Date: July 9th, 2020

"Rapid flood risk screening model for compound flood events in Beira"

Reviewers comments and author response

We would like to thank the reviewers for their time and effort. Their helpful and constructive comments have been valuable for improving the manuscript. This document carefully addresses all comments by both reviewers (in black), together with the response by the authors (in blue). When comments have directly led to changes to the manuscript, this is mentioned in the response. For a complete overview, please view the new manuscript with tracked changes, which has been added at the end of this document. Throughout the new manuscript, there are many small changes, due to a thorough grammar check and an update of references.

Comments Referee #1 (Jay Lund):

Comment 1: Is construction and repair cost also an expected value, or a probability distribution?

Response 1: The construction and repair costs are also an expected value; this has been adjusted in the manuscript. For the construction cost, this fully depends on the chosen measures. The repair costs also depend on the probability of failure of each measure.

Comment 2: Models cannot be validated; they can only be invalidated. But all models can be tested.

Response 2: The section 'Model validation' is changed into 'Model evaluation', along with other mentions of the word 'validate'.

Comment 3: The word "measures" can be ambiguous. I suggest the more precise words options or actions, depending on the context.

Response 3: The word 'measures' was used to include both structural and non-structural design options, which would be less clear if we used the word 'actions'. In this results section, which is complicated enough on itself, 'measures' has been replaced by 'options'/'design options'.

Comment 4: Please also note the supplement to this comment: https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2020-56/nhess-2020-56- RC1-supplement.pdf

Response 4: Thank you for your other smaller comments, we have applied changes to the manuscript according to your suggestions.

Comments Referee #2:

Comment 1: My main comment is with regards the main focus of the paper. It is unclear to the reviewer whether the main purpose of this paper is to present the overall framework of FLORES, with an example demonstration in Beira to enrich this presentation; or whether the application of the framework in Beira is in itself the main aspect of the paper. In the case of the former, the framework needs to be more thoroughly described, whilst in the case of the latter, more details on the application would be required. It is my understanding that the main aim is to present the framework (see paragraph on objectives and scope). However, it is then confusing that the authors state that the framework is already presented in Van Berchum et al. (2018). If the framework is already presented there, one could ask why another paper is needed to describe the framework. Therefore, this should be clarified. That said, I do see value in using this paper to better document this very interesting and certainly useful tool as a paper in NHESS, and so I would encourage this. However, I believe that it should then be able to read it as a standalone paper, without having to flip back and forth with an existing paper.

Response 1: We understand the concern with the focus of the paper. Our goal is to have a mixture of both, with the main focus on the framework. We've chosen this setup because focusing solely on the framework would be very abstract and the screening results would look very strange. And the difference with the model used in Houston (2018) is too big to just focus on the case study.

The FLORES model is built according to the same principles as the model used in the earlier paper (van Berchum et al. 2018), and the schematization of the storm surge routing is roughly similar. However, it has been built from the ground up with different goals in mind and all other parts are therefore much different. Changing the basis of schematization from layers to drainage basins allowed us to include a whole new range of hydrological balances in the model, among which the ability to model rainfall and surface flow. On the other side, we do want to demonstrate its applicability in the form of a real case study, also to demonstrate that this model is already capable to be useful in real situations, despite that it is still work in progress. Therefore, we hope that you agree that it is useful to combine both the explanation of the framework with the demonstration of the case study. As the framework is the main focus, we have looked through the paper and added statements (mostly throughout the methods section) that should make the paper more readable stand-alone, without having to look back at the 2018 paper.

Comment 2: For the application part (Beira), I would like to see more details on the data used in this specific case. For example, what vulnerability curves are used? What measures are implemented, etc. – see other examples in the specific points.

Response 2: A problem that we ran into writing this manuscript was that we were very limited on the length of the paper. Many iterations of the manuscript were needed to make it as short as possible without losing crucial information. This is why a reader might need some explanation at some points in the paper, which we fully understand. We therefore thanks you for your detailed comments on this topic, as this shows us where the explanation might have been too brief. We will look at your specific points and answer them accordingly (and adjust the manuscript if necessary), and we will look through the entire manuscript again with these comments in mind. As a result, minor additions will be made throughout the manuscript to further explain the case study and what the model is able to do in this case. We do hope that you understand that we still try to keep the adjustments and additions as brief as possible. To answer your specifically mentioned example, we will add an appendix with data on the measures used in the model. Other information is added to the main text. More specific information on added data can be found in the comments below.

Comment 3: The results section is very shallow and needs more depth. Some figures are shown, but they are difficult to follow and require more interpretation in the text. On the other hand, a lot of results are interpreted in the text without actually being displayed in the figures. See examples in the specific review points below.

Response 3: We will look through the results and add explanation where needed. Your specifically mentioned comments on the results section will all be taken into account as well. From your comments, we notice that the problem is mostly one of connection (what results lead to which conclusions), so we have looked through the results section to make sure that for every statement, it is clear where it came from. However, due to manuscript length limitations, as mentioned in the response to the previous comment, we hope that you understand that we kept additions as short as possible, minimizing the addition of entire figures of tables.

Comment 4: The title points to a compound analysis, but there is actually little focus on this in the manuscript. Indeed, the model can include pluvial and storm surge flooding, which is great. But I miss an attempt to place this within the growing scientific literature on compound flooding. It is not conceptualized in the introduction, and there is little reflection on this aspect throughout the manuscript.

Response 4: Parts of the introduction have been expanded on the subject of compound flooding. We have added several references to recent literature to correctly place and compare this research.

Comment 5: More generally, a lot of the references used are rather outdated.

Response 5: Many of the references in quickly developing research fields have been replaced or supplemented with newer references.

Comment 6: I would recommend a careful proofreading – below I list several typos but there are many more that could be listed.

Response 6: Thank you for this comment and the typos you mentioned in the review. The manuscript has been thoroughly checked for grammar.

Comment 7 (Page 1): Floods are currently the most recurring and dam- ´ aging type of natural hazard, posing major threats to socio-economic development and safety of inhabitants (Adikari and Yoshitani, 2009): this is a rather outdated reference for the claim being made. Is this still the case in 2020 and can this be supported by a reference from 2009?

Response 7: This is still very much the case. The reference has been changed to a more recent one with similar conclusions.

Comment 8 (Page 1): 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): Whilst the first part of the sentence seems okay, the second part states that vulnerability to flooding is growing rapidly. But is this really the case? There is ample literature to suggest that vulnerability may actually be decreasing in many regions (e.g. Bouwer and Mechler, 2015; Jongman et al., 2015; Tanoue et al., 2016; Kreibich et al., 2017).

Response 8: The word 'vulnerability' is indeed poorly chosen here. We didn't want to explicitly divide the flood risk into the three commonly used parts (hazard, exposure, vulnerability), as this was a different definition than used in this research, which could be confusing. However, for this particular statement it is better to state that especially the flood hazard and exposure are growing rapidly in many places around the world. And even though vulnerability seems to be decreasing in many places, including Bangladesh, the flood risk is generally still increasing. Changes are made to the statement in the paper to reflect this consideration, and a more recent reference is added.

Comment 9 (Page 2): "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." Please clarify what is meant here: less accurate compared to what?

Response 9: These models use a high rate of simplification on the city layout. For example, several references mentioned in this paragraph model a city as a series of barriers with land (agricultural/urban) in between. This is necessary when we want to run detailed economic analyses or look at many options/futures, but do limit our ability to represent the urban layout very accurately. This sentence does imply a comparison, however. What is meant is that it is less accurate than real life (which all models are of course) and common flood simulation models mentioned in the next paragraph. It is better to rephrase this as a 'high level of schematization, which limits the ability to model a city's layout accurately'. The statement has been adjusted in the paper.

Comment 10 (Page 2): "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)." Again, given the rapid expansion in the field, these references are not so "recent" to back up the "in recent years" claim.

