysis.ipynb' . This notebook introduces and explains a number of analysis possibilities. Further explanation is provided in the Notebook.

Appendix B : Rapid Flood Inundation Models literature

Background information

- *The background knowledge on Urban stormwater flooding is mostly based on the book* 'Urban Drainage' *by Butler and Davies (2003). Other sources are mentioned separately.*

Accurate modelling of inundation due to rain requires fundamental knowledge on the hydrological processes that occur. When rainwater falls on a surface, it can infiltrate into the ground (and runoff in the form of ground water), it can evaporate back into the atmosphere, or it can flow over the surface (surface runoff).

In urban areas, infiltration into the ground is often hindered due to artificial surfaces (pavement, asphalt). This increases the amount of surface runoff. Developed urban areas generally have a sewerage system in place that can drain this surface runoff, which is called *stormwater* in the context of an urban drainage system, on top of their daily task of draining wastewater. The urban drainage system is a complicated network of transportation lines (gullies, pipes) and storage areas in place to quickly and safely dispose of

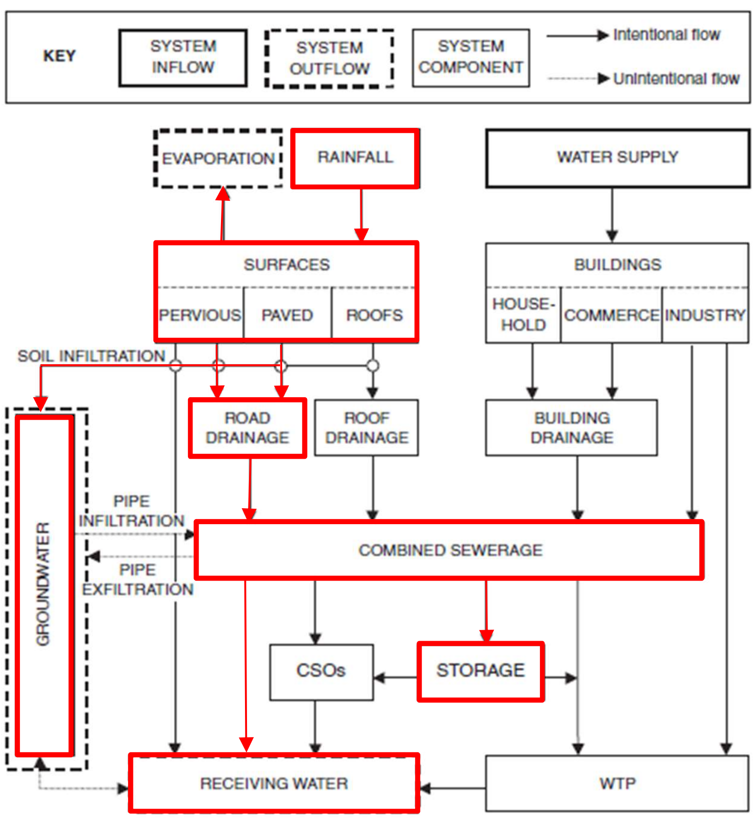


Figure 32 – General schematization of urban drainage system. Red denoted parts and processes that are considered in the FLORES-model. From: (Butler and Davies, 2003)

stormwater and wastewater from the urban area into either the ground or receiving waters.

Although this system in its entirety is complicated to model, the journey of stormwater (rainfall in the figure) can be simplified rather well, taking other parts of the system into account.

Well-established high-detail models like SWMM, Infoworks, SOBEK or MIKE URBAN generally simulate urban flood inundation with the use of a dual drainage model (Djordjević et al., 1999). This type of numerical model simulates both the sewerage/drainage system and the surface flow separately, connected through inlets and manholes. Over the past few decades, the use of Geographic Information System (GIS)-based software has become common use, allowing the mentioned high-detail models to include a 2D hydrodynamic model. Sewerage and drainage systems are mostly characterized by pipelines, which makes a 1D model detailed enough for highly accurate representation.

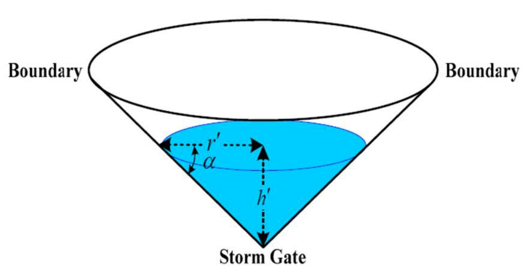
Although these models are commonly used for design and assessment of urban drainage systems, they require detailed data and have a high computational load. Therefore, earlier research has already attempted to develop simpler and faster alternatives to the 1D-2D dual drainage models (Chen et al., 2009; Yang et al., 2015). Different types of simplifications have been described by Bermúdez et al. (2018):

- Lower-fidelity models. In this case, the calculations are simplified, but still based on physical processes. Due to the computational load, often only the 2D-surface model is simplified.
- Data-driven models, which emulate the results of more-detailed models.

