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Date

18 October, 2018

To: Editor, Natural Hazard and Earth System Sciences Journal

Re: Revised manuscript nhess-2018-169, "Flood risk assessment due to cyclone induced dike breaching on coastal areas of Bangladesh"

Dear Dr. Bruno Merz

Please find in the manuscript section the revised manuscript for the above mentioned paper, along with the letter of response for reviewers.

Based on the comments of reviewers, to whom we are thankful for the comments, authors made modifications and adjustments to the manuscript. These comments helped us improve the manuscript.

The letter of response to the reviewers explains all the changes that were done to the manuscript based on their comments.

Due to the large changes in the manuscript, we have uploaded two versions of the revised manuscript; one with track changes ("FloodRisk-CoastalBangladesh_NHESS_With_track_Changes.pdf"); and one with all track changes accepted, for making reading of the manuscript easier ("FloodRisk-CoastalBangladesh_NHESS.pdf"). The page and line numbers referred into the response to reviewer letter ("Response_to_Reviewer.pdf") refers to the "FloodRisk-CoastalBangladesh_NHESS.pdf" file.

We hope that the revised version of the manuscript will be answering all requests of reviewers, and we look forward for their feedback. We are happy to answer any further questions that may arise.

Should you have further questions please do not hesitate to contact us.

Md Feroz Islam, MSc, on behalf of all authors

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On behalf of Md Feroz Islam, Biswa Bhattacharya and Ioana Popescu

Response to review comments

Manuscript title: Flood risk assessment due to cyclone induced dike breaching on coastal areas of Bangladesh
Manuscript Id: NHESS-2018-169

Review comments of Reviewer # 1

Comment:

Methodology: The methods used for calibration, breaching analysis and scenario development are all unclear and open to debate, but the biggest problem is the 1D2D model used. It is not described clearly, and as I understand it, models the sea in the 1D component. If this is the case, it requires a much better explanation and/or figures.

Authors' response:

Thank you for the comment. The revised manuscript provides more detailed information in the methodology section, by adding a flow chart to bring more clarity, following your suggestion. The methodology section has been improved in adding explanations on data, model development, scenario development and maps.

Message: I find the message of the paper ambiguous. The discussion and start of the conclusion mention the dynamics of the case-study, which make sense as discussion topics. However, conclusions about flood forecasting and early warning systems seem out of place. Perhaps the potential development of PFMs for other polders is better suited to be discussed in the conclusions. Lines such as 'end the problem of poverty' should certainly be reconsidered (discussion and conclusion section has been adjusted to provide more focused and clearer message, limitations of the research and scope of future research).

Authors' response:

Please see the revised version of the Conclusion in the new submitted manuscript. Authors hope that it is more coherent and connected to the sections of the paper..

English: Multiple mistakes are found which distract the reader and give the impression of a careless approach to the work. In the specific comments below, only the ones found in the introduction are listed, but many more exist throughout the manuscript (discussion and conclusion have been adjusted according to the research objective and provide a coherent message).

Authors' response:

To improve the level of English, native English speakers have been consulted and the revised version of the manuscript has been adjusted following their suggestion.

Reviewer 1:
"P1, Line 22: Presumably this second smaller abstract is not meant to be part of the main abstract. This is perhaps a formatting error during the upload process.**"**

Authors' Response:

Thank you for pointing this out. The error been corrected and the manuscript has been adjusted (please see the revised abstract).

Reviewer 1:
"P2, Line 7: "…to protect the land from flooding due to diurnal high tide". The English here is incorrect. Either 'high tides' or 'the diurnal high tide'.**"**

Authors' Response:

To improve the level of English, native English speakers have been consulted and the revised version of the manuscript has been adjusted following their suggestion (on page 2, line 4).

Reviewer 1:
"Also, do the polders not also protect from the heavy rainfall mentioned just before this sentence?**"**

Authors' Response:

Most of the polders of Bangladesh were built under the project titled as Coastal Embankment Project (CEP) in the 1960s. However, several articles and reports such as Mondal et al., 2006, Islam 2006, Islam et al., 2013, Bangladesh Delta Plan 2100, Coastal Embankment Improvement Project (Phase I) (Main Report) etc. indicated that the polders were constructed to protect the land from tidal flooding and salinity intrusion.

Reviewer 1:
"P2, Line 14: "Rising the crest level...". English.**"**

Authors' Response:

As mentioned previously English has been checked for improvement.

Reviewer 1:
"P2, Line 16: "Effect of…". English**"**

Authors' Response:

English has been checked and corrected .

Reviewer 1:

"P2, Line 16: "Moreover, non-structural flood mitigation measures such as (…) and (…) is currently unavailable for the coastal areas of Bangladesh". English.**"**

<u>*Authors' Response:*</u>

English has been checked and corrected following the suggestion of native English speakers.

Reviewer 1:

"P2, Line 23: "Furthermore..". This sentence suggests that SLR is not an effect of climate change. Did Mendelsohn et al. include this in their study?**"**

<u>*Authors' Response:*</u>

Authors acknowledge that the Sea Level Rise is indeed result of climate change and the paragraph was rearranged and adjusted to clarify the message. Moreover, English was checked and corrected as needed (on Page 2, line 21 to 25).

Reviewer 1:

"P2, Line 31: I cannot find where the variables of breach width, height and propagation are analysed in the study**"**

<u>*Authors' Response:*</u>

As the reviewer indicated in the later comments that the breach properties were not independent variables, it should not be stated as a parameter of scenario development. Authors acknowledge the suggested correction and the revised version was adjusted accordingly (on page 2, line 30 to 33).

Reviewer 1:

"P2, Line 31: Scenarios mentioned only previously in abstract. Authors could consider a minor revision here**"**

<u>*Authors' Response:*</u>

Authors acknowledge the suggestion and manuscript was adjusted accordingly (on page 2, line 27 to 33).

Reviewer 1:

"P3, Fig. 1: Upazilla term used in figure, but not explained in text. Presumably it is a form of district**"**

Authors' Response:

Thank you for raising this issue the manuscript has been adjusted accordingly (on page 3, line 5).

Reviewer 1:

"P3, Fig. 1: Would it be possible to indicate the extent of the mangrove forests?**"**

Authors' Response:

The maps were adjusted and the extent of the mangrove forest was added in the maps (figure 1, 3, 8, 12 and 13).

Reviewer 1:

"P3, Line 7: Who has classified this? The authors or a governmental body?**"**

Authors' Response:

The classification was done by the Ministry of Land of Bangladesh. The information was added in the revised version (page 3, line 8).

Reviewer 1:

"P4, Line 18: "…simulated using discharge as the upstream boundary…". What discharge? Is it important? Is it correlated to the cyclonic rainfall? Is it negligible in relation to the water level.**"**

Authors' Response:

The authors were trying to describe the developed 1D model which was calibrated against the measured water level and discharge on the river stations and then couples with 2D model. The 1D model was calibrated for normal condition (without cyclones) as hydrometric data during cyclonic events were not available. Moreover, the simulated cyclonic event "Sidr" made landfall in the coast of Bangladesh during the month of November which is post monsoon season. In the past, most of the cyclones his the coast of Bangladesh during the months of April-May or October-November which are pre and post monsoon where discharge from rivers don't play a significant role. The authors acknowledge this and the "Methodology" section was adjusted to provide more detailed and clearer description.

To make it more clear, flow chart of activities performed (Figure 2), 1D model network, 2D mesh extent and resolution in the map (Figure 3), sample cross sections (Figure 4 and 5), water level on the sea side network (Figure 6) has been added. More about modelling tool (page 6, line 1 to 9), data used (Table 1) and explanations about the model were added.