Response 10: More recent references are indeed available. These particular references were named partly because of their impact and similarity with this research, as we have learned a lot from these and partly based my research on lessons learned of these references. Because this is unclear in the current statement, we have changed the references to more recent ones. In addition, the references mentioned here are moved to the model description.

Comment 11: In the Methods section, it is explained that "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)." What do the authors mean here in the context of compound flooding? A given storm can have a storm surge and rainfall with quite different return periods, and an essential question of compound flood analysis is how to deal with this, yet I miss this here.

Response 11: Both the storm surge and rainfall have their own return period. The paper has been adjusted to: "of a flood event, represented by a storm surge and rainfall event, each with a specific return period (Figure 1). " The term 'flood event' was used to highlight the fact that both flood hazards are occurring simultaneously, as part of the same storm.

Comment 12: (Page 2): "High-resolution flood simulation software ´ (e.g. Delft3D, SWMM, MIKE) has become standard practice. . .". Change to: "The use of high-resolution flood simulation software (e.g. Delft3D, SWMM, MIKE) has become standard practice"

Response 12: We have changed the statement.

Comment 13 (Page 5): “The schematization of the storm ´ surge is based on van Berchum et al. (2018)”. Please expand here, given that this is an exposé of the framework – I also did not find much elaboration of this element in the cited paper.

Response 13: For the storm surge, the city is schematized as a series of layers, which are either a line of defense (with barriers or flood defense structures) or a protected area (where people can live). The flood runs through the city in sequence from the outside water towards inland. If it encounters a line of defense, the probability of failure is calculated and the amount of overtopping/overflow into the protected area behind the barrier. For the current FLORES model, these protected areas consist of drainage basins. This is mostly explained in the next sentences. The paragraph has been adjusted to make this clearer.

Comment 14: Example of more details needed: the manuscript talks about the ´ “probability of failure being taken into account”. But how is this done? What curves etc.?

Response 14: The probability of failure is taken into account through fragility curves. The fragility curves used in the current version are schematized as cumulative normal distributions, based on the expected height of failure and estimated uncertainty bounds (which differ between soil-based and concrete structures). In future versions, we would like to include fragility curves based on actual failure mechanisms, but this is not included yet. More clarification is added to the manuscript. The fragility curves are explained in more detail in 'van Berchum et al. (2018)'.

Comment 15 (Line 134-135): “Maintenance cost is not taken into account, but can be included as a ´ fraction of the construction cost.” This confused me. Here it first seems like the framework does not take it into account, but the second half of the sentence indicates that it is taken into account.

Response 15: It is not included in the current research, as it was not part of the initial requirements that led to this research. This sentence was structured like this to indicate that if a future research would require maintenance cost, this could easily be included. However, we understand the confusion, as this is not a 'future outlook'-section. the sentence has been adjusted in the paper.

Comment 16 (Line 138-139): “using the definition of risk as expressed by ´ Kaplan and Garrick (1981).” Please state what this definition is, rather than expecting the reader to go and look up the definition.

Response 16: The definition is added to the paper.

Comment 17 (Line 139-140): “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” Indeed, this is an important aspect: explain here how this is done in a compound sense (i.e. the different kinds of hazards need to be both varied and somehow combined).

Response 17: This paragraph explains the idea of the risk profile, as we thought it would be too complicated to explain the definition of risk, the risk profile and the numerical modelling solution for compound flooding in one paragraph. The problem of modeling compound flooding is therefore explained in a later paragraph (on which your next remark is also based). This paragraph can be a bit more precise and was badly structured, this has been adjusted.

Comment 18: It is stated that ´ "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." More detail of this method is needed. It is good that the risk calculation can be adjusted based on the correlation, but please explain how this is done. What method is used?

Response 18: The model simulates a number of situations (currently 25 different), which means that for every strategy, we look at 25 different combinations of storm surge and rainfall. Afterwards, the model calculates the probability of each situation, taking the correlation into account. For example, when storm surge and rainfall are fully correlated or independent, the model will still look at the same 25 different combinations (5-year storm surge and 10-year rainfall, etc.). However, their probability will change based on the correlation. When all the impacts and probabilities are calculated, the model integrates the risk profile using a simpson numerical integration. This is indeed not directly clear from the paper; more explanation has been added.

Comment 19 (Page 6): Section 2.1.3 states that there is a flood ´ risk reduction strategy screening component. However, I miss an explanation of how it works. What strategies are included that the user can choose from? What methods are used to implement them? How are they parameterized?

Response 19: This section was severely shortened in order to limit the length of the paper. So, we will limit the explanation of the toolkit to adding a few examples of analyses that we have used so far. What could be mentioned more explicitly is that the FLORES model runs many randomly chosen combinations of flood risk reduction measures (doesn't have to be random, but we have used that every time so far), which are used by the EMA toolkit to run the analyses. The goal is to use as many strategies as necessary to cover the entire design space of different combinations of measures and measure elevations, if applicable. This has been added to the paper.

Comment 20 (Page 6/7): Section 2.2 is also ´ rather vague. It is stated that the tool should work on limited data, but I would like to see a description of what the minimum data required are, for example in the form of a table.

Response 20: We've restructured section 2.2. It now includes a table with the minimum requirements for the FLORES model. The model is vague on this part because it will work with very minimal data (apart from the DEM), to the point where a total lack of data on exposure, or measures can be filled by having qualitative assessments by local authorities (i.e. pointing areas on a map where urban and industrial areas are). This will change the output of the model (e.g. from damage estimates in currency to an abstract score) and will of course influence the accuracy of the model, which should be taken into account.

Comment 21 (Line 194): "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." It seems like there is a missing word in this sentence?

Response 21: Correct, the sentence was strange like this, it has been adjusted in the manuscript.

Comment 22: Several ´ locations: use "number of people" instead of "amount of people"

Response 22: The manuscript has been checked and adjusted for any wrong use of number of/amount of.

Comment 23 (Page 8/9): Section 3.2.2 "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." The methods need explaining. What is this "first analysis" – how was it carried out?

Response 23: This is indeed formulated a bit vague. ERA-Interim is a dataset, which among other includes rainfall data. This was needed, because the data we used for the model had only little information on the rainfall events themselves. With the more complete rainfall dataset, we compared rainfall events and storm surge events to find any correlation. This was complicated due to the lack of clear storm surge data, but the results showed that at least for the area of Beira, almost no correlation could be found. This has been clarified in the manuscript.

Comment 24 (Page 9): In Table 2, the maximum ´ surge level is stated, which as far as I can include also includes tide. Usually, the surge level is only the surge component (i.e. without tide). Why not refer to something like still water level? (i.e. average water surface elevation at any instant, excluding local variation due to waves and wave set-up, but including the effects of tides, storm surges and long periods"?

Response 24: We understand that this can be confusing. As the storm surge is currently the only changing part of the equation (of finding the maximum water level during a storm surge in this case), the table is adjusted to show the maximum surge level without including the mean sea level and the effect of the tide.

Comment 25: This is a semantics question, but what is meant by "improve ´ the flood resistance of Beira". In what sense is the word "resistance" used?

Response 25: The word 'resistance' was used instead of flood protection in order to include non-protective measures, like emergency measures. As 'flood resistance' might be confusing, this has been changed into 'flood risk management'.

Comment 26 (Page 9): In ´ section 3.2.3, a "few examples" of measures in Beira are stated. But as a reader I want to read and understand the actual ones that are used in the model. What combinations? How are they schematized etc.?

Response 26: The model creates 500 strategies, consisting of random combinations of flood risk reduction measures. For structural measures, also a random crest elevation will be chosen. This has been added in the paper for clarification.

Comment 27 (Page 9): Similar to the previous comment, for the reader it would be valuable to know the values used for the maximum damages, the forms of the vulnerability curves, etc. There is a reference to the report of Huizinga et al., which is a good starting point. However, the data from Huizinga would still need to be transformed to the current case study – I would like to see this kind of information, for example in a Supplementary Information section.

