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Rapid flood risk screening model for compound flood events in Beira, Mozambique

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Abstract. Coastal cities combine intensive socio-economic activity and investments with high exposure to flood hazards. Developing effective strategies to manage flood risk in coastal cities is often a costly and complicated process. In the design of these strategies, engineers rely on computationally demanding flood simulation models and only compare a few strategies due to computational constraints. This limits the efficacy of standard flood simulation models in the crucial conceptual phase of flood risk management. This paper presents the Flood Risk Reduction Evaluation and Screening (FLORES)-model, which specifically aims to provide useful risk information early on in the planning process. FLORES performs numerous quick simulations and compares the impact of many storms, strategies, and future scenarios. This article presents the screening model and demonstrates its merits in a case study for Beira, Mozambique. Our results demonstrate that expansion of the drainage capacity and strengthening of its coastal protection in the southwest, are crucial components of any effective flood risk management strategy for Beira.

1. Introduction

1.1 Background

Coastal cities are under increasing pressure of flood events. Floods are currently the most recurring and damaging type of natural hazard, posing major threats to socio-economic development and safety of inhabitants (Adikari and Yoshitani, 2009). As both social-economic activity and extreme weather events are increasing, it is not surprising that vulnerability to flooding is growing rapidly (Doocy et al., 2013). The main processes leading to urban flooding are extreme rainfall (pluvial flooding), high river levels (fluvial flooding), and storm surge (coastal flooding). For coastal cities these flood hazards interact and can be correlated. Single meteorological events, like hurricanes, can simultaneously cause extreme rainfall and high storm surges simultaneously. These compound events further increases both the vulnerability and the complexity of flood risk management in coastal cities. The impact of flooding can be reduced through measures that improve the city’s hydraulic ability to deal with the flood hazard – the probability of a flood event -, or reduce the amount of damage caused by a particular flood event.

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Managing flood risk is often the role of local governments, which need to develop effective strategies to reduce flood risk. This planning process can be supported though flood risk analysis that inform decision-makers on where the most significant risks lie and how to best manage them (Sayers et al., 2013). The type and detail of risk information required varies throughout the phases of the planning process. This is however not always recognized in the tools that are used to generate the information required.

Quantitative flood risk analysis is often provided through computer models. The first models, limited by computational power and available input data, focused on analytical optimization in order to explain and compare concepts (Van Dantzig, 1956;USACE, 1996;Vrijling et al., 1998). These models mostly focused on the economic impact of floods only. First because this was needed most, and second, because multi-objective optimization quickly complicates the calculations. More recent developments allow the optimization to account for intangible damages (Kind, 2014), nature-based flood protection (Vuik et al., 2016), and multiple lines and types of defense within the same flood protection system (Custer, 2015;Dupuits et al., 2017). These developments were made possible through highly schematized regional layouts that limit computational load. They are, however, a less accurate representation of the situation in a specific coastal city.

On the other side of the spectrum, numerical flood modelling has developed into standard practice for the design of flood risk management systems. High-resolution flood simulation software (e.g. Delft3D, SWMM, MIKE) has become standard practice in large flood risk management design projects. These models build on increased knowledge of fundamental hydraulic processes and the use of Geographic Information System (GIS)-based tools (Kovar and Nachtnebel, 1993), made possible by the growth in computational power. These models provide accurate simulation for specific coastal cities and for complicated situations. However, these simulations are complex, labor-intensive, time consuming, and expensive. In addition, their high accuracy demands lots of input data and computational power. This type of model is therefore not well suited for analyses where many simulations are required, such as uncertainty analysis, investment strategy analysis or the comparison of many flood risk reduction measures (Haasnoot et al., 2014).

The gap between conceptual, analytical models and high-resolution, spatial flood simulation models leaves room for models that take local spatial circumstances into account, but still can evaluate many scenarios and many flood risk management options. In recent years, several of these models have been developed, mostly for particular case studies (Gouldby et al., 2008;Aerts et al., 2014;Shen et al., 2016). These models run relatively quickly because of their simplified schematization of the project area and the flood hazard, which restricts their ability to be applied to other areas. Therefore, this paper describes a fast, widely-applicable flood risk screening model, able to adapt to local circumstances, investigate multiple flood hazards, many different scenarios, and many possible flood risk management options.