Reviewer 1:

"P4, Line 29-30: "…and the location furthest from the dike breach is most sensitive." Given we don't (yet) know the locations of the breach or in which direction from the breach you mean, this is very ambiguous. You presumably mean in areas of low flow.**"**

Authors' Response:

As suggested by the reviewer, authors' intention was to indicate about the sensitivity of the low flow areas to the coefficient of roughness "n", indeed and the manuscript was adjusted accordingly by moving the corrected section to page 14, line 29.

Reviewer 1:

"P5, Line 3: This paragraph about data gathering seems out of place, considering that data gathering was described before the previous paragraph about sensitivity analysis.**"**

Authors' Response:

Authors adjusted accordingly in the reviewed version and moved to page 5, line 14 to 19.

Reviewer 1:

"P5, Line 6: Perhaps you should mention that the flood extent data from MODIS data was (presumably) used for calibration.**"**

Authors' Response:

The manuscript was adjusted accordingly (on page 5, line 18, 19 and on page 14, line 23, 24).

Reviewer 1:

"P5, Fig. 2. Please indicate the Khaprabhanga river on the map**"**

Authors' Response:

The maps were adjusted accordingly (figure 1, 3, 8, 12 and 13).

Reviewer 1:

"P5, Fig. 2. As I understand it, the 1D component of the model stretches right around the polder, from the start of the Khaprabhangra river into the foreshore. Can you indicate the extents on the map?**"**

Authors' Response:

The 1D components were added in the map (figure 3).

Reviewer 1:

"P5, Line 12: "For the rivers, the surveyed cross…". You are presumably referring to the Andharmanik and Galachipa rivers on the east and west sides of the polders, but the previous sentence mentions only river. Please clarify this.**"**

<u>*Authors' Response:*</u>

The revised version of the manuscript was adjusted to have more clarity (on page 7, line 12 to 16).

Reviewer 1:

"P5, Line 13: I find the use of 1D channels to simulate the foreshore very irregular, and feel it deserves more explanation or references of previous methods. Are these channels connected to the river channels? Is discharge a factor? It is not mentioned."

<u>*Authors' Response:*</u>

Thank you for the comment. The authors tried to represent the condition of the water bodies adjacent to the dikes with 1D model with synthetic boundary condition. As the coast of Bangladesh is flat and shallow, a 2D model for coastal hydrodynamics will require inclusion of larger area of the sea which was not the area of interest and which would have increased the simulation time too. The utilised 1D network was not connected with the rivers as explained earlier the river water didn't play a major role during the previous cyclones as it's pre or post monsoon. The authors acknowledge this requires clearer description. The revised version was adjusted to provide more detailed and clearer explanation (on page 7, line 12 to page 8, line 2).

Reviewer 1:

"P5, Line 14: 13 control structures are mentioned here, which are presumably the 'Sluice gates' indicated on the map. If they are, please use the same term, and also, why are 13 not indicated?**"**

<u>*Authors' Response:*</u>

The map was adjusted accordingly (figure 3).

Reviewer 1:

"P5, Line 16: "Therefore, the canal network inside the polder was not included in the 1D model". The canals will have no effect on the dynamics outside the polder, but once flooding occurs they almost certainly will. I understand the DEM resolution will be too coarse to capture them, but this fact should be mentioned.**"**

<u>*Authors' Response:*</u>

The canal network inside the polder was not connected to the river network as during a cyclone the gates of the control structure will remain closed. But the larger canals were included in the DEM. The width of the larger canals were wide enough to be included in the DEM. This was explained in page 8, line 3 to 7.

Reviewer 1:
"P5, Line 19: Surely the foreshore data has no average slope?"

Authors' Response:

The authors agree that the rivers had higher slope than the foreshore area. As the distance between computational points is inversely proportional to slope, the rivers will require smaller Δx and same Δx will reduce instability for the foreshore area too. A clearer explanation was provided in the revised version (on page 10, line 2 to 4).

Reviewer 1:
"P6, Line 13: Are these storm surge heights directly applied as boundary conditions to the 1D model at every 1D cross-section location on the foreshore. I find this very difficult to understand."

Authors' Response:

To ensure same water level at all the points of the foreshore reach, same water level was applied at both ends of the reach as hydro dynamic boundaries. The authors acknowledge this requires clearer description. The revised version was adjusted (on Page 7, line 17 to page 8, line 2 and figure 6).

Reviewer 1:
"P6, Line 16: This seems out of place, perhaps more suited to the literature review earlier."

Authors' Response:

Thank you for the suggestion. Agreed that part of the paragraph can also be suited in the literature review section and part of the paragraph was moved to page 10, line 23 to 28.

Reviewer 1:
"P6, Line 26: Where is this section? As mentioned it should be in the map"

Authors' Response:

Following your suggestion, the extent of mangrove forest was depicted in the maps (figure 1, 3, 8, 12 and 13).

Reviewer 1:
"P6, Line 30: It was previously indicated that the breach geometry and propagation were variable in the scenario make-up (Abstract and Introduction). However in the end they are dependent on the other variables. This should be made clear"

Authors' Response:

Indeed these are not independent variables and should not be stated as parameters for scenario development and the revised version was adjusted accordingly (on page 10, line 32).

Reviewer 1:

"P7, Line 6: Why not call the scenarios east west and central for simplicity?"

<u>*Authors' Response:*</u>

Thanks for the suggestion. However, the change of the tittle of the scenarios will require the adjustment of most of the figures and tables. Therefore, no change was made.

Reviewer 1:

"P7, Table 1: The SLR variation is based on current conditions and a possible future rise in 2100. This raises the question as to which period the PFMs that have been developed correspond. Perhaps it makes more sense to vary SLR for a given future moment according to the RCP scenarios. Also, the 1/25yr surge height used for the cyclone is presumably for current conditions, but as you explain earlier, this is subject to change."

<u>*Authors' Response:*</u>

Thank you for your suggestion. As stated earlier SLR has been considered according to the RCP scenarios. The storm surge height for 1/25 yr event was based on current condition. As not enough measured data was available, previous literatures were used for determining the storm surge height for simulation. Time series data for sea level rise for the study area was not available either. Therefore, the scenarios were developed for the years for which data was available. The section was described more clearly in the revised version (on page 10, line 16-17).

Reviewer 1:

"P7, Line 9: I don't understand this. If flooding results from the 3 worst case scenarios are available, it surely means breach locations are already selected. So how does this allow for a critical breach location to be selected? Is this flooding from overtopping of the dikes?"

<u>*Authors' Response:*</u>

The flooding occurred for breaching only as the crest level of the dike was considered to be elevated to a height suggested by CEIP in the future. Breaching of the dike was considered for all the scenarios, therefore, authors agree that dike was breached already in the three worst case scenarios as well. The intention was to present a methodology to compare and identify a critical location based on damaged caused by flood in case of breaching of dike which could be applied in other locations. Providing better protection at the critical locations might reduce the damage significantly during and after a cyclone. The authors adjusted the revised version to provide clearer explanation (on page 11, line 3 to 5).

Reviewer 1:

"P8, Line 3: "…depth-damage curves from elsewhere." This is explained later, but at this point the sentence is very ambiguous."

<u>*Authors' Response:*</u>

It was adjusted accordingly (on page 12, line 9 and 10).