Response 27: The FLORES model combines the structural exposure (how many buildings of a particular land use type are present in each area) with the information from Huizinga et al. (2017), which has data on maximum damage per structure/m2 and a damage curve, which is basically a flood depth/damage curve. For this case study, we use the max-damage figure for Mozambique (updated to 2019 dollars) and the damage curves available for Africa (Residential, Industrial and Agriculture). As the source for the structural exposure uses more land use types, some needed to be grouped (like small-residential and large-residential). Exposure data are property of the World Bank Group, who wish not to share this online publicly, outside of their own publications. I can share these with you upon request. To limit the length of the manuscript, this has been explained in text, rather than adding a Supplementary Information section, we hope you find this sufficient.

Comment 28 (Page 10): “little data ´ is available”. Change to “few data are available” (also check other instances of data, should use plural)

Response 28: This has been checked throughout the manuscript.

Comment 29 (Page 10): In section 3.3 ´ it is stated that there is very limited validation. Whilst this is understandable, please provide the results of the benchmarking exercise that you did carry out. Where are there differences? What are the possible causes?

Response 29: Benchmark tests were undertaken on different levels. First, the model-level: does the city flood if we have no incoming flood? What floods if we have a continuous, enormous flood incoming? On the same level, we also looked at water levels of individual drainage basins, which could show strange jumps of water level in earlier versions. The goal is to develop trust that the dynamics are working as they should. Next is the level where we try to find out whether the local situation in Beira is represented sufficiently accurate. Besides the lack of data to compare, this is complicated further by the large changes in the local hydrology (new drainage system, new urban storage facilities, new groyne) over the past decades. Here, a few benchmark tests were done to see whether the right parts of the city flooded at the right storm intensity, based on talks with locals and local authorities. e.g. some parts of the city were known to flood roughly every 2 years; storm surge levels corresponding to the 5-year storm surge were expected to damage mostly the southeastern part of the city. The results were comparable to what's in the manuscript: the flood extent was as expected, although some estimates were underestimating the flood depth in the lowest parts.

Comment 30 (Line 236): Capital letter “between”

Response 30: This has been adjusted.

Comment 31 (Page 10/11): The results in section 3.4.1 ´ are too brief. For example, I would like to see a table with the impacts for the different combinations. Later on, I noticed that this is what is shown in Figure 7, but that is in a section called “Screening of flood risk reduction strategies” – suggest to move that here.

Response 31: Yes, we agree that the current risk profile would fit better in the 'current risk profile' chapter. This has been changed.

Comment 32 (Page 11): “As a result, damages due to compound flooding are more than the ´ sum of damages of the individual flood hazards.” This is an interesting statement, but where do I see this in the results? I would like to see a table with the results for the different ones individually and together? Moreover, the reader does not actually see the EAD results, which should be added.

Response 32: This statement was mostly meant for the 10-year rainfall and 10-year storm surge events, which were shown in figure 6. Here, areas were flooding that didn't flood in either the 10-year storm surge or the 10-year rainfall case. This is also reflected in the risk profile in figure 7. Also shown in figure 7 is that this does not hold true for all cases.

When looking at the 100-year storm surge and the 100-year rainfall event, this both floods most of the city, making it practically impossible for the compound event to do more damage than both events. This consideration is added to the statement in the manuscript.

Comment 33 (Line 242-243): "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". Similar comment as above: where do I actually see this in the results.

Response 33: This statement was based on historical data from local government. This is however also shown in the model results, which is added to the manuscript.

Comment 34 (Page 11): Section 3.4.2: what is a zero-year event?

Response 34: For the model, a zero-year event is no event, so 100-year rainfall and 0-year storm surge, means that there is only rainfall. A clarifying statement has been added.

Comment 35 (Line 251): "there performance". ´ Change to "their performance"

Response 35: This has been adjusted.

Comment 36 (Page 11): "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)." Indeed, but as mentioned earlier I would like to see these EAD results, and also some kind of summary table of the different measures/strategies and how much EAD they reduce. In the current state, I don't actually have a clear understanding of what all the measures are that are implemented.

Response 36: We have added the EAD for the standard situation, depicted in Figure 7. However, we try to focus on the relative impact of strategies and measures, as using absolute EAD values can be very confusing and can give a false idea on the objectives of the model. The FLORES model (with the current level of data available in Beira) cannot be used for detailed economic cost/benefit analysis, but for support decision-makers on getting a grasp on the consequences of their choices. However, we noticed that when we included many EAD-results, discussions often went in the other direction. Besides, it was often confusing, because these figures also change depending on the future scenario (climate scenario in this case). So it was very hard to compare between different scenarios, because the absolute risk reduction was always higher in more extreme cases, even though a particular combination of measures could be relatively less efficient.
EAD results per measure cannot be visualized, as these greatly depend on the rest of the chosen strategy. The Feature Scoring analysis is built specifically for this purpose and shows which measures are most effective to what output, although it is not possible to quantify this in terms of EAD. EAD results of strategies will result in a very long list (500 strategies have been evaluated) and are visualized in terms of relative risk reduction in Figure 8. We have chosen this style as this gives significantly more useful and comparable information than the absolute values.

Comment 37 (Page 12): Not until line255 does the reader learn that the strategies are based ´ on 500 randomly drawn measures. This should be in the Methods, including which measures they are drawn from and how this works.

Response 37: This has been added to the methods section.

Comment 38 (Page 12): Figure 9 and related text talks ´ about sensitivity using “feature scoring”. It is good that this is added, but again I miss this in the methods. How is this done? Are the things listed on the left the measures from which strategy combinations are drawn?

Response 38: Feature scoring is part of the EMA-workbench, which is explained in section 2.1.3 on screening. A clarifying statement is added to the methodology to link the feature scoring analysis to the EMA-workbench. The list on the left side are all things are input as variable and can influence the screening output. Most of them are indeed the measures, but also uncertainties of the scenarios are shown, like the climate scenario. The figure caption has been adjusted to mention the measures more clearly.

Comment 39 (Page 13): There are some more statements ´ where I cannot make out where the results are actually shown. For example, “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.”. Please show these findings and point the reader to them – more generally, please refer more clearly to the figures etc. in the interpretation.

Response 39: This particular statement was based on several simulations that are not shown in the manuscript and simulations shown in Figure 6, to which a reference is added in the manuscript. I didn't add any other simulation flood maps, due to the restriction in paper length. The rest of the results section has been checked for findings that needs extra reference.

Comment 40 (Page 13): Towards the end ´ of the results (lines 275) a new analysis is then introduced. Again, this should be described in the Methods section. It is not clear to me at present how it works. For example, Table 3 has “design choices” in the heading. But what do you mean? What is a design choice? It has not been mentioned earlier. Does this mean an individual measures? And the strategy is a combination of measures?

Response 40: The PRIM-analysis, which is a type of scenario discovery algorithm, is indeed relatively complicated. In this paper, we have chosen not to explain how the algorithm itself works (this is explained in more detail in the references), but to explain how we use it for this model. This choice is made because explaining the algorithm itself will cost at least another page. We understand that some of the terminology might be confusing, adjustments are made to the paper text to align this better with the rest. Design choices was used, because it is more than just a choice of measure. A choice to use a measure can be design choice, but also the choice to not use a measure, or to have a measure of a particular elevation (not specifying the exact measure). A design choice is therefore much broader than just a chosen measure.

So in short (1) the user sets a 'goal', which are demands for the outcome, like a minimum risk reduction or a maximum budget. (2) the algorithm starts by finding all 'strategies of interest', which are all strategies that comply with the goals. (3) the algorithm makes design choices and throws away all strategies that do not have this design choice. The aim is to get rid of all useless strategies and focus on these strategies of interest. Of course, this is not a black-and-white thing, so by making these choices, also strategies of interest get thrown away and the resulting design space still has noninteresting strategies in it. That is why also the final design space is shown in table 3. This shows how many of the 500 strategies actually have the design choices made along the way, and how many of those are 'strategies of interest'. The algorithm always focusses on the largest concentration of interesting strategies. It is possible to do the whole analysis again, excluding the strategies you found the first time, just to learn what type of interesting strategies we threw out along the way. The explanation it the paper has been adjusted to make this clearer.