1.2 Objective and scope

This paper introduces the Flood Risk Reduction Evaluation and Screening (FLORES) model as a generally applicable decision-support model for the early planning stages of flood risk management. It has been developed with the goal to explore and evaluate the impact of many different flood risk reduction strategies within a flood-prone area. The FLORES model is based on a framework applied before to coastal flooding in the Houston-Galveston Bay area (van Berchum et al., 2018). Here, we describe how the model has been further developed into a generally-applicable flood risk screening model by including pluvial flooding of urban areas. The schematization has been upgraded such that more diverse types of urban layout can be modelled systematically. In addition, it allows for the simulation of multiple interacting flood hazards, in this case coastal and pluvial flooding.

These improvements strengthen the main characteristics upon which the FLORES model is based; the model (1) makes risk-based assessments of flood risk reduction strategies, (2) minimizes computational load, (3) considers structural and non-structural measures, (4) compares flood risk reduction strategies based on multiple performance metrics, and (5) is applicable to a wide range of urban layouts and situations. The model is demonstrated through a case study of Beira, Mozambique, which represents a case with compound flooding in a data-poor environment.

2. FLORES model description

2.1 Model structure

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

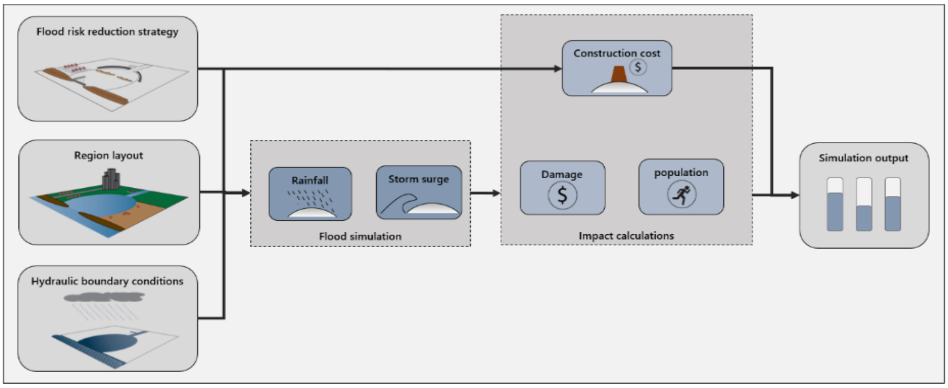

Figure 1 – Schematization of a flood event simulation

can be assessed, as well as different possible future scenarios (i.e. climate scenarios) to get a clear picture of the options and their consequences.

2.1.1 Flood event simulation model

One flood simulation consists of two parts: the hydraulic flood simulation and the impact calculation. The first part simulates how water flows into and through the urban area during the storm event, resulting in maximum water levels throughout the city. The impact calculation uses these maximum water levels to estimate impact in terms of economic damage and amount of people affected.

The hydraulic flood simulation takes both rainfall and storm surge into account. Urban flooding is schematized through a combination of an urban inundation model and a drainage system model. For the schematization, the city is divided into drainage basins, which are areas where all water drains towards the same place, see Figure 2.

Throughout the simulated storm, the hydraulic response is calculated by viewing the hydrological balance for each of basins for each time step:

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

The volume of water in a drainage basin after time step i (V_i) depends on the volume at the previous time step (V_{i-1}), the length of the time step (t), and a number hydrological processes that cause an in or outflow of water. Inflows are: rainfall (Q_r), storm surge overtopping nearby barriers (Q_s), surface flow from neighboring basins (Q_{fi}), and drainage of upstream basins (Q_{di}). Outflows are: infiltration (Q_{in}), drainage flow (Q_{do}), and surface flow towards neighboring basins (Q_{fo}). The difference between inflow and outflow is stored in the basin itself (Q_{rt}), starting with retention. When the retention capacity is fully utilized, water floods the streets, starting at the lowest part (often the drainage point) of the basin.