For the FLORES-model, lower-fidelity models are preferred, because these models do not require more detailed models to emulate and can therefore be used in a larger range of situations. Over the past years, several studies have attempted to develop a Rapid Flood Inundation Model, combining fast, data-scarce modeling with reasonable simulation accuracy (Liu and Pender, 2010; Krupka et al., 2007). Most fast urban flood inundation models try to imitate the methodology of more advanced 1D-2D dual drainage models, for instance by simplifying the surface model, resulting in a 1D-1D dual drainage model.

A method that fits the goals of FLORES well is the New Rapid Simplified Inundation Model (NRSIM), developed by Shen et al. (2016). This model divides the area into calculation cells, based on storm drains. These are the points where water from the surface enters the drainage system. The calculation cells act as virtual reservoirs, which can fill during a flood and eventually spill into neighboring cells. This spilling simulates the flow of water towards the lowest points of the study area and has also been described in (Gouldby et al., 2008). Both methods are fast, able to cope with many different situations and mostly require elevation data. Therefore, the FLORES-model simulation for urban flood inundation will generally be based on these methods.

NRSIM takes two flooding situations into account: Filling and spilling. Filling occurs when the surface runoff exceeds the storm drain capacity, which results in the drainage basin filling up (see Figure 33). To simplify the calculation, each drainage basin is schematized as a circular cone, where the storm drain is at the lowest point. Using geometric relations, the inundation depth can be computed from the flood volume.



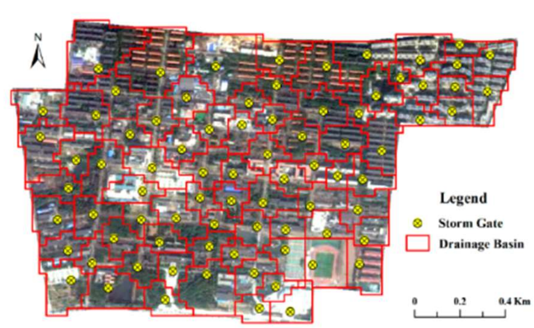


Figure 33 – (left) schematization of a drainage basin during the filling phase and (right) an example schematization of a case study area using drainage basins. From (Shen et al., 2016)

Spilling occurs when the entire drainage basin is flooded and the residual water will spill into adjacent basins. The flow direction has been determined beforehand according to the eight-direction (D8) flow model (as explained by Garbrecht and Martz (1997)), which is included in GIS-software [6]. This algorithm does assume that in a gridded system, water can only flow to one of the adjacent cells.

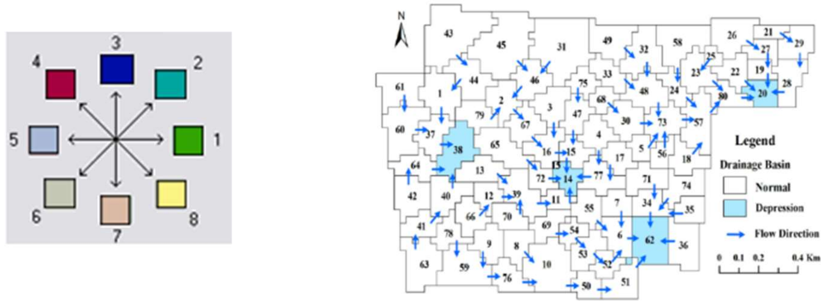


Figure 34 – (left) schematized version of the eight-direction flow model. In a grid where each cell has a value (e.g. average elevation), the water will flow to the adjacent grid cell with the highest drop in value. (right) example as used in Shen et al. (2016), where this has been applied.

Within such a system, there are also grid cells that do not have an outgoing flow, because all adjacent cells slope towards them. These cells are called depression cells (the example in figure 34 has 4 in light-blue). When water rises above the drainage cell boundary, the volume keeps accumulating and the inundation level keeps rising above the schematized cone. This will continue until the water level rises beyond the mean elevation of any adjacent drainage cells that has not been flooded yet.