Revised manuscript with tracked changes

Below the new manuscript is shown with tracked changes. All comments by the referees have been considered for this version. Layout may differ from the version without tracked changes because the manuscript is written in the NHESS template, with other margins.

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

Erik C. van Berchum[1], Mathijs van Ledden[2], Jos S. Timmermans[3], Jan H. Kwakkel[3], Sebastiaan N. Jonkman[1]

[1]Department of Hydraulic Engineering, Delft University of Technology, Delft, 2600GA, Netherlands
[2] Global Facility for Disaster Reduction and Recovery, Washington, DC, 20433, United States
[3] Department of Multi-Actor Systems, Delft University of Technology, Delft, 2600GA, Netherlands

Correspondence to: Erik van Berchum (E.C.vanBerchum@tudelft.nl)

Abstract. Coastal cities combine intensive socio-economic ~~activity~~activities 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~~designing strategies, engineers rely on computationally demanding flood simulation models~~ and~~, but they can only compare a ~~few~~limited number of 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~~provides useful risk information in this early ~~on in the planning process.~~conceptual phase. FLORES rapidly performs numerous~~ quick~~ simulations and compares the impact of many storms, strategies, and future scenarios. This article presents ~~the screening model~~FLORES 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~~ Currently, 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~~(Fraser et al., 2016). Both social-economic activity and extreme weather events are increasing rapidly, and even though cities in many cases are becoming less vulnerable due to effective flood risk management, flood risk is growing in many flood-prone regions around the world (Doocy et al., 2013;Mechler and Bouwer, 2015;Salman and Li, 2018). The main processes leading to urban flooding are extreme rainfall (pluvial flooding), high river discharge (fluvial flooding), and storm surges (coastal flooding). For coastal cities, these flood hazards interact and can be correlated. Individual meteorological events, like hurricanes, can simultaneously cause extreme rainfall and high storm surges~~ simultaneously.~~. These compound events further ~~increases~~increase both the vulnerability and the complexity of flood risk management in coastal cities. Research on compound flooding is growing, as it plays an important role in flood risk management of cities along coasts and rivers, and the occurrence of compound floods is growing significantly (Wahl et al., 2015;Zscheischler et al., 2018;Paprotny et al., 2018).

The impact of flooding can be reduced through measures that improve the city's hydraulic ability to deal with the flood hazard – the probability of a flood event -, or reduce the damage caused by a flood event. Managing flood risk is often the role of local governments. The planning process can be supported through flood risk analysis which informs decision-makers on the most significant risks and how to best manage them (Sayers et al., 2013). The type and detail of risk information required varies throughout the phases of the planning process. ~~amount of damage caused by a particular flood event.~~This is, however, not always recognized in the tools that are used to generate the required information.

~~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~~supported by computer models. The first models, limited by computational power and available input data, focused on analytical optimization in order to explain and compare concepts (Van Dantzig, 1956;USACE, 1996;Vrijling et al., 1998). -These models mostly focused on the economic impact of floods only. First because this was needed most, and second, because multi-objective optimization quickly complicates ~~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~~This does, however, limit the ability to model a ~~less~~city's layout sufficiently 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~~The use of high-resolution flood simulation software (e.g. Delft3D, SWMM, MIKE) ~~has become~~is standard practice in large flood risk management design projects. These ~~models~~simulations build ~~on increased~~in-depth knowledge of fundamental hydraulic processes and the use of Geographic Information System (GIS)-based tools (Kovar and Nachtnebel, 1993), made possible by the growth in computational power. ~~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 recent years, several models have also been developed, specifically aiming to simulate compound flooding (Pasquier et al., 2019;Gori et al., 2020). These models provide accurate simulation for specific coastal cities. These simulations, however, are complex, labor-intensive to develop, time consuming to run, and expensive. In addition, their high accuracy demands lots of input data and computational power. This type of model is therefore not well suited for analyses where many simulations are required, such as uncertainty analysis, investment strategy analysis or the comparison of many flood risk reduction measures (Haasnoot et al., 2014).

The gap between conceptual, analytical models and high-resolution, spatial flood simulation models leaves room for models that take local spatial circumstances into account, but still can evaluate many scenarios and many flood risk management options. In recent years, several of these models have been developed, mostly for particular case studies ~~(Gouldby et al., 2008;Aerts et al., 2014;Shen et al., 2016).~~ (Jamali et al., 2018;de Ruig et al., 2019;Shen et al., 2016). These models run relatively quickly because of their simplified schematization of the project area and ~~the ~~flood hazard~~, which~~. But this restricts their ability to be applied to other areas. ~~Therefore, this~~This paper describes a fast, widely-applicable flood risk screening model~~, able to adapt~~. This model can be adapted to local circumstances~~,~~. It can be used to investigate multiple flood hazards, many different scenarios, and many possible flood risk management options.

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~~for exploring and ~~evaluate~~evaluating 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~~generalizes a model originally developed to study coastal flooding in the Houston-Galveston Bay area (van Berchum et al., 2018b). ~~Here~~In this paper, 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~~generalized such that more ~~diverse ~~types of urban ~~layout~~layouts can ~~be modelled ~~systematically be modelled. In addition, ~~it allows for the simulation of~~FLORES can simulate multiple interacting flood hazards, in this case coastal and pluvial flooding.

~~These improvements strengthen the~~The main characteristics ~~upon which the~~of FLORES ~~model is based; the model~~are to (1) ~~makes~~make risk-based assessments of flood risk reduction strategies, (2) ~~minimizes~~minimize computational load, (3) ~~considers~~enable considering structural and non-structural measures, (4) ~~compares~~compare flood risk reduction strategies based on multiple performance metrics, and (5) ~~is~~be applicable to a wide range of urban layouts~~ and situations. The model~~. FLORES is demonstrated ~~through~~using 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~~can assess and compare many different strategies for reducing flood risk in coastal cities. At the heart of the model is a flood simulation model, ~~that~~which calculates the extent and resulting impact (i.e. economic damage, ~~amount~~number of people affected) of a flood event, represented by a storm surge and rainfall event, each with a specific return period (Figure 1). The use of FLORES in the ~~development~~design of flood risk management system for a coastal city, requires many simulations that evaluate a range of hazards and risk reduction strategies, under many scenarios on multiple impacts. Simulating the resulting ~~amount~~number

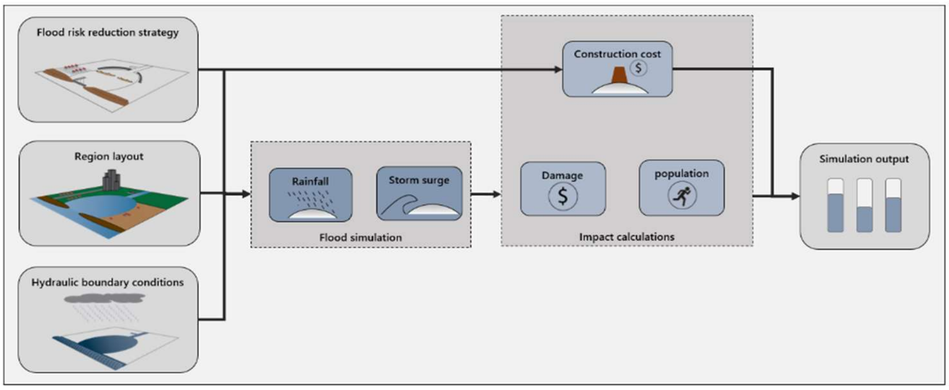

Figure 1 – Schematization of a flood event simulation

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

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

Similar schematizations have been used before, for example by Gouldby et al. (2008) and Shen et al. (2016). Throughout the simulated storm, the hydraulic response is calculated by viewing the hydrological balance for each of basins for each time step:

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

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}).