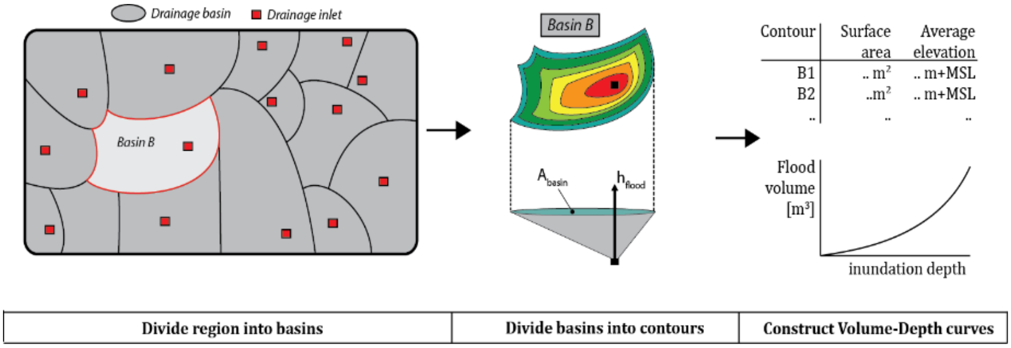

Figure 2 – Schematization of the city from GIS data into input data for the FLORES model. Based on the DEM, the region is divided into basins and contours, leading to a Volume-Depth Curve of every basin. This schematization does not include coastal boundaries yet.

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The schematization of the storm surge is based on van Berchum et al. (2018). The borders between land and water are schematized as line elements that separate the outside water from the drainage basins inside. Here, barriers can be placed in the form of dunes, levees, storm surge barriers, etc. For each time step, basic formulas calculate the amount of overtopping or overflow passing the barrier, which acts as inflow for the drainage basin on the inside of the barrier. By dividing the area into layers (e.g. coastal zone, bay side, inner city), the model can simulate flood protection based on multiple lines of defense. For structural flood defenses, the probability of failure is also taken into account, as levee failure has a huge effect on the flood impact. The simulation considers all possible scenarios (which structures fail) combinations of outcomes (flood structural scenarios) and their resulting inundation depths.

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

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

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

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

2.1.2 Risk profile assembly

The performance of a flood risk reduction strategy cannot be based on a single flood event simulation. Therefore, multiple simulations are combined to build a more representative risk profile, using the definition of risk as expressed by Kaplan and Garrick (1981). By varying the intensity and return period of the incoming hazard, the risk profile shows how the city and the implemented measures perform under different circumstances. When modelling, it is impossible to look at all possible scenarios. Therefore, the impact of one simulation is weighted by its probability, which results in the conditional risk (the risk, given a particular situation). Hereafter, a number of simulations is numerically integrated to represent the entire risk curve. The corresponding performance metrics, used to compare flood risk reduction strategies, are the expected annual damage (dollar/year), expected annual affected population (people/year), and construction and repair costs.

The development of a risk profile is complicated by compound flooding, where both extreme rainfall and coastal storm surge are threatening the city. This influences the performance of some measures, and should therefore not be ignored. For example, the efficiency of a drainage system, which drains on outside water, can decrease when outside water levels are raised due to storm surge. Several different combinations are simulated, resulting in a risk profile that depends on two variables – the probability of occurrence of the rainfall and storm surge. For each flood hazard, 5 different storm intensities are used, which means that 25 simulations are needed for one risk calculation. An example, based on the case study, can be seen in figure 7.

A common problem of risk analysis of compound flood events is correlation between the flood hazards (Wahl et al., 2015). Several types of large storms, such as cyclones, generally lead to both storm surge and rainfall. Considering the hazards separately and independently would be underestimating the potential risk. Although complicated, correlation can be estimated based on historical data and expert judgement. In many countries, this data is not or only sparsely available. In FLORES, the risk calculation can be adjusted based on correlation.

2.1.3 Screening flood risk reduction strategies

FLORES can quickly asses how a flood risk reduction strategy affects the risk profile. This leads to a huge amount of data available for analysis, which will be processed using the Exploratory Modelling and Analysis (EMA) workbench (Kwakkel, 2017b). This python-based toolset runs common analysis- and optimization algorithms to visualize and support decision making and planning. It has been used in several research fields in the past (Rostampour et al., 2019;Ciullo et al., 2019a). FLORES uses these tools to visualize screening results, prioritize measures, and search for trade-off and trends.