Reviewer 1:
"P9, Line 5: "The critical location of breaching…" Why is this included here? It adds to my existing confusion about how these locations are selected."

<u>*Authors' Response:*</u>

It was adjusted accordingly (page 13, line 3 to 5).

Reviewer 1:
"P10, Line 2: "we have assumed that the probability of occurrence of the hazard and the probability of failure of dike as the same". Can the authors estimate the accuracy of this assumption? Presumably no flooding occurs (from overflow) of the dike in the simulations without breaching, but perhaps wave overflow would occur?"

<u>*Authors' Response:*</u>

The crest level of the dikes was considered to be at the design height suggested by Islam et al., 2013 and CEIP. Wave action was considered during the calculation of design crest level and a free board was also considered. It can be safely concluded that the crest level suggested by Islam et al., 2013 will be sufficient enough to protect area inside the dike from overtopping during a 1/25 year event. Moreover, the breaching of a dike depends on the physical condition of the dikes and it's soil properties. Neither of these data were available. Therefore, the calculation of probability of the dike breach was not possible. To simplify and to investigate the effect of dike breach, the breaching probability was considered same as the cyclonic event. This was described more in the revised version (page 11, line 2 to 5 and page 13 line 15 and 19).

Reviewer 1:
"P10, Line 4: I don't understand the relevance of this reference, as all scenarios used in the study have the (assumed) same probability"

<u>*Authors' Response:*</u>

The authors intention was to provide reference for the equation used for calculation of probabilistic flood maps. It was rephrased in the new version of the manuscript, for better clarity (page 14, line 3 and 4).

Reviewer 1:
"P10, Line15: "…comparing the observed and simulated water level and discharge". As mentioned previously, you have not mentioned what discharges are being simulated, or what you are calibrating them to. Also if the cyclone water levels are applied as boundary conditions, surely the calibration is trivial?"

<u>*Authors' Response*</u>

As mentioned earlier the calibration of 1D model was done for normal condition, not for a cyclone event as no data was available during that event and very few data was available for calibrating the 2D model. The intention of the authors was to present a methodology with which flood risk maps and

PFMs can be generated for different locations. More detailed description was provided in the revised version (on page 6, line 16 and 17and page 7, line 21 to page 8, line2).

Reviewer 1:
"P14, Figure 7: Can the authors explain why the damage decreases for larger flood depths?"

Authors' Response

The damage is a function of flood depth but the unit is per unit area(per m^2). Therefore, if the flood extent for higher depth is lower, the damage due to flood might be lower too. It was explained in the revised version (on page 21, line 6 and 7).

Reviewer 1:
"P15, Line 6: Ignoring depths less than 0.5m seems quite extreme, can the authors explain why this was done?"

Authors' Response

The developed damage curves suggest that the damage for flood depth below 0.5 m is minimal. Moreover, the authors tried to explore the effect of living with flood concept. Also tried to consider the uncertainty of the DEM and the 2D inundation model. The depth as 0.5m is an arbitrary depth. For a country where flood is a recurrent phenomenon with larger depth, living with flood might be already adopted by the local people. This was explained in the revised version (on page 19, line 6 to 11).

Reviewer 1:
"P16, Line 22: "Figure 4 demonstrates that the depth of flooding gradually decreases as the water moves inland". This is not true, the figure only shows inundation extent. Perhaps the authors mean imply."

Authors' Response

Authors agrees and thanks the reviewer for identifying and was adjusted accordingly by removing the statement.

Reviewer 1:
"P17, Line 18: "…(Fig. 8). Therefore, although canals play a crucial role in the economy and social life of the area, they also increase the risk of flooding". This is a strange, and in my view, inaccurate conclusion. Figure 8 shows the residential areas as high risk because they are more valuable. They happen to be situated beside canals."

Authors' Response

Indeed the residential areas had higher depth damage ratio than other land classes. But the residential areas were flooded primarily for being by the side of the canal. The authors' intention was to state that as these areas are adjacent to the canals for various reasons such as being advantageous for transportation, also makes them susceptible to flooding and higher damage. The authors will try to explain more clearly in the revised version (page 21, line 23 and 24).

Reference

Mondal, M.K., Tuong, T.P., Ritu, S.P., Choudhury, M.H.K., Chasi, A.M., Majumder, P.K., Islam, M.M. and Adhikary, S.K., 2006. Coastal water resource use for higher productivity: participatory research for increasing cropping intensity in Bangladesh. *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture-Fishery-Aquaculture Conflicts.*, pp.72-84.

Islam, M.R., 2006. 18 Managing Diverse Land Uses in Coastal Bangladesh: Institutional Approaches. *Environment and livelihoods in tropical coastal zones*, p.237.

Islam, M.S., Alam, R., Khan, M.Z.H., Khan, M.N.A.A. and Jahan, S.N., 2013. Methodology of crest level design of coastal polders in Bangladesh. In *4th International Conference on Water & Flood Management*.

Review comments of Reviewer # 2

Review of manuscript: *"Flood risk assessment due to cyclone induced dike breaching on coastal areas of Bangladesh".*

Overview

The paper describes the methods and suggests tools for the probabilistic flood mapping in a polder area of Bangladesh. The study area selected by the author is interesting in terms of its geographical complexity and challenges related to the data collection. The methods used are rather simplified and aimed at giving a general overlook on the problem.

Authors: Thanks for the comments

The main concerns

There are however, some major concerns about the idea behind methods and scenarios selection. The research questions should be addressed in Discussion section. One of the main problems is the description and structure of Study area and Methods sections. Some additional references are required in places where it is not clear where exactly the data or information come from. In addition, there is a large amount mistakes in language usage, both grammar, punctuation and word selection. The figures are not consistent throughout the manuscript. Therefore, my recommendation is to return this manuscript to authors for major revisions.

Authors: We acknowledge the concerns raised by the reviewer. The manuscript was revised and adjusted to bring more clarity in the description of the study area and the presented methodology (see section "Study area" and "Methodology". The discussion section was revised as well. More specific answers were provided in the following sections (the manuscript was revised to present more clear objectives, coherent findings and innovation of the research).

General comments

Reviewer 2:

Study area. Due to the specific conditions of the region, it is important to give more clarity and structure to this section. Probably it is a good idea to consider removing some unnecessary information and add more visualisation to more important aspects that are crucial for this specific research.

Authors: The authors acknowledge the suggestion. More information about the study area was provided to improve the description of the study area.

Reviewer 2:

Research question. Should be stated clearly what exactly is developed within the study and to which degree it is considered innovative.

Authors: The authors understand that the innovation remained unclear in the draft. The main innovation of the research was presented clearly in the revised manuscript (The introduction and Conclusion section have been adjusted to present the research questions and innovations).

Reviewer 2:

Methodology. Here are major rewritings are required to increase the quality of the paper. Modelling sub-section needs more clarifying in tools selection and usage. In addition, I suggest more description of the data used for model set-ups and calibration.

Authors: The authors acknowledge the suggestion. More detailed information was provided in the methodology with a flow chart to bring more clarity in the revised version. The description of the data used for the setting up of the model and its calibration were elaborated (Methodology has been revised by adding a flow chart of activities performed (figure 2), more about the software and data used (page 6, line 1 to 9, table 1), example of cross sections used (figure 4 and 5), the extent of 1D network and 2D mesh (figure 3), simulated water level on the sea side and adjusted write up).

Reviewer 2:

The subsection 3.2 Cyclonic scenarios considered; the selection of the values for different scenarios based on the IPCC report is rather subjective. It is suggested to consider regional sea level changes rather than global mean, as there is a significant difference specifically for Bangladesh. This may bring more impact on the outcomes of the study.