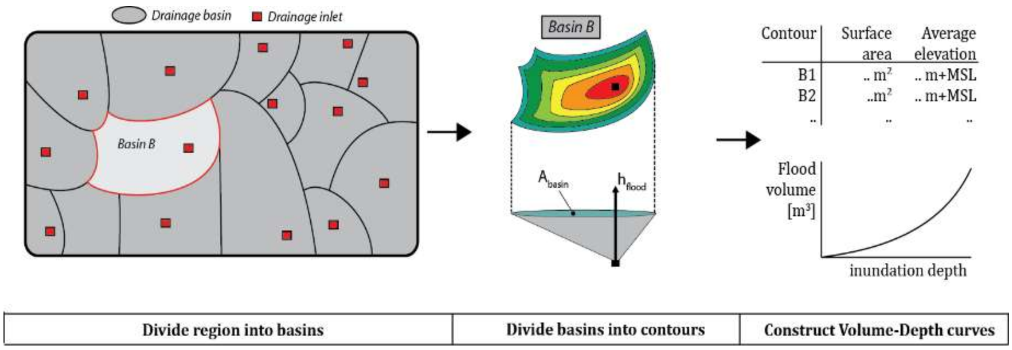

Figure 2 – Schematization of the city from GIS data into input data for the FLORES model. Based on the DEM, the region is divided into basins and contours, leading to a Volume-Depth Curve of every basin. This schematization does not include coastal boundaries yet.

The difference between inflow and outflow is stored in the basin itself (Q_{rt}), starting with retention. When the retention capacity is fully utilized, water floods the streets, starting at the lowest part (often the drainage point) of the basin.

The schematization of the storm surge routing is based on van Berchum et al. (2018b)~~. The~~: the borders between land and water are schematized as line elements (lines of defense) 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~~a barrier~~, which acts~~. This counts as inflow for the drainage ~~basin on the inside of~~basins behind the barrier. By dividing the area into layers (e.g. coastal zone, bay side, inner city), the model can simulate flood protection based on multiple lines of defense. For structural flood defenses, the probability of failure is also taken into account through fragility curves, as levee failure has a huge effect on the flood impact. The fragility curves are currently schematized as cumulative normal distributions. The simulation considers all possible scenarios (which structures fail) by running the entire hydraulic flow model for all scenarios, which leads to different combinations of outcomes (flood structural scenarios) and their resulting inundation depths.

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

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

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

The third performance metric is the expected cost of new constructions and repair. This depends on the choice of measure and the scenario (which measures fail and require repair). Construction cost depends on the length and height of a structural measure. The length of a measure cannot be changed, as a measure is placed on a predefined border between land and water. Besides these constant costs, some costs depend on the chosen structure height, such as material and manpower. When a structure fails, it is assumed that it will be repaired up to its ~~old~~original value. Maintenance cost ~~is~~currently 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~~scenario. Therefore, multiple ~~simulations~~scenarios are combined to build a more representative risk profile~~, using the definition of~~. Here, risk is defined 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.~~ a combination of scenarios that can affect you, each of which has a probability of occurrence and a potential consequence (Kaplan and

Garrick, 1981). When modelling, it is impossible to look at all possible scenarios. Therefore, ~~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~~ profile. For each individual scenario, the impact is weighted by its probability, which depends on the return period of the incoming flood ~~risk reduction strategies,~~hazard (and the correlation between hazards if there are ~~the expected annual damage (dollar/year), expected annual affected population (people/year), and construction and repair costs.~~multiple). By varying the intensity and return period of the incoming hazards, the risk profile shows how the city and the implemented measures perform under different circumstances.

The development of a risk profile is complicated by compound flooding, where both extreme rainfall and coastal storm surge are threatening the city. This influences the performance of some measures~~, and should therefore not be ignored.~~. For example, the efficiency of a drainage system, which drains ~~on~~to outside water, can decrease when outside water levels are raised due to storm surge. Several different combinations are simulated, resulting in a risk profile that depends on two variables – the probability of occurrence of the rainfall and storm surge. For each flood hazard, 5 different storm intensities are used, which means that 25 simulations are needed for one risk calculation. An example, based on the case study, can be seen in figure 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~~these data ~~is~~are not or only sparsely available. In FLORES, the ~~risk calculation~~same flood hazard combinations (e.g. a 10 year storm surge and a 100 year rainfall event) are simulated, regardless of correlation. However, each combination will have a different probability, also depending on the correlation. This correlation value can be adjusted ~~based on correlation.~~ in the model.

2.1.3 Screening flood risk reduction strategies

FLORES can quickly asses how a flood risk reduction strategy affects the risk profile. Subsequently, it is also possible to look at many different strategies, covering the entire design space of different combinations of measures (and elevation of measures, if applicable) under different scenarios. This leads to a huge amount of data available for analysis, which will be processed using the Exploratory Modelling and Analysis (EMA) workbench (Kwakkel, 2017a)~~. This python~~(Kwakkel, 2017a). This Python-based toolset runs common analysis- and optimization algorithms to visualize and support decision making and planning~~.~~ (e.g. Feature Scoring, Scenario Discovery). It has been used in several research fields in the past (Rostampour et al., 2019;Ciullo et al., 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~~FLORES should run ~~based on~~with only minimal ~~amount of local~~need for detailed local data. Therefore, open-source ~~dataset~~datasets can be used for most of the required data, such as elevation, population density, damage curves, hazard data, and future scenarios. However, for some types of data, local information is necessary. For example, information on the local hydrology (e.g. drainage system, sewerage), considered measures, and the structural exposure. If for these inputs, no data are available, they can also be based on qualitative assessment, in cooperation with local authorities or organisations. However, this does affect the results and their accuracy, which should be taken into account. A list of required input and their minimum requirements can be found in Table 1.

Table 1 - minimum requirements for FLORES data sources.

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

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

3. Case study in Beira, Mozambique

3.1 Background

To demonstrate the capabilities of FLORES, we use it to analyze flood risk in the coastal city of Beira, Mozambique. ~~This coastal city~~ Beira is one of the ~~biggest in~~largest cities of Mozambique with more than 600,000 inhabitants. It is also home to an important ~~harbor~~port, connecting an extensive hinterland – which includes Zimbabwe – with the Indian Ocean. In the past, Beira has been subjected to large-scale flood events, resulting from both coastal storm surges and extreme rainfall events. Most notably, the city was in the 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~~informal settlements.

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~~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 2~~Table 1~~. Regarding the elevation data, this LiDAR DEM ~~data~~dataset has been developed as a part of an earlier project financed by the World Bank, aiming to enhance local research. The DEM was calibrated with locally used elevation units (meter above Chart Datum [m+CD], which is equal to the lowest astronomical tide). For damage estimates, the structural exposure is combined with damage curves. Huizinga et al. (2017) provides maximum damage estimates for all countries and flood depth-damage curves per continent for different land use types. As the number of land use types with a damage curve in Africa is limited to three (Residential, Industrial, Agricultural), the structural exposure will be divided into these three groups as well.

Table 2~~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 [-]

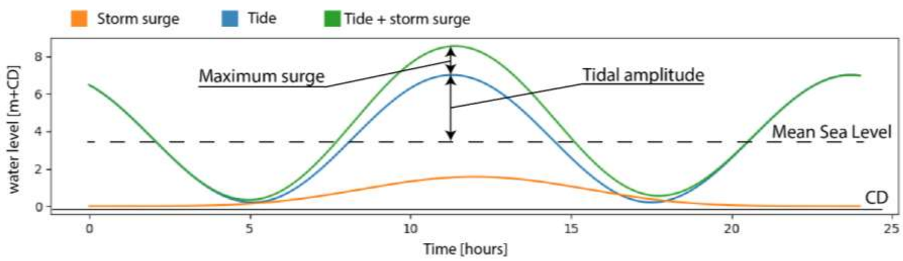

Figure 3 - Example time series of coastal storm surge event. (orange) run up due to storm surge, (Blue) elevation of tide, and (green) total elevation of tide plus surge

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~~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 3~~Table 2~~. Two climate change scenarios are taken into account, which will affect the boundary conditions by increasing the surge level and rain intensity.