2.2 Model data usage

FLORES is intended to be generally applicable to flood-prone cities worldwide. Therefore, it should work based on easily accessible data sources. Examples are global elevation maps (often GIS-based DEMs) or reports containing global estimates of damage curves. FLORES requires three categories of information: the region layout, flood risk reduction strategy, and hydraulic boundary conditions. As many of the most vulnerable cities are located in developing countries which often lack detailed datasets, the model's goal is to run based on minimal amount of local data. Therefore, open-source dataset can be used for most of the required data, such as elevation, population density, damage curves, hazard data, and future scenarios. However, for some types of data, local information is necessary. For example, information on the local hydrology (e.g. drainage system, sewerage), considered measures, and the structural exposure.

3. Case study in Beira, Mozambique

3.1 Background

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

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

3.2 Model setup

3.2.1 Input data

For each type of information, the most detailed, yet easily-obtainable, data source is used. The data sources used in this case study are listed in Table 1. Regarding the elevation data, this LiDAR DEM data developed as a part of an earlier project financed by the World Bank, aiming to enhance local research. The DEM was calibrated with locally used elevation units (meter above Chart Datum [m+CD], which is equal to the lowest astronomical tide).

Table 1 - Data sources for the FLORES model in Beira

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

3.2.2 Compound flood hazard setup

The hydraulic boundary conditions are based on extreme-value analyses of coastal storm surge- and extreme rainfall events. Input for the model is the return period of both types of flood hazards. A coastal storm surge is simulated as a time series of water levels at the coast, also taking tide into account, see Figure 3. Rainfall is simulated as a constant inflow for duration of the storm. At events where both hazards are occurring, the joint probability is important. For this particular case, first analysis using ERA-Interim (Dee et al., 2011) suggests independence between coastal storm surge and extreme rainfall, which was therefore also used for this screening. Future analysis should examine whether this assumption is valid for extreme cases. The hydraulic boundary conditions for several return periods is shown in Table 2. Two climate change scenarios are taken into account, which will affect the boundary conditions by increasing the surge level and rain intensity.

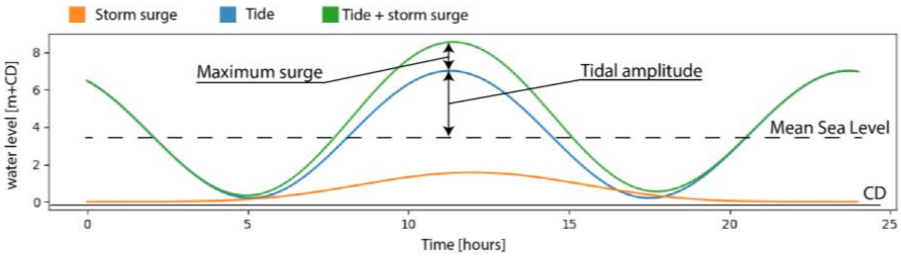

Figure 3 - Example time series of coastal storm surge event. (orange) run up due to storm surge, (Blue) elevation of tide, and (green) total elevation of tide plus surge

Table 2 - hydraulic boundary conditions for Flores application in Beira. Note that the maximum surge level is mainly attributed to the tide (3.4 meter amplitude) and the mean sea level (3.6 m+CD). The Flores model will assume a storm duration of 24 hours.

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

3.2.3 Flood risk reduction measures

We consider various measures to improve the flood resistance of Beira, based on measures considered by the local government, as well as measures suggested in meetings with local stakeholders, as well as scoping studies (Deltares et al., 2013;Letitre et al., 2018). The set of measures showcase the different types of measures that can be considered with FLORES, including structural flood defenses, drainage systems, retention basins, and non-structural emergency measures. Note that a part of the overgrown drainage system has already been rehabilitated through widening of the canals and addition of a retention basin and a coastal inlet structure. A map of Beira, with some of the measures, is shown in Figure 4.