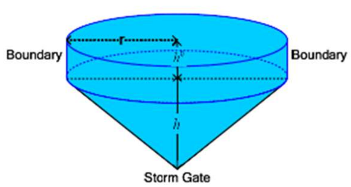


Figure 35 - schematization of a fully flooded depression cell, source: (Shen et al., 2016)

[6] See https://docs.qgis.org/testing/en/docs/user_manual/processing_algs/taudem/basic_grid_analysis_tools.html

Appendix C : Spatial data input - Beira

For the case study of Beira, Mozambique, a combination of public and non-public data sources is used. These were already listed in Chapter 4. This appendix will further explain the types of data that were used and their alternatives for use in other areas. The following data was used:

Required input	Source	Reference	Data type [resolution]
Elevation	LiDAR Digital elevation model (DEM)		Local data [2 m]
Exposure- structural	ADFR (R5) – Building exposure	Eguchi et al. (2016)	Satellite measurements [450 m]
Exposure - population	ADFR (R5) – population exposure	Eguchi et al. (2016)	Satellite measurements [450 m]
Damage curves	Global flood depth-damage functions	Huizinga et al. (2017)	Global open data [-]
Flood risk reduction measures	Expert mission report, earlier research		Local / global open data
Surge data	GAR15 storm surge[1]	(Cardona et al., 2014)	Global open data [-]
Rain data	Adaption to climate change Feasibility study	(CES and Lackner, 2013)	Local data [-]
Wind data	GAR15 cyclonic wind	(Cardona et al., 2014)	Global open data [-]
Future changes	Global scenario reports	IPCC (2014)	Global open data [-]

[1]The time series of a storm surge also requires tidal data, which was provided by CES and Lackner (2013)

C.1 Elevation

For the elevation data, LiDAR images are available for the city of Beira. The collecting of the data was part of a feasibility study on the rehabilitation of the Rio Chiveve, in the center of Beira. The spatial resolution is 2 meters and the measurements were done in 2013.

C.2 Exposure

The economic and human exposure is represented by the potential direct damage to structures in the area. This form of information is often the hardest to obtain, because it requires knowledge on the type of structures in the area, their use and their value. Moreover, reasonably detailed data is needed in order to be able to differentiate between what a meter of inundation would result to in an urban environment compared to a rural outskirt.

In the case of Beira, Mozambique, the structural and human exposure will be based on data coming from the 'GFDRR Africa Disaster Risk Financing (R5)' database. This project aims to 'support African countries in developing national risk financing tools and strategies that have the potential to significantly reduce disaster losses, speed recovery, and build resilience to natural hazards(GFDRR, 2017).' As a part of this project, well-structured and documented exposure data has been developed for several Sub-Saharan African countries.[7]

[7] Similar data is also available for Ethiopia, Kenya, Niger, Senegal, Uganda, Cabo Verde, Malawi and Mali.

C.2.1 Data description

Name of File

MOZ_buildings_exposure_20171213.shp

Format and Type

ESRI shapefile – Point data. Geographic coordinates, WGS 84.

Description of dataset:

The dataset provides a building count and cost estimates (replacement) at a resolution of 15 arc-seconds (approx. 450 m). Every datapoint provides the amount of buildings, sorted in seven different datatypes, as well as an indication of the dominant development pattern in the area and the replacement cost of the buildings. The building count is based on analysis of remote sensing data, compared to 'development patterns' (explained below). Replacement cost estimates are based on information from local experts. More information on the background of the data is provided by Eguchi et al. (2016).