Table 32 - hydraulic boundary conditions for FloresFLORES application in Beira. Note that the maximum surge level is mainly attributed tocalculated above the still water level. Other factors like the tide (3.4 meter amplitude) and the mean sea level (3.6 m+CD).) should also be taken into account. The FloresFLORES 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	70.2	7	4	3
5	70.3	9	6	4
10	70.5	11	7	5
50	81.6	14	9	7
100	92.2	16	10	8

3.2.3 Flood risk reduction measures

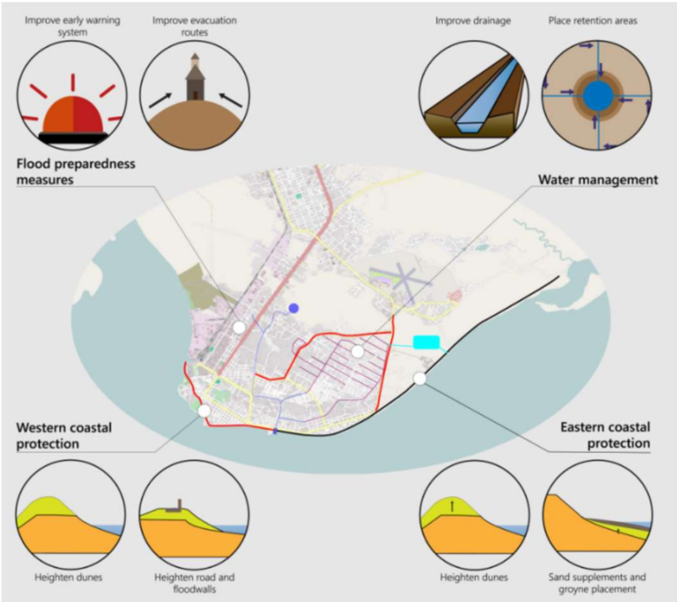

Figure 4 - Map of Beira, Mozambique. Denoted are a few examples of flood risk reduction measures. Background image © OpenStreetMap contributors 2018. Distributed under a Creative Commons BY-SA License

We consider various measures to improve thefor improving flood resistance of risk management in Beira, based on including measures considered by the local government, as well as measures –suggested in meetings withby local stakeholders, as well asand measures explored in scoping studies (Deltares et al., 2013;Letitre et al., 2018). The set of measures showcase the different types of measures that can be considered with FLORES, including structural flood 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. A complete list of all measures used in this case study can be found in the appendix.

3.3 Model ~~validation~~evaluation

~~Little~~Limited data ~~is available to validate~~for evaluating the accuracy of the flood simulations is available. Cyclone Idai provided some insight into one situation, with verifiable data and known hydraulic conditions. During other extreme events, however, no detailed measurements were taken. ~~Moreover, only~~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~~FLORES predicts ~~higher~~lower flood levels in lower areas of the city, especially in areas with steep slopes. Other than this comparison, benchmark tests were used to test the accuracy of the flood simulation. For example, storm surge events up to the 5-year storm surge hardly affect the city, and larger storm surges affect areas known for their relatively weak flood defenses and storage capacity (south-eastern part of Beira).

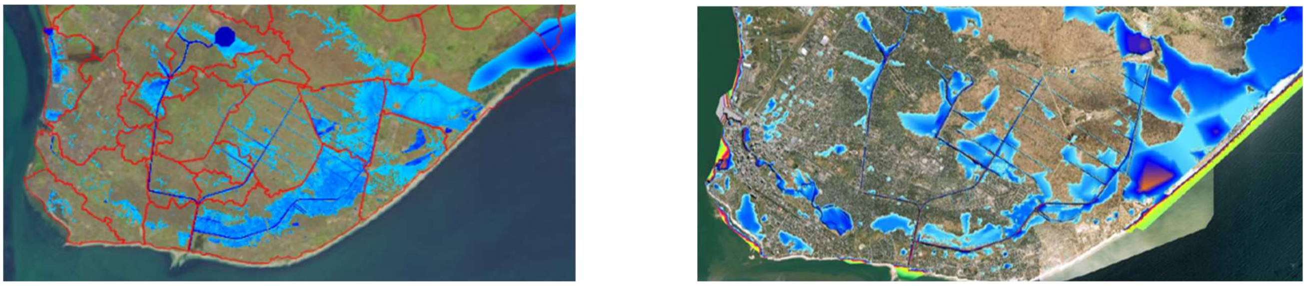

Figure 5 - flood extent resulting from a 10 year rainfall event for FlORES (left) and an ANUGA simulation, which was part of the Rio Chiveve feasibility study. Background image: Sentinel-2 (© ESA).

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

3.4.1 Current risk profile

Looking closer to the hydrological situation in Beira, a number of phenomena stand out. First, the city has a large lower-lying area, which does not have a natural connection to open water. Not surprisingly, the most common cause of flooding is extreme rainfall, as also shown in historical reports and flood simulations. The lower parts of the city experience flooding on an almost yearly basis, although this has decreased due to the new drainage system, see Figure 6~~Figure 6~~ (left). For more severe rainfall events, the entire city is affected, see Figure 6~~Figure 6~~ (middle). ~~between~~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~~Figure 6~~ (right). Here,

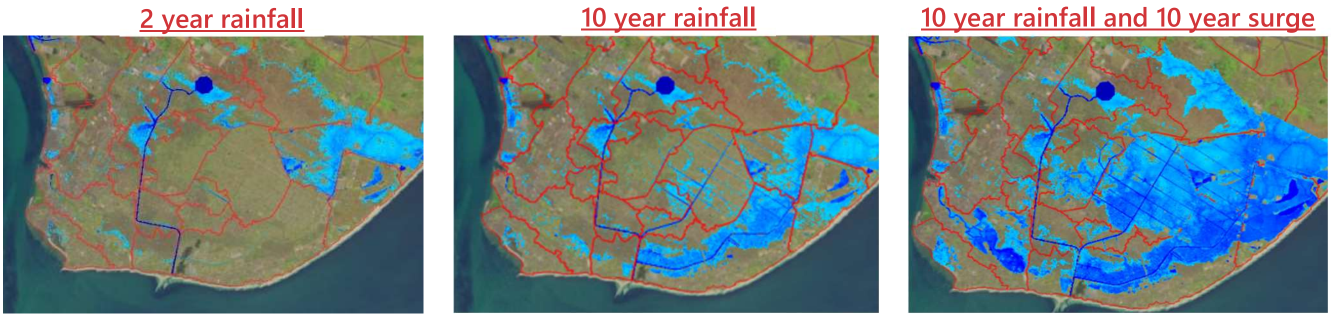

Figure 6 – flood map for a 2 year rainfall event (left), 10 year rainfall event (middle), and a 10 year rainfall event plus a 10 year coastal surge event (right). Background image: Sentinel-2 (© ESA).

even areas that are not directly affected by the storm surge ~~flood~~are flooded due to the ~~lower~~reduced effectiveness of the drainage system. As a result, damages due to compound flooding are more than the sum of damages of the individual flood hazards. Please note that this does not have to hold true for all cases. More extreme storm surge or rainfall events (100-year return period) can damage most of the city, and an added hazard leads to little added damage.

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

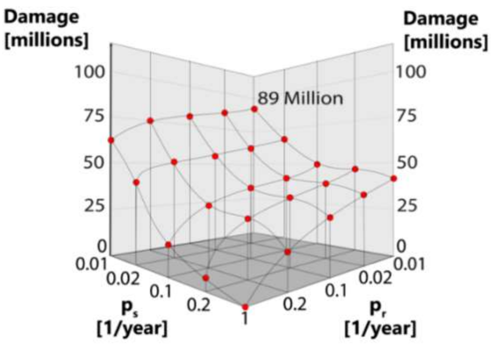

Figure 7 – Risk profile of the current situation in Beira, Mozambique. Shown is the expected damage of a compound flood event with a probability of occurrence of the storm surge (p_s) and the rainfall (p_r).