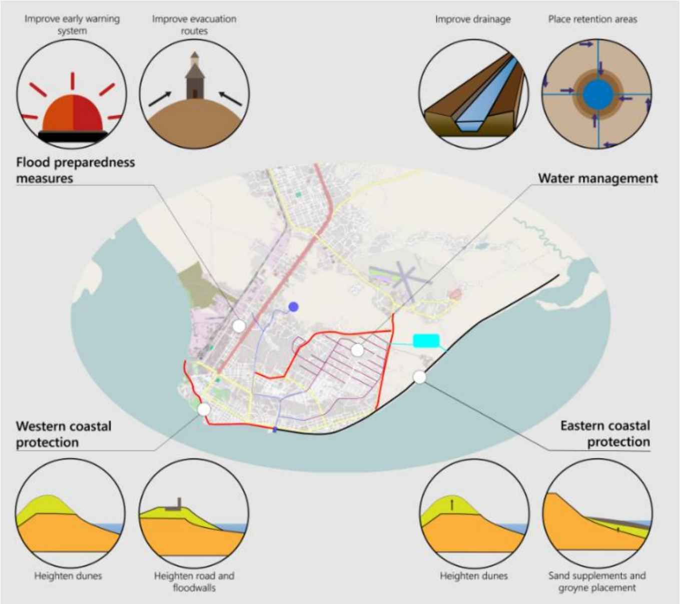

Figure 4 - Map of Beira, Mozambique. Denoted are a few examples of flood risk reduction measures. Background image © OpenStreetMap contributors 2018. Distributed under a Creative Commons BY-SA License

3.3 Model validation

Little data is available to validate the flood simulations. Cyclone Idai provided some insight into one situation, with verifiable data and known hydraulic conditions. During other extreme events, however, no detailed measurements were taken. Moreover, only few detailed flood simulations have been conducted (CES and Lackner, 2013). As a part of the design of the drainage system, which completed in 2018, a 10-year rainfall event was simulated. This simulation is compared with a FLORES flood simulation, which is shown below (Figure 5). It predicts higher flood levels in lower areas of the city, especially in areas with steep slopes.

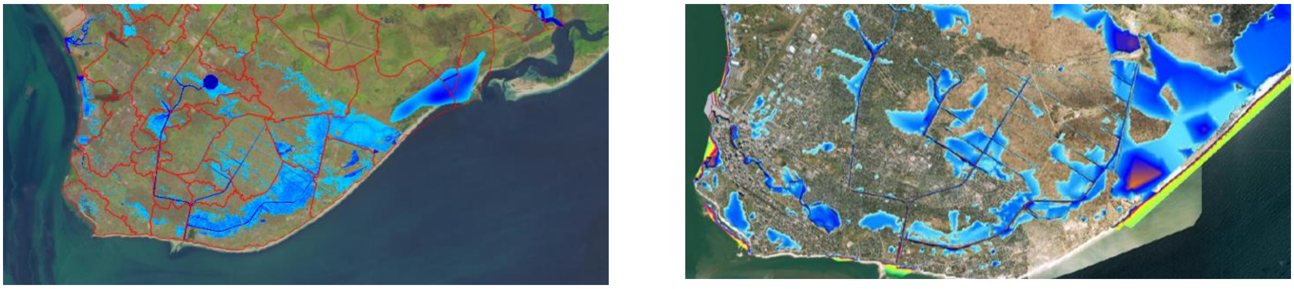

Figure 5 - flood extent resulting from a 10 year rainfall event for FlORES (left) and an ANUGA simulation, which was part of the Rio Chiveve feasibility study. Background image: Sentinel-2 (© ESA).

3.4 Results

FLORES is used to analyze the current situation, as well as potential future situations and strategies for the city of Beira. First, we examine the current risk profile of Beira. Next, we quantify the effects of the different possible flood risk reduction strategies under different potential future scenarios. Their effectiveness is measured based on their ability to decrease flood risk compared to the current situation. In total, 500 different strategies (combinations of measures) are considered for two future climate change scenarios. The runtime was roughly 10 hours for the entire screening on a single computer. For this screening, 8-core (3.2GHz) multiprocessing was used.

3.4.1 Current risk profile

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

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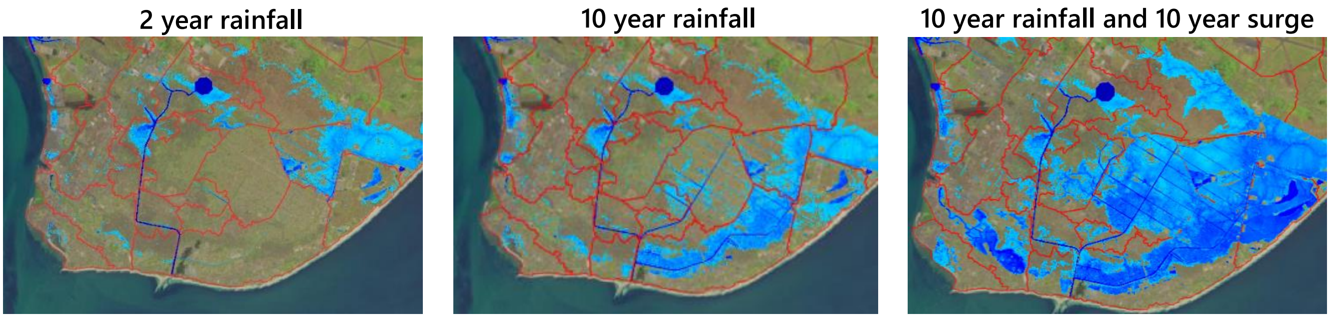