Authors: The authors' intention was to present a global methodology applicable to everywhere. The relative sea level rise for RCP 8.5 of IPCC AR5 for the coast of Bangladesh is 0.56 m (GERIC, 2015) which is slightly lower than what was considered by the authors (0.63 m).

Reviewer 2:

Discussion and Conclusion. It would be worth writing how/if the future studies would improve the current outcomes.

Authors: The authors acknowledge the suggestion. The manuscript was revised and recommendation for future studies was added as well. (please see "conclusion" section).

Reviewer 2:

The take-home message is rather vague. The discussion section needs major re-writing in accordance to the research questions stated in Introduction. In my opinion such general methods used in this study should be accompanied with rather more detailed (sub)-section on the sources of errors and limitations.

Authors: The discussion section was adjusted with the reflection on the research questions. Limitations of the study were added in the conclusion (please see "Discussion" and "Conclusion" section).

Reviewer 2:

Heroic assumptions such as "lead to economic growth" and "end the problem of poverty" should be avoided.

Authors: The authors acknowledge the suggestion and such phrases were removed.

Reviewer 2:

English. A serious revision of the language is necessary to improve the quality and readability of the manuscript. Among main issues I would outline: plural vs. singular, passive voice use, punctuation, repetitions of the same structures in consecutive sentences/paragraphs, repetitions of abbreviation explanations, articles selection, language use, etc.. The specific remarks do not cover language issues.

Authors: To improve the level of English, native English speakers have been consulted and the revised version of the manuscript has been adjusted following their suggestion.

Specific remarks

Reviewer 2:

p.2 line 2. According to Neumann et al (2015) 49% of population located in low elevated coastal zone for the year 2000, at that time the overall population of Bangladesh was 139 mil. Values should be corrected.

Authors: The authors acknowledge the suggestion and the manuscript was adjusted accordingly (on page 1, line 26 and 27).

Reviewer2 :

p.2 line 11. The number US$1.67 million seems rather small, needs additional check.

Authors: The authors thank the reviewer for pointing it out. The revised manuscript was corrected accordingly (on page 2, line 7).

Reviewer 2:

p.2 line 14. “Raising the crest level …” the sentence is unclear.

Authors: Agreed and revised (on page 2, line 12).

Reviewer 2:

p.2 line 15. References needed to indicate which exactly previous studies were done in this matter.

Authors: The authors acknowledge the suggestion and the revised manuscript was adjusted accordingly (on page 2, line 13).

Reviewer 2:

p.2 line 17. It needs more clarification how land use zoning address the flood mitigation.

Authors: The authors think that land use zoning is widely used as a flood risk mitigation measure. Reference was added to bring more clarity (on page 2, line 18).

Reviewer 2:

p.2 line 19. “…of these tropical cyclones will increase…” the statement will is rather confident, however it is likely increase. We are not 100% sure it will increase the intensity of storms. Look further through the manuscript for same errors.

Authors: Indeed, it was adjusted accordingly (on page 2, line 19).”

Reviewer 2:

p.2 line 26. Which exactly severe consequences specifically in Bangladesh? Look at Neumann et al (2015) for ideas.

Authors: As suggested, adjusted in the revised version.

Reviewer 2:

p.3 line 3. It is recommended to visualise coordinates in Figure 1.

Authors: Coordinates were added in Figure 1 (figure 1).

Reviewer 2:

p.3 line 6. The source of census data is missing.

Authors: We thank the reviewer for pointing it out. Source was added in the revised version (on page 3, line 6).

Reviewer 2:

p.3 line 12. Consider the importance of putting the local names of seasons to the manuscript.

Authors: The local names of the copping seasons have been mentioned. However, the calendar months are mentioned as well and therefore, Authors think that any lack of clarity is not obvious.

Reviewer 2:

p.3 line 15. Some figures on the land subsidence rates may bring more light on the severity of the problem in the region.

Authors: Value for land subsidence for the region was searched and added (on page 3, line 16).

Reviewer 2:

p.4 line 12. “Model set up” rather than “model development”

Authors: Thank you for the suggestions. As we were unable to identify the mistake, native English speakers were consulted for clarity and following there suggestion, no further change was made.

Reviewer 2:

p.4 line 20. The reference on FINMAP is missing.

Authors: Reference for FINMAP was added (page 5, line 10).

Reviewer 2:

p.4 line 26. More details on the computation mesh are recommended.

<u>Authors:</u> This was explored and more detailed was added (on page 7, line 4 and 5).

Reviewer 2:

p. 5 line 9. The version of the model is missing.

<u>Authors:</u> We have used version 5 of the HEC-RAS tool. This information was added in the revised manuscript (on page 6, line 1).

Reviewer 2:

p.6 line 17. I would include the figures on the land subsidence.

<u>Authors:</u> Value for land subsidence for the region was searched and added (on page 3, line 16).

Reviewer 2:

p.6 line 23. The figures of SLR indicated could be updated to the ones for 2100.

<u>Authors:</u> The Authors' intention was to state the probable sea level rise suggested by IPCC. The authors took a look and no further adjustment was not required.

Reviewer 2:

p. 7 line 15. It is better not to describe indirect damages if they are not consider further.

<u>Authors:</u> We have not elaborated on indirect damages. We have just defined it to bring clarity.

Reviewer 2:

p.8 line 16. More reasoning for choosing of the figure of 50% would bring more light on the selection.

<u>Authors:</u> Muktadir and Hasan, 1985 stated in their study that the rural house hold of Bangladesh usually are built around a large country yard. The land classification by the Ministry of Land defines the whole house hold including the country yard as residential area. But the damage curve considered for the residential area was for the damage to the house and the country yard will not have significant damage if flooded. Considering this the authors tried to exclude the country yard from the residential area. The satellite image of the area indicated that the about half of the area of residential complex (house hold) is usually empty. Therefore, the figure 50% was considered. This was added in the revised version (on page 12, line 15 to 19)

Reviewer 2:

p.9 line 7. "More research…" is rather suitable for conclusion.

<u>Authors:</u> Authors acknowledge the suggestion and the manuscript was adjusted accordingly by removing the statement.

Reviewer 2:

p.9 line 16. This definition of risk was presented earlier by Helm 1996. See Helm, P. (1996). Integrated Risk Management for Natural and Technological Disasters. Tephra, 15(1), 4-13.

<u>Authors:</u> Authors acknowledge the suggestion and the manuscript was adjusted accordingly (on page 13, line 8).

Reviewer 2:

p.10 line 9. It is not clear where M and N are in your formula.

<u>Authors:</u> The parameters M and N were defined in the manuscript following the equation. The equations were adjusted to bring more clarity (on page 14, Equation 5).

Reviewer 2:

p.11 Figure 4. The boundaries are not clear, some simplification of shapes could bring more readability to the map.

<u>Authors:</u> Authors acknowledge the suggestion and the map was adjusted to increase readability (figure 8).

Reviewer 2:

p.12 Figure 5. There is some confusion what exactly this figure is supposed to show.

<u>Authors:</u>

Authors' intention was to depict the effect of different variables of the scenario development. For example: to depict the effect of sea level rise, two scenarios with keeping all the other variables (except from sea level rise) constant and changing the SLR, were compared. Authors acknowledge that this requires clearer explanation and the revised manuscript was adjusted (on page 20, line 3 and 4).

Reviewer 2:

p.15 Figure 8. The map layout is not consistent with other maps.