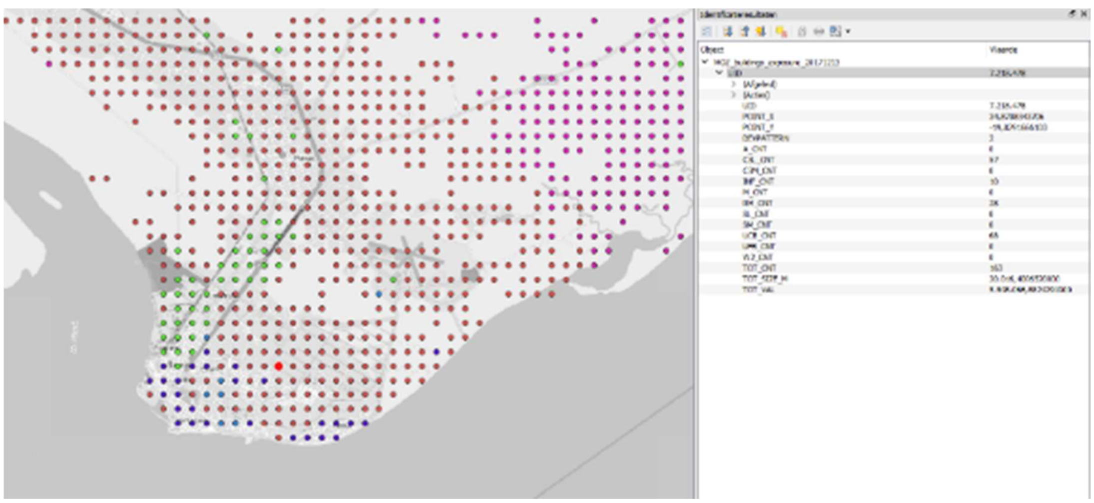


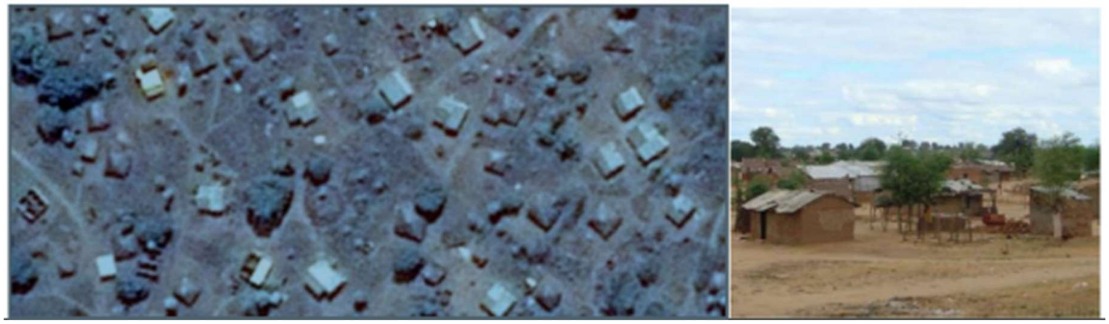
Figure 36 - Map of Beira with an example of the structure exposure.

Example output:

Development patterns

The R5 Exposure dataset counts the buildings and sorts according to seven development patterns. The following patterns are used:

- Pattern 1: Agricultural development

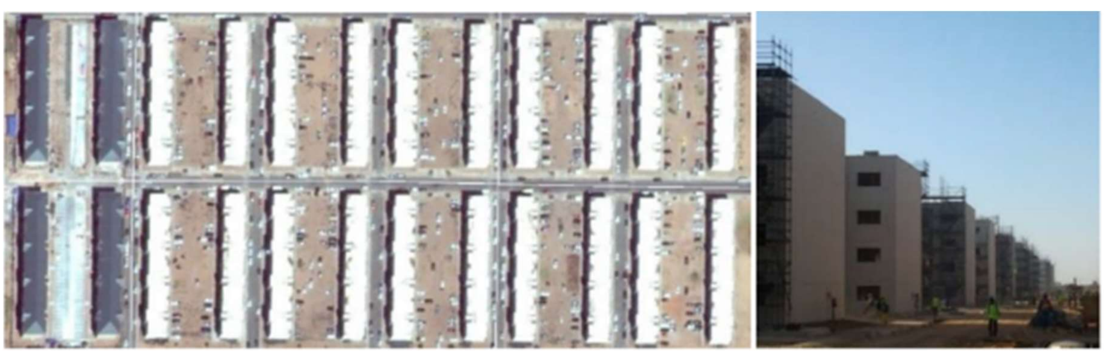


Mostly found in areas outside of the city. Small remote villages with buildings of 1 to stories placed far apart.

- *Pattern 2: Low rise residential area*

Mostly consist of single-family residential structures. More densely built than pattern 1, although open areas are still present.

- *Pattern 3: Multi-family residential buildings*



The land is mostly occupied by large apartment blocks. Mostly 3-5 stories high, built of stronger materials than earlier mentioned patterns.

- *Pattern 4: informal settlements*

Informal settlements are often characterized by unplanned, extremely dense housing. The buildings are small and built of local and cheap material.

- *Pattern 5: Urban area*

These areas are often better-built structures, low to mid-rise residential and commercial structures. The buildings are close together.

- *Pattern 6: Central business district*

This area is reserved for the big cities. Mid to high-rise apartment buildings or offices. Lower buildings can be present in between and the overall building quality is high.

- *Pattern 7: Industrial*

This pattern indicates warehouses, ports, mining or industrial activities. Most buildings are single story warehouses.