Figure 6 – flood map for a 2 year rainfall event (left), 10 year rainfall event (middle), and a 10 year rainfall event plus a 10 year coastal surge event (right). Background image: Sentinel-2 (© ESA).

effectiveness of the drainage system. As a result, damages due to compound flooding are more than the sum of damages of the individual flood hazards.

Coastal storm surge is mostly problematic when resulting from a tropical cyclone. These situations do not occur regularly, which is why the effects of coastal storm surge only become significant for more extreme events. Smaller storms only create coastal surges up to 0.5 meter, which are insignificant compared to the tidal range, which can grow up to 6-7 meters. This also shows the importance of timing. For example, the 3.5 storm surge from Cyclone Idai hit during neap tide, and damage due to coastal flooding was relatively small. In some scenarios compound flooding can occur, where the effects of coastal storm surge and extreme rainfall strengthen each other. In Beira, the capacity of the drainage system depends on outside water levels. Due to high water, there is a time window where no drainage is possible. This time window grows during a storm surge and also grows as a result of sea level rise.

3.4.2 Screening of flood risk reduction strategies

In order to assess the effectiveness of flood risk reduction strategies, there performance is compared with the current situation and with each other based on their risk profile. Both flood hazards – coastal storm surge and extreme rainfall - are represented by five intensities, based on their return period (0-, 5-, 10-, 50-, 100 year event). The resulting risk profile can be seen in Figure 7. Integration of probabilities and consequences of events result in the expected annual damage (dollar/year).

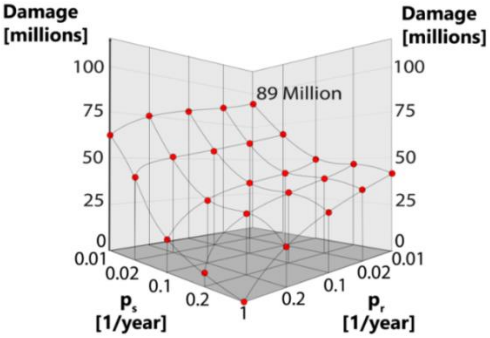

Figure 7 – Risk profile of the current situation in Beira, Mozambique. Shown is the expected damage of a compound flood event with a probability of occurrence of the storm surge (p_s) and the rainfall (p_r).