<u>Authors:</u> The maps were adjusted to have consistent layout (figure 3, 8, 12 and 13).

Reviewer 2:

p.15 line 6. Some elaborate clarification why 0.5 m is used. My guess, some damages might be underestimated by selecting such high value.

<u>Authors:</u> The developed damage curves suggest that the damage for flood depth below 0.5 m is minimal. Moreover, the authors tried to explore the effect of living with flood concept. Also tried to consider the uncertainty of the DEM and the 2D inundation model. The depth as 0.5m is an arbitrary depth. For a country where flood is a recurrent phenomenon with larger depth, living with flood might be already adopted by the local people. Moreover, this arbitrary was used for PMFs and the estimation of damage due to flood was not affected. This was added in the revised manuscript (on page 19, line 7 to 11).

Reference

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Muktadir, M.A. and Hasan, D.M., 1985, December. Traditional house form in rural Bangladesh: a case study for regionalism in architecture. In Regional seminar on Architecture and the Role of Architects in Southern Asia (pp. 19-23).

Flood risk assessment due to cyclone induced dike breaching on coastal areas of Bangladesh

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Abstract. Bangladesh, one of the most disaster-prone countries in the world, has a dynamic delta with 123 polders protected by earthen dikes. Cyclone induced storm surges cause severe damages to these polders by overtopping and breaching of~~the~~ dikes. Nineteen major tropical storms hit the coast in last 50 years and the storm frequency~~intensity~~ is likely~~predicted~~ to increase due to climate change. The present paper presents an investigation of the inundation pattern in a protected area behind dikes due to floods caused by storm surges and identifies possible critical locations of dike breaches. Polder 48 in the coastal region, also known as Kuakata, was selected as the study area. A HEC-RAS 1D-2D hydrodynamic~~inundation~~ model was developed to simulate inundation in the polder under different ~~scenario~~s~~S~~cenarios. ~~Scenario~~Scenarios were developed by considering t~~T~~idal variations, angle of ~~the~~ cyclone at landfall, possible~~different~~ dike breach locations, geometrical properties of the breach, breach propagation time and the sea level rise due to climate change according to the fifth assessment report (AR5) of Intergovernmental Panel on Climate Change (IPCC)~~ were combined to develop the scenarioScenarios~~. The critical location of the dike breach among the chosen possible locations was identified by comparing the inundation extent and damage due to flood corresponding to ~~three worst cases of~~ the developed s~~scenario~~Scenarios. ~~Generated f~~A flood risk map~~s~~ corresponding to the breaching at the critical location was developed, which indicated that settlements adjacent to the canals in the polders were exposed to~~face~~ higher risk. A ~~The~~ probabilistic flood map (PFM) was developed ~~calculated from~~ using the simulation results corresponding to ~~of all~~ the developed ~~scenario~~s~~S~~cenarios, which was used to recommend~~ indicated~~ the need of appropriate land use zoning to minimize the vulnerability to flooding. The developed hydrodynamic model can be used~~applied~~ to forecast ~~generate location based flood forecasting~~ inundation, to identify critical locations of the dike requiring maintenance~~to reduce the risk from flooding~~ and to study the effect of climate change on flood inundation in the study area .

~~Bangladesh, one of the most disaster-prone countries, has a dynamic delta with 123 polders. Cyclone induced storm surges cause severe damages to these polders. This paper presents an investigation of the inundation pattern inside a polder due to dike failure caused by storm surges and identifies possible critical locations of dike breaches. Moreover risk of flooding was assessed and probabilistic flood map was generated due to breaching of dike to assist land use planning to increase preparedness~~

1. Introduction

Bangladesh is the low lying delta of three major rivers: Ganges, Brahmaputra and Meghna. Eighty percent of the country's land is located below 10m AMSL (above mean sea level) (Heitzman and Worden, 1989) and it is formed of sediments carried by the above mentioned rivers. The population of Bangladesh ~~is~~ was about ~~160~~ 131.5 million by the year 2000 (World Bank, 2018) of which about 49% were living ~~lived~~ in the coastal zones (Neumann *et al*., 2015). The coastal areas of Bangladesh are flooded frequently due to cyclone induced storm surges and occasionally due to high water levels in the rivers caused by heavy rainfall in the upstream catchments of Ganges, Brahmaputra and Meghna. The coast was hit by 5 severe cyclones between~~from~~ 1995 and~~to~~ 2010 causing flooding, huge damages and loss of life (Dasgupta *et al*., 2014).

Bangladesh has 123 polders in the coastal area, each surrounded by earthen dikes, which are designed to protect the inland from flooding due to ~~the diurnal~~ high tides. The existing crest level of these dikes are only adequate enough to protect the coastal area from cyclones with 5 to 12 year return periods (Islam *et al*., 2013). These dikes usually get damaged by tropical cyclones of high intensity due to overtopping~~ and scouring in the landside~~, which causes flooding inside the protected areas, damages to~~ing~~ properties and ~~causing~~ loss of life. For example, cyclone Sidr hit the coast of Bangladesh in 2007 affecting 8.9 million people, causing US$1.~~6~~7 ~~million~~ billion of damage (GOB, 2008)~~ and US$70.3 million of damage to the dikes and control structures~~ (Dasgupta *et al*., 2014). In 2009. Cyclone Aila affected 3.9 million people with an estimated damage of US$270 million (EMDAT, 2009).

Crest levels of the coastal dikes were redesigned recently for an event of 25 year return period under the Coastal Embankment Improvement Project (CEIP) (BWDB, 2013). Crest levels were designed considering w~~W~~ave actions, astronomical tides and the required free-~~-~~board~~ were included in the design crest level of the dikes by CEIP~~. Raising the crest level was considered as the only mitigating measure ~~Raising the crest level was only considered as mitigating measure~~. Various ~~Previous~~ studies on the coastal areas of Bangladesh (e.g. Karim and Mimura, 2008;~~,~~ IWM, 2005;~~,~~ Azam *et al*., 2004~~,~~; Madsen and Jakobsen, 2004;~~,~~ CSPS, 1998;~~,~~ Flather, 1994) considered flooding only due to overtopping of the dikes during storm surges. Effect of breaching of the dikes due to piping and scouring on the landside during cyclones have not been studied. Moreover, non-structural ~~flood mitigation~~ measures for flood risk management such as land use zoning using the flood risk map (FRM) and probabilistic flood maps (PFM) to locate the vulnerable areas ~~is~~ are currently unavailable for the coastal areas of Bangladesh. Flood zoning can be a useful risk mitigation measure a~~A~~s land use governs the exposure and may aggravate the hazard~~, one of the factors of flood risk assessment~~ (Barredo and Engelen, 2010)~~, land use zoning can be a tool for mitigating flood risk~~.

Moreover, the intensity and frequency of these tropical cyclones is likely to increase in the future due to climate change~~ causing more damages~~. It is projected that by the year 2100, the frequency of the most intense cyclones will increase substantially and the intensity of tropical cyclones will increase by 2 to 11% due to global warming (Knutson *et al*., 2010). Flooding by tropical cyclones will also increase in the future as a result of sea level rise (SLR)~~ due to climate change~~ (Woodruff *et al*., 2013). SLR and sea surface temperature (SST) will affect the cyclone induced storm surge height in the Bay of Bengal (Karim and Mimura, 2008). With increasing SST, the storm surge height may~~can~~ increase from 21% to 49%~~ (Karim and Mimura, 2008)~~ and with

SLR, the flood depth due to storm surges may increase by 30-40% (Karim and Mimura, 2008). The land subsidence in the delta will exacerbate the effect of SLR. Furthermore, by the year 2100 Dthe annual estimated damage due to tropical cyclones maywill increase by US$53 billion per year by the year 2100 due to climate change which is almost twice the damage without the effect of climate change (Mendelsohn *et al.*, 2012). Furthermore, flooding by tropical cyclones will increase in the future as a result of sea level rise (SLR) (Woodruff *et al.*, 2013). Countries situated at lower latitudes are predicted to suffer most from climate change (Mendelsohn *et al.*, 2006).

