Nat. Hazards Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/nhess-2020-56-AC2, 2020

Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Rapid flood risk screening model for compound flood events in Beira, Mozambique" *by* Erik C. van Berchum et al.

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Received and published: 25 June 2020

We would like to thank you for your time and effort put into reviewing this manuscript. Your comments have led to many adjustments, and we feel these have greatly improved the readability and quality of the manuscript. Please find the attached file for a formatted response to all comments by both reviewers.

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. âĂČ 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. âĂČ 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 non-interesting 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.

Please also note the supplement to this comment:
https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2020-56/nhess-2020-56-AC2-supplement.pdf

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Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2020-56, 2020.