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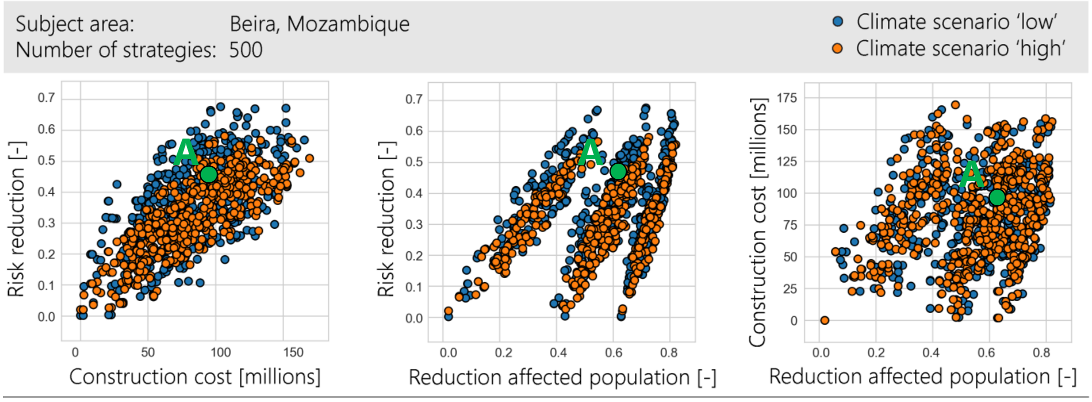
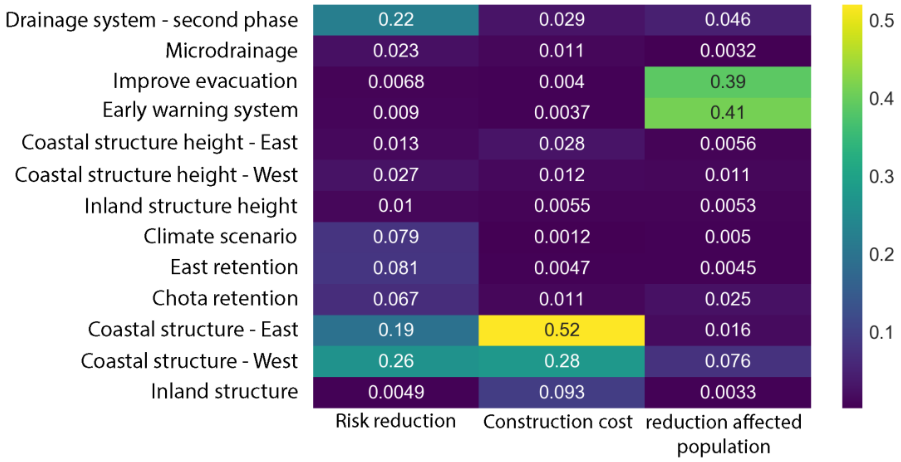


Figure 8 – Pair wise plotting graphs for the Beira case study. Each dot represents one flood risk reduction strategy. Each strategy can be assessed by their risk reduction, reduction of affected population, and cost of construction. Here, those outcomes are plotted against each other. Different colors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

The screening of flood risk reduction measures is based on 500 randomly sampled strategies, for two different future climate scenarios. Here, we show the results of several analyses on this data. Figure 8 shows how each strategy performs on their output parameters (Risk reduction, reduction in amount of people affected, and construction cost). Each dot represents one flood risk reduction strategy and the two colors denote the climate scenarios.

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



	Risk reduction	Construction cost	reduction affected population
Drainage system - second phase	0.22	0.029	0.046
Microdrainage	0.023	0.011	0.0032
Improve evacuation	0.0068	0.004	0.39
Early warning system	0.009	0.0037	0.41
Coastal structure height - East	0.013	0.028	0.0056
Coastal structure height - West	0.027	0.012	0.011
Inland structure height	0.01	0.0055	0.0053
Climate scenario	0.079	0.0012	0.005
East retention	0.081	0.0047	0.0045
Chota retention	0.067	0.011	0.025
Coastal structure - East	0.19	0.52	0.016
Coastal structure - West	0.26	0.28	0.076
Inland structure	0.0049	0.093	0.0033

Figure 9 – Feature scoring analysis for the Beira case study. It shows the relative importance of system choices and uncertainties (listed on the left) for the outcomes (below). Higher numbers indicate higher importance.

Figure 9 quantifies the dependency of output variables on the input choices and uncertainties through a feature scoring analysis (Breiman, 2001;Jaxa-Rozen and Kwakkel, 2018) (Jaxa-Rozen and Kwakkel, 2018). At the left side, all potential measures are listed, as well as future scenarios. The numbers indicate how much the outcome variables (below the table) depend on the choice on the left. A higher number indicates a higher importance, where 0 means that the measure has no influence and 1 indicates that the output is fully dependent on the choice for that input. The results underline the importance of both coastal measures and inland measures, in particular further improvement of the drainage system. Increasing retention areas are relatively less effective. Simulations show that retention areas are effective only for smaller pluvial events, but have insufficient capacity when a storm surge overpowers the coastal defenses and reduces the effectiveness of the drainage system.. This effect is increased because the high outside water level during storm surge events prevents the drainage system from functioning. This is an example of how compound flood events lead to high damages by affecting hydrological processes in ways that are of less importance when considering individual hazards.