The study area is not benefitted with an enabled flood forecasting system. Bangladesh Water Development Board (BWDB), which is mandated to protect the area, does not have a clear picture about the inundation patterns corresponding to various climatic conditions. Moreover, identifying zones in the embankment critical to flooding in the polder will help BWDB in prioritising their maintenance. This paper presents an methodology to investigateeion of the inundation pattern behind the dikes due to flooding caused by storm surges. Different sScenarios of storm surges were utilised by considering storms of different frequencies with varying tidal conditions, angle of cyclone at landfall and SLR. The simulated flood inundations were used in creating a probabilistic flood map of the area. and produce FRM and PFM due to breaching during a cyclone induced storm surge using a 1D-2D coupled model. The variation of storm surge height due to tidal conditions (diurnal, semi-diurnal and seasonal), and angle of cyclone at landfall along with different breach geometry (width, height and propagation) and different breach locations were considered in developing the scenarios. Analysis of the results of different scenarios led to the identification of critical locations of dike breaching.

2. Study area

Polder 48, which was considered as the study area for this research, is surrounded by dikes and has a sea facing dike of about 20 km length on the southern side of the polder. The polder is located in the south western coast of Bangladesh Delta (Figure 1Figure 1) stretching from 21^{0}50’28” N 90^{0}05’17” E to 21^{0}50’06” N 90^{0}14’14” E. The area is also known as Kuakata and it is in the administrative zone of Kalapara sub-district (Upazilla) of Patuakhali District. It has an area of 50.75 km^2 with 24,240 inhabitants according to the census of 2011 (BBS, 2012). Most of the inhabitants are farmers and fishermen (Nasreen *et al.*, 2013). Shrimp culture and tourism are also part of the economic activities. The land use is mainly classified into the following four classes: rice fields, settlements, shrimp ponds and water bodies (river/canal) by the Ministry of Land, Bangladesh. Climate of Kuakata is similar to the climate of the country (Bangladesh). The average yearly rainfall in Kuakata is 2590mm (Climate-Data, 2016). The month with the highest rainfall is July with an average of 611mm. The annual average temperature of Kuakata is 25.9˚C with minimum and maximum temperature as 13˚C and 34˚C respectively (Climate-Data, 2016). There are three seasons for growing crops (DAE, 2009). They are, Rabi (November to February), Kharif-I (March to May) and Kharif-II (June to October). The area is relatively flat and low lying, with 80% of its elevation below 1.55m PWD, the vertical datum established by Public Works Department of Bangladesh, which is 0.46m below the MSL. The land level surveys at different times have indicated that this polder is facing land subsidence issues. Brown and Nicholls (, 2015), suggested that the reported the estimated mean subsidence rate of Ganges-Bhrahmaputra-Meghna (GBM) delta a~~is~~ 5.6 mm per year with an overall median of 2.9 mm per year.

The area was severely affected by recent storms Sidr, Aila and Mohasen in 2007, 2009 and 2013 respectively. For example, during cyclone Sidr, 94 people died and 45% of the crops were lost~~ in Kalapara sub-district~~ (Ahamed, 2012).

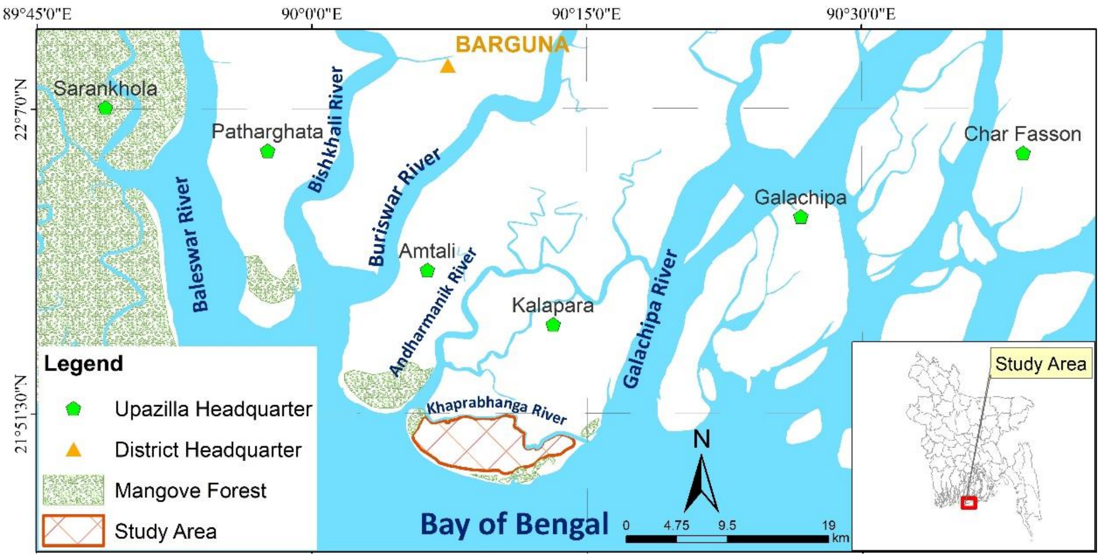

Figure 1: Location map of the study area Polder 48 (Kuakata).

Andharmanik, Galachipa and Khaprabhanga rivers are on the east, west and north of the study area respectively, whereas the Bay of Bengal is on the southern side of the study area (Figure 1~~Figure 1~~). Galachipa River is the widest among the rivers surrounding the area. On the southern side, the study area has sea shore of 20 km width, which is partly protected by the mangrove forest at~~in~~ several locations. There is a narrow sea beach in the south-western side of the area. The western part of the sea facing dike was overtopped during cyclone Sidr causing flood inside the polder (Hasegawa, 2008). The loss of livestock and food grains were such that it created partial deficiency of food in Kuakata (TANGO International, 2010). The average crest level of Polder 48 in the northern side is 4.5m PWD and in the southern side (sea facing side) is 6m PWD~~ at present~~ (Islam *et al.*, 2013). The existing embankments of 17 polders of the region, including Polder 48, were redesigned and rehabilitated during the first phase of CEIP (Islam *et al.*, 2013). CEIP proposed a crest level of 7.36 m PWD for the dike of Polder 48 (Islam *et al.*, 2013).

3. Methodology

The methodology followed is presented in Figure 2 and described in the following sub-sections. ~~A 1D-2D hydraulic model was developed to simulate inundation corresponding to different scenario, which were formed by considering varying storm surges and breach location, and climate change. The inundation pattern consequent to dike breaching was analysed, tangible~~

damages were estimated and flood risk maps were developed. A probabilistic flood map was generated using the result of all the simulated scenarios. A flow chart of the activities performed is presented in Figure 2.