3.4.2 Screening of flood risk reduction strategies

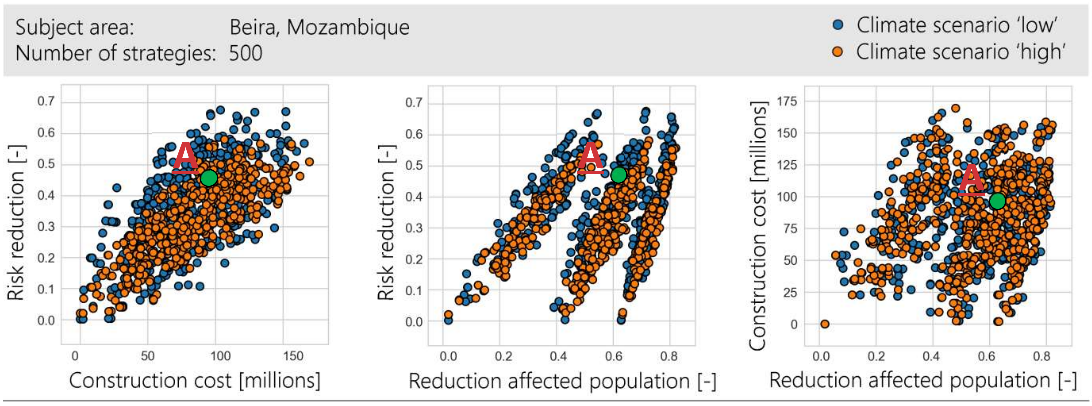

Figure 8 – Pair wise plotting graphs for the Beira case study. Each dot represents one flood risk reduction strategy. Each strategy can be assessed by their risk reduction, reduction of affected population, and cost of construction. Here, those outcomes are plotted against each other. Different colors 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.

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

Figure 8~~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.

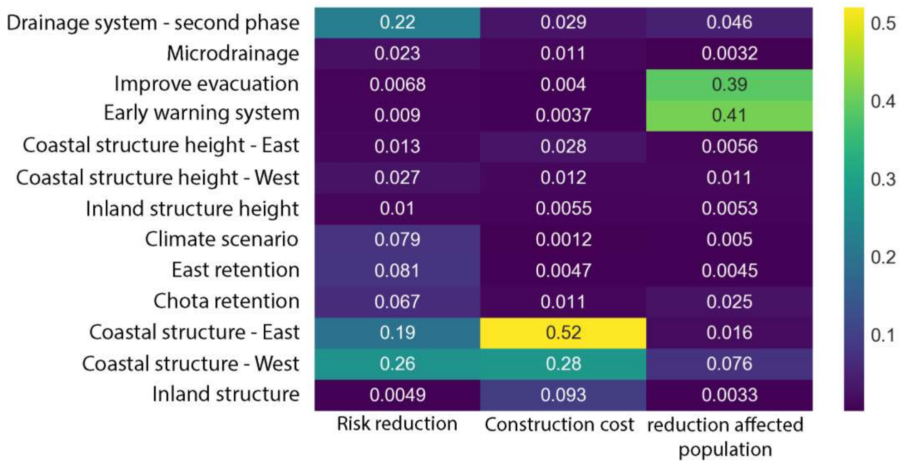

Figure 9 – Feature scoring analysis for the Beira case study. It shows the relative importance of the choice of measures and uncertainties (listed on the left) for the outcomes (below). Higher numbers indicate higher importance.

Figure 9~~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~~ . On the left, all potential measures are listed, as well as the future climate change scenario. The numbers indicate how much the outcome variables (below the table) depend on the choice on the left. A higher number indicates a higher importance, where 0 means that the measure has no influence and 1 indicates that the output is fully dependent on the choice for that input. The results ~~underline~~underscore the importance of both coastal measures and inland measures, in particular further improvement of the drainage system. Increasing retention areas are relatively less effective. Simulations show that retention areas are effective only for smaller pluvial events, but have insufficient capacity when a storm surge overpowers the coastal defenses and reduces the effectiveness of the drainage system~~.~~. (see Figure 6). This effect is increased because the high outside water level during storm surge events prevents the drainage system from functioning. This is an example of how compound flood events lead to high damages by affecting hydrological processes in ways that are of less importance when considering individual hazards.

~~Finally, FLORES identifies promising combinations of measures using a PRIM analysis~~ (Kwakkel, 2017b;van Berchum et al., 2018a)~~. 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.~~

Finally, we identify promising combinations of options using Scenario Discovery (Bryant and Lempert, 2010;Kwakkel and Jaxa-Rozen, 2016), using the Patient Rule Induction Algorithm (PRIM) (Friedman and Fisher, 1999) . Specifically, we use scenario discovery to identify which combinations of design choices are most effective when pursuing a predetermined set of goals. A design choice can be the choice to use (or not to use) a particular measure, or a minimum/maximum build elevation. The aim is to find a combination of design choices that will maximize the chance of reaching a predetermined set of goals. PRIM calculates which are most effective and removes strategies out of the comparison that do not include this option. Finally, a number of strategies is left, of which many comply with the goals set in advance, see Table 4.

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

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

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

4. Discussion

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

5. Conclusion

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

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

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

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

Appendix A: Model input

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

Name	**Type**	**Fixed cost**	**Variable cost**	**Remarks**
Heighten dunes east	Structural	3 million $/km	1.5 million $/km/m	Rural area
Sand supplements east	Structural	2 million $/km	0.5 million $/km/m	Rural 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 $		

Acknowledgements. We would like to thank the World Bank in Washington, D.C. for hosting us. This research was financed by the European Union (EU)-funded Africa Disaster Risk Financing (ADRF) Initiative, managed by the Global Facility for Disaster Reduction and Recovery (GFDRR). The sole responsibility of this publication lies with the author. The European Union is not responsible for any use that may be made of the information contained therein.

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.

Competing Interests. The authors declare that they have no conflict of interest.

References

Adikari, Y., and Yoshitani, J.: Global trends in water-related disasters: an insight for policymakers, World Water Assessment Programme Side Publication Series, Insights. The United Nations, UNESCO. International Centre for Water Hazard and Risk Management (ICHARM), 2009.

Aerts, J. C., Botzen, W. W., Emanuel, K., Lin, N., de Moel, H., and Michel-Kerjan, E. O.: Evaluating flood resilience strategies for coastal megacities, Science, 344, 473-475, 2014.

Arcadis: Integrated coastal zone management programme for Beira, Mozambique, Arnhem, the Netherlands, 1999.

Breiman, L.: Random forests, Machine learning, 45, 5-32, 2001.

Bryant, B. P., and Lempert, R. J.: Thinking inside the box: a participatory, computer-assisted approach to scenario discovery, Technological Forecasting and Social Change, 77, 34-49, 2010.

Butler, D., and Davies, J.: Urban drainage, Crc Press, 2003.

Cardona, O., Bernal, G., Ordaz, M., Salgado, M., Singh, S., Mora, M., and Villegas, C.: Update on the Probabilistic Modelling of Natural Risks at Global Level: Global Risk Model, GAR15,(CIMNE & INGENIAR) UNISDR, Geneva, 2014.

CES, and Lackner, I.: Adaptation to climate change in beira. rehabilitation, extension and operation of the urban storm water drainage system, Beira. (Technical report), Ministry of Public Works and Urban Settlement, Beira, Mozambique, 2013.

Ciullo, A., de Bruijn, K. M., Kwakkel, J. H., and Klijn, F.: Accounting for the uncertain effects of hydraulic interactions in optimising embankments heights: Proof of principle for the IJssel River, Journal of Flood Risk Management, e12532, 2019a.