Finally, FLORES identifies promising combinations of measures using a PRIM-analysis (Kwakkel, 2017a;van Berchum et al., 2018). This type of analysis is able to identify which combinations of measures are most effective when pursuing a predetermined set of goals. The aim is to find a combination of measures that will maximize the chance of reaching those goals. The algorithm calculates which measures are most effective and removes strategies out of the comparison that do not include this measure. Finally, a number of strategies is left, where most will comply with the goals set in advance, see Table 3.

Table 3 - Results of PRIM-analysis for Beira case study 'Goals' shows what output we are looking for, 'Start' shows how many strategies out of initial 500 comply with the goals. 'Results' show which design choices are made, focusing on the most promising strategies. 'Final' indicates how many strategies are left– after filtering for the measures listed under 'results' – and how many of those comply with the goals.

Goals	**Start**	**Results**	**Final**
	Strategies of interest	Design choices (priority from top down)	Strategies of interest
Focus on risk reduction and construction cost			
For 'low' climate scenario: *Risk reduction > 0.35* *Construction cost < 80 M$*	**84** out of 500	1. Drainage system second phase 2. **No** coastal structure east 3. Coastal structure west	**43** out of **64**
For 'high' climate scenario: $risk\ reduction > 0.25$ $construction\ cost < 75\ M\$$	**88** out of 500	1. **No** dune heightening at eastern coast 2. **No** inland barrier 3. Height coastal structure west > 8.5 m 4. Retention Chota	**41** out of **67**

Balanced goals			
For ‘low’ climate scenario: $risk\ reduction > 0.40$ $construction\ cost < 125\ M\$$ *reduction in affected population > 0.65*	**89** out of 500	1. Drainage system second phase 2. Coastal structure west 3. Height coastal structure west > 8.6 m 4. Improve evacuation 5. **No** dune heightening at eastern coast	**42** out of **52**
For ‘high’ climate scenario: $risk\ reduction > 0.35$ $construction\ cost < 125\ M\$$ *reduction in affected population > 0.6*	**114** out of 500	1. Coastal structure west 2. Height coastal structure west > 8.5 m 3. Coastal structure east 4. Improve evacuation	**50** out of **57**

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

4. Discussion

FLORES aims to provide useful information in the early planning stages of flood risk management, when limited time and input data are available. Therefore, several limitations should be taken into account. Many physical processes are simplified. First, the simulation mainly revolves around solving the hydrological water balance for a defined number of drainage basins for every time step. Measures acting on a smaller scale are therefore hard to represent correctly. Second, storm surge is modelled as a time series of water levels during a storm, leading to inflow into coastal basins through overtopping or overflow. A coastal barrier can prevent this, but could also fail. The moment of failure, as well as the portion of the barrier that fails when it does, is set beforehand. Sensitivity to these choices has not been investigated as part of this study, but could be included by integrating fragility curves and breach models (Ciullo et al., 2019b). Third, the drainage system is simplified compared to common urban drainage models (Butler and Davies, 2003). For example, water drainage between basins is limited by the downstream basin. Therefore, water cannot flow in the upstream direction, which would occur if the outside water level is especially high.

FLORES is being developed further. In earlier case studies, the coastal storm surge simulation and the resulting damage have been extensively validated (van Berchum et al., 2018). However, lack of data prevents similar testing for Beira. Also, several model variables require further sensitivity analysis. For example, storms are simulated using a 6 minute time step, which provided reasonable accuracy and computational speed in earlier case studies. However, this is not tested for compound flood simulations. Similar assessments are needed for other variables, such as the step in elevation for the contours – which was 0.25 meter – and the amount of simulations required to construct a realistic risk curve. The optimal choice for these variables will mostly depend on the complexity and size of the project areas, as well as the available input data. For this case study, a combination of publicly available and local data was used. In general, most required data is available publicly, with the exceptions of information about the measures, local hydrology, and structural exposure. Most crucial is the choice of DEM, which is available almost globally.

5. Conclusion

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

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

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

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

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Code Availability. The FLORES model code, as well as the case study information for Beira, is open-source and available on GitHub (github.com/ErikBerch/FLORES-Beira).

Data availability. Sentinel-2 data are freely available from the ESA/EC Copernicus Sentinels Scientific Data Hub at https://scihub.copernicus.eu/.

Author Contribution. EB developed the model and prepared the paper. All co-authors contributed to the development of the model's methodology and review of the paper. ML contributed in the application of the model to the case study. JK contributed to the model code.

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