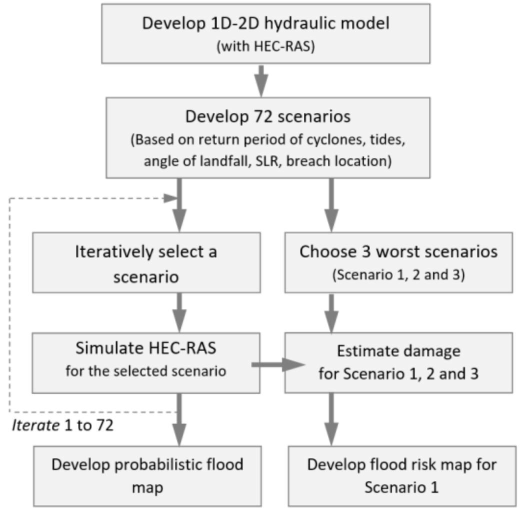

Figure 2: Methodological approach followed in this study.

3.1 1D-2D coupled model development

In order to build a 1D-2D inundation model field measurements (land level surveys, observed water levels, canal alignments and cross sections of the river and canals) and information from remote sensing (satellite imagery) were gathered (Figure 3). Institute of Water Modelling (IWM) of Bangladesh collected hydraulic, hydrologic and land level data of the study area (along with other polders) in the framework of the feasibility study of Coastal Embankment Improvement Project (CEIP). IWM has kindly provided the measured data for the study area.

The Digital Elevation Model (DEM) was generated by combining the land level surveys conducted by IWM and FINMAP (a company from Finland). The land level survey of IWM (conducted in 2012) did not cover the whole study area. FINMAP conducted the topographic survey of the study area in 1988 (MIWF, 1993). The differences in elevation between land surveys of IWM and FINMAP indicated the land subsidence. An average subsidence was computed, which was used to update the elevations of the FINMAP survey for the areas within Polder 48 for which survey data from IWM was not available. The combined DEM has a resolution of 50 m.

The bathymetry of the sea near the coast was collected from global bathymetric chart of ocean (GEBCO) (Smith and Sandwell, 1997). The land use data was collected from the Ministry of Land of Bangladesh. MODIS reflectance data was used for the analysis of previous flood events. The methodology and equations suggested by Hoque *et al*. (2007) were used to analyse the MODIS reflectance data to determine flood extents during previous flood events. The intention was to utilise the flood extent generated from MODIS reflectance for calibration of the hydraulic model. However, no flood image from MODIS was available during the simulation period.

~~A 1D-2D inundation model was developed for the study area. Field measurements (land level survey, observed water level, canal alignment, cross sections of the rivers and canals etc.) and information from remote sensing (satellite imagery) were gathered for developing the model (Figure 3). Institute of Water Modelling (IWM) of Bangladesh carried out the feasibility study of Coastal Embankment Improvement Project (CEIP) and collected hydraulic, hydrologic and land level data for the polders. IWM has kindly provided the measured data for the study area.~~ The river analysis tool HEC-RAS (v~~V~~ersion 5.0) from the US Army Corps of Engineers was used to develop the 1D-2D coupled inundation model. The flow in the river was modelled in 1D whereas the flow over the floodplain was modelled in 2D. HEC-RAS 5.0 is a free tool which can simulate 1D, 2D and 1D-2D coupled models for steady and unsteady flow. The 2D module of HEC-RAS provides option to simulate flow of water either with the~~of~~ diffusion wave equation or with the ~~and~~ full shallow water equation (St. Venant equation). The flow equations are solved using Skyline/Gaussian reduction matrix solution technique by HEC-RAS. HEC-RAS -also provides the Pardiso solver for complex systems. The two dimensional module in HEC-RAS is computationally efficient. ~~built for the use of maximum available cores which reduces the computational time.~~ Moreover, HEC-RAS generates irregular flexible mesh to represent a complex shape of the 2D flow area.– As HEC-RAS is a free tool, a model developed by it can be utilized by anyone~~universally~~. ~~T~~The availability of irregular flexible mesh and~~,~~ option for faster simulations ~~and freely availability~~ lead to the selection of HEC-RAS 5.0 as the mathematical modelling tool for this research. Data utilized for developing the model and their sources are presented in Table 1~~the~~.

Table 1: The data used in developing the mathematical model and their sources.
IWM, GEBCO and JSCE stand for Institute for Water Modelling, General Bathymetric Chart of the Oceans and Japan Society of Civil Engineers respectively.

Component of the Model	**Data collected and used**	**Source**
1D networks	Alignment	River network: IWM; The network on the sea side: Satellite image (Google Earth)
	Cross section	River: IWM; Bathymetry of the sea side: GEBCO
	Water Level	IWM
	Discharge	IWM
2D Mesh	DEM	IWM and FINMAP
	Land Use	Ministry of Land
	Dike Alignment	IWM
1D-2D coupled m~~M~~odel	Crest Level of the existing dike	IWM
	Geometric properties of the dike	IWM

Component of the Model	Data collected and used	Source
	Design cCrest level of the dike for future development	Islam *et al.*, 2013
	Storm sSurge hHeight	Azam *et al.*, 2004, Islam *et al.*, 2013 and Dasgupta *et al.*, 2014
	Flood dDepths of previous events	JSCE

The 1D section of the model was initially developed and calibrated using the information shared by IWM. The 1D part of the developed model was calibrated for non-floodnormal conditions as measured discharge/ water level data during a cyclone event was unavailable. The model was simulated using discharge as the upstream boundary and water level as the downstream boundary conditions (Figure 3). The calibrated 1D model was then -coupled with the 2D model of flow over the floodplain using the a Digital Elevation Model (DEM) of the study area to include the 2D component and overland flow. The DEM was generated from the land level survey conducted by IWM and FINMAP. The land level survey of IWM did not cover the whole study area. The gaps in land level survey of IWM were filled in with the data from a previous survey conducted by FINMAP, which was provided by IWM. FINMAP (a company from Finland) conducted the topographic surveys in 1988 (MIWF, 1993). The elevation differences of land survey of IWM (conducted in 2012) and FINMAP indicated the land subsidence. The FINMAP data was corrected for land subsidence using the arithmetic average of the differences of these two land level surveys for Polder 48. The combined DEM has a resolution of 50 m.

The bathymetric data for the sea was collected from global bathymetric chart of ocean (GEBCO) (Smith and Sandwell, 1997). The land use data was collected from the Ministry of Land of Bangladesh. MODIS reflectance data was used for the analysis of previous flood events. The methodology and equations suggested by Hoque et al. (2007) were used to analyse the MODIS reflectance data to determine flood extents during previous flood events. The intention was to utilise the flood extent generated from MODIS reflectance for calibration. But the MODIS data during the event was not available and the analysis of earliest available image after the cyclone event did not indicate of flooding.

For the 1D-2D inundation model, a computational mesh with a resolution of 25 m was used. with flexible shape was developed in HEC-RAS (**Error! Reference source not found.**Figure 3). HEC-RAS generates mesh with irregular shapes. The rectangular cells of the developed 2D mesh had a resolution of 25 m and rest of the cells had an area of 625 square meters. The roughness coefficient (Manning's *n* varying from 0.025 to 0.05) was provided according to the landuse of each cell. A sensitivity analysis as suggested by Hall *et al.* (2005) was carried out by varying Manning's roughness coefficient *n* before the calibration of the 2D inundation model. The analysis indicated that the inundation model is not highly sensitive to the roughness coefficient and the areas of low flows (locations furthest from the dike breach) areis most sensitive. The sensitivity analysis was done for the breaching on the western part of the dike only. It was considered that the breaching at other locations will have similar effect as the area inside the polder is flat and low lying with mostly farmlands near the dike.