Ciullo, A., de Bruijn, K. M., Kwakkel, J. H., and Klijn, F.: Accounting for the uncertain effects of hydraulic interactions in optimising embankments heights: Proof of principle for the IJssel River, Journal of Flood Risk Management, 12, e12532, 2019b.

Custer, R.: Hierarchical Modelling of Flood Risk for Engineering Decision Analysis, 2015.

de Ruig, L. T., Barnard, P. L., Botzen, W. W., Grifman, P., Hart, J. F., de Moel, H., Sadrpour, N., and Aerts, J. C.: An economic evaluation of adaptation pathways in coastal mega cities: An illustration for Los Angeles, Science of the Total Environment, 678, 647-659, 2019.

Dee, D. P., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., and Bauer, d. P.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quarterly Journal of the royal meteorological society, 137, 553-597, 2011.

Deltares, Witteveen+Bos, Wissing, Consulting, V. d. B., and Niras: Masterplan Beira Mozambique, Deltares, Delft, the Netherlands, 2013.

Doocy, S., Daniels, A., Murray, S., and Kirsch, T. D.: The human impact of floods: a historical review of events 1980-2009 and systematic literature review, PLoS currents, 5, 2013.

Dupuits, E., Schweckendiek, T., and Kok, M.: Economic optimization of coastal flood defense systems, Reliability Engineering & System Safety, 159, 143-152, 2017.

Eguchi, R. T., Huyck, C. K., Bevington, J. S., Eguchi, M. T., Esquivias, G., Huyck, M., Ghosh, S., Hu, Z., Chen, R. S., Levy, M., Pistolesi, L., Yetman, G., and Porter, K.: GFDRR Africal Disaster Risk Financing - Result Area 5. Exposure Development (Phase II). Final Report, GFDRR, World Bank Group (technical report), Washington, D.C., U.S.A., 2016.

Florczyk, A., Corbane, C., Ehrlich, D., Freire, S., Kemper, T., Maffenini, L., Melchiorri, M., Pesaresi, M., Politis, P., and Schiavina, M.: GHSL Data Package 2019, Luxembourg. EUR, 29788, 2019.

Fraser, S., Jongman, B., Balog, S., Simpson, A., Saito, K., and Himmelfarb, A.: The making of a riskier future: How our decisions are shaping future disaster risk, Global Facility for Disaster Reduction and Recovery, 2016.
Friedman, J. H., and Fisher, N. I.: Bump hunting in high-dimensional data, Statistics and Computing, 9, 123-143, 1999.
Gori, A., Lin, N., and Smith, J.: Assessing Compound Flooding From Landfalling Tropical Cyclones on the North Carolina Coast, Water Resources Research, 56, e2019WR026788, 2020.
Gouldby, B., Sayers, P., Mulet-Marti, J., Hassan, M., and Benwell, D.: A methodology for regional-scale flood risk assessment, Proceedings of the Institution of Civil Engineers-Water Management, 2008, 169-182,
Haasnoot, M., Van Deursen, W., Guillaume, J. H., Kwakkel, J. H., van Beek, E., and Middelkoop, H.: Fit for purpose? Building and evaluating a fast, integrated model for exploring water policy pathways, Environmental modelling & software, 60, 99-120, 2014.
Huizinga, J., de Moel, H., and Szewczyk, W.: Global flood depth-damage functions: Methodology and the database with guidelines, Joint Research Centre (Seville site), 2017.
IOM: Mozambique Cyclone Idai Response: Situation Report No.3 04-08 April 2019, International Organization for Migration, reliefweb.int, 2019.
IPCC: Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change, IPCC, 2014.
Jamali, B., Löwe, R., Bach, P. M., Urich, C., Arnbjerg-Nielsen, K., and Deletic, A.: A rapid urban flood inundation and damage assessment model, Journal of hydrology, 564, 1085-1098, 2018.
Jaxa-Rozen, M., and Kwakkel, J.: Tree-based ensemble methods for sensitivity analysis of environmental models: A performance comparison with Sobol and Morris techniques, Environmental Modelling & Software, 107, 245-266, 2018.
Kaplan, S., and Garrick, B. J.: On the quantitative definition of risk, Risk analysis, 1, 11-27, 1981.
Kind, J. M.: Economically efficient flood protection standards for the Netherlands, Journal of Flood Risk Management, 7, 103-117, 2014.
Kovar, K., and Nachtnebel, H. P.: Application of geographic information systems in hydrology and water resources management, International Association of Hydrological Sciences, 1993.
Kwakkel, J. H., and Jaxa-Rozen, M.: Improving scenario discovery for handling heterogeneous uncertainties and multinomial classified outcomes, Environmental Modelling & Software, 79, 311-321, 2016.
Kwakkel, J. H.: The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making, Environmental modelling & software, 96, 239-250, 2017a.
Letitre, P., Huthoff, F., Vroeg, H. d., and Berchum, E. v.: Scoping study at pre-feasibility level for Beira's long term coastal protection and flood preparedness, Netherlands Enterprise Agency (RVO), 2018.
Mechler, R., and Bouwer, L. M.: Understanding trends and projections of disaster losses and climate change: is vulnerability the missing link?, Climatic Change, 133, 23-35, 2015.
Paprotny, D., Vousdoukas, M. I., Morales-Nápoles, O., Jonkman, S. N., and Feyen, L.: Compound flood potential in Europe, Hydrology and Earth System Sciences Discussions, 1-34, 2018.
Pasquier, U., He, Y., Hooton, S., Goulden, M., and Hiscock, K. M.: An integrated 1D–2D hydraulic modelling approach to assess the sensitivity of a coastal region to compound flooding hazard under climate change, Natural Hazards, 98, 915-937, 2019.
Rostampour, V., Jaxa-Rozen, M., Bloemendal, M., Kwakkel, J., and Keviczky, T.: Aquifer Thermal Energy Storage (ATES) smart grids: Large-scale seasonal energy storage as a distributed energy management solution, Applied energy, 242, 624-639, 2019.
Salman, A. M., and Li, Y.: Flood risk assessment, future trend modeling, and risk communication: a review of ongoing research, Natural Hazards Review, 19, 04018011, 2018.
Shen, J., Tong, Z., Zhu, J., Liu, X., and Yan, F.: A new rapid simplified model for urban rainstorm inundation with low data requirements, Water, 8, 512, 2016.
USACE: Risk-based analysis for flood damage reduction studies, US Army Corps of Engineers, Engineer Manual 1110-2-1619, 1996.
van Berchum, E., Mobley, W., Jonkman, S., Timmermans, J., Kwakkel, J., and Brody, S.: Evaluation of flood risk reduction strategies through combinations of interventions, Journal of Flood Risk Management, e12506, 2018a.
van Berchum, E. C., Mobley, W., Jonkman, S. N., Timmermans, J. S., Kwakkel, J. H., and Brody, S. D.: Evaluation of flood risk reduction strategies through combinations of interventions, Journal of Flood Risk Management, e12506, 2018b.
Van Dantzig, D.: Economic decision problems for flood prevention, Econometrica: Journal of the Econometric Society, 276-287, 1956.
Vrijling, J., Van Hengel, W., and Houben, R.: Acceptable risk as a basis for design, Reliability Engineering & System Safety, 59, 141-150, 1998.
Vuik, V., Jonkman, S. N., Borsje, B. W., and Suzuki, T.: Nature-based flood protection: the efficiency of vegetated foreshores for reducing wave loads on coastal dikes, Coastal engineering, 116, 42-56, 2016.

Wahl, T., Jain, S., Bender, J., Meyers, S. D., and Luther, M. E.: Increasing risk of compound flooding from storm surge and rainfall for major US cities, Nature Climate Change, 5, 1093-1097, 2015.

Zscheischler, J., Westra, S., Van Den Hurk, B. J., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., and Wahl, T.: Future climate risk from compound events, Nature Climate Change, 8, 469-477, 2018.