The bathymetric data for the sea was collected from global bathymetric chart of ocean (GEBCO) (Smith and Sandwell, 1997). The land use data was collected from the Ministry of Land of Bangladesh. MODIS reflectance data was used for the analysis of previous flood events. The methodology and equations suggested by Hoque *et al.* (2007) were used to analyse the MODIS reflectance data to determine flood extents during previous flood events.

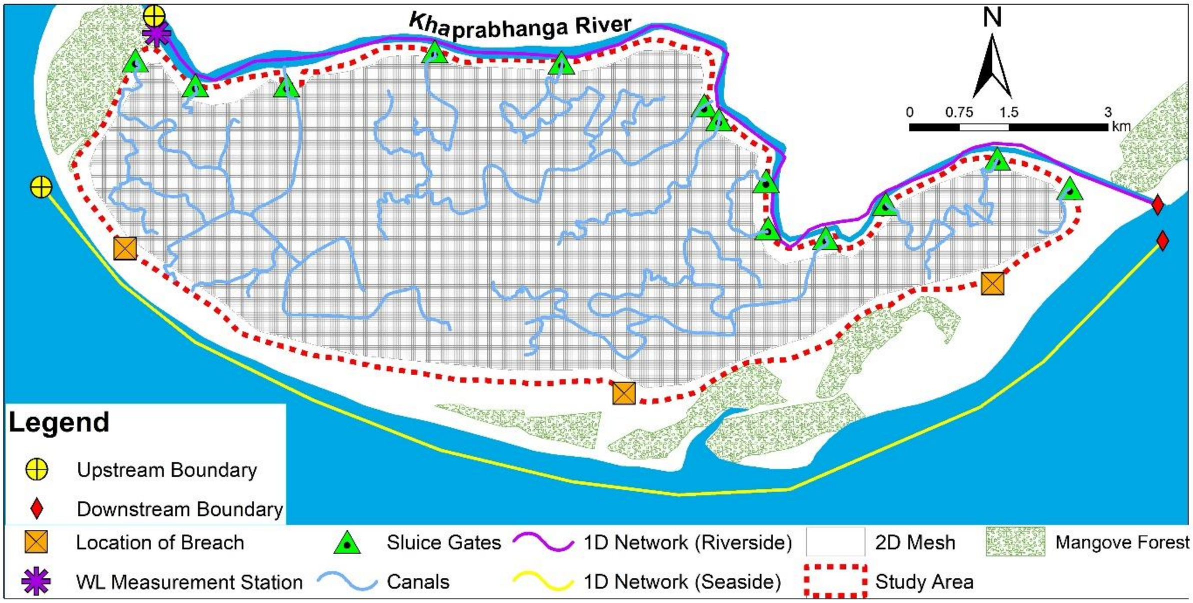

Figure 3: **Schematic diagram of the study area with location of control structures and gauges and the considered breach locations.**

The river analysis tool HEC-RAS from the US Army Corps of Engineers was used to develop the 1D-2D inundation model. Building and calibrating the 1D model was the preliminary step for developing the 1D-2D coupled model. The water bodies surrounding the study area were included in the 1D model. The study area has Khaprabhanga River on the northern side and sea on the southern side (Figure 3). The connection of Khaprabhanga River with other rivers was not considered in the model. This was due to the fact that storm surges are observed during the pre or post monsoon periods whereas fluvial floods are observed during the monsoon. Flow through rivers did not play a major role during the previous cyclones. The western and eastern side of the embankment have mangrove forest between the rivers and the embankment (**Error! Reference source not found.**Figure 3Figure 3).

For the rivers, the surveyed cross sections were used in the 1D model (Figure 4). The western and eastern side of the embankment have mangrove forest between the rivers and the embankment (Figure 3). The storm surges on the sea was conceptualised as a water surface profile in a To represent the sea and the storm surges, a 1D channel on the southern side of the study area (Figure 3). was added using tThe GEBCO bathymestryic data from GEBCO (Figure 5) was used for the channel. An alternative was to develop s the coast of Bangladesh is flat and shallow, a 2D model for the coastal hydrodynamics. However, as the coast of Bangladesh is flat and shallow a will require inclusion of larger area of the sea would have been included in the model. As the focus was on studying the inundation in Polder 48 and not the coastal sea we followed a simpler representation of the storm surges using a 1D model. which was not the area of interest and which would have increased the simulation time too. The utilised 1D network was not connected with the rivers considering that the river water didn't play a

~~major role during the previous cyclones as most of the cyclones hit the coast of Bangladesh in pre or post monsoon.~~ The water surface profile corresponding to each s~~S~~cenario (Table 2, discussed in Section 3.2) was considered as the profile in ~~boundary condition for~~ the 1D model of the sea side ~~was utilised as such that the water level along the 1D network representing the sea side remains similar throughout the simulation time~~ (Figure 6).

The dense canal network of 122 km, inside the study area, is connected with the Khaprabhanga River, which regulates the in- and out flow into the river network through a system of 13 control structures. The regulators remain closed during ~~a~~ cyclones making the canal network isolated. Therefore, the canal network inside the polder was not included in the 1D model. However, the simulation of the overland flow consequent to ~~canal will affect the flow after~~ breaching of the dike will be affected by the canal geometry and ~~. T~~therefore, the wider and larger canals were included in the DEM.

The geometry and propagation of the breach of the dike depends primarily on the storm surge height, angle of landfall, soil properties and wave action. The coastal embankments of Bangladesh are usually earthen ~~embankments~~. The geometrical properties of the breaching of the dike and the time required for breaching were calculated following the instructions of US Bureau of Reclamation. An *S*-curve was used for breach propagation with time (Oumeraci, 2006). As the geometry of the breach is not independent, it was not considered as a parameter for s~~S~~cenario development.

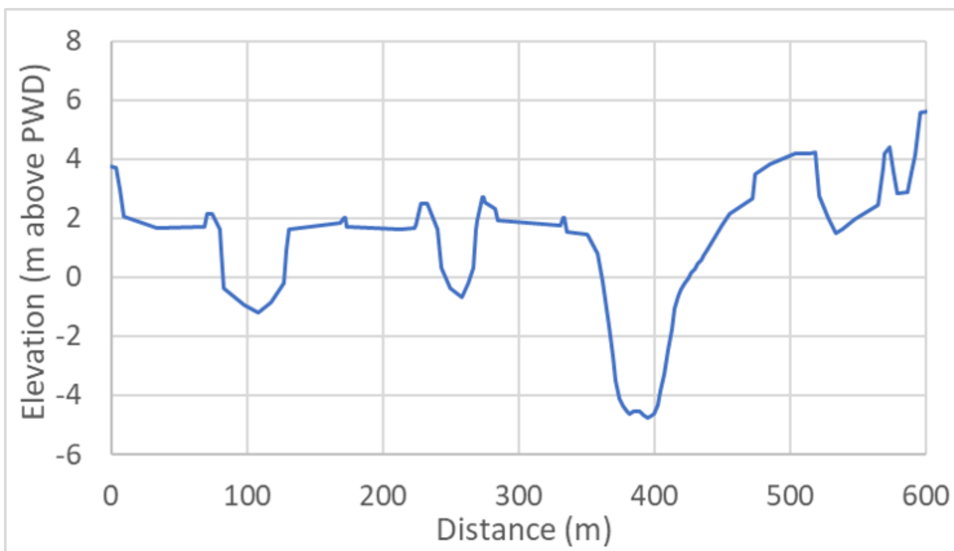

Figure 4: A typical ~~Example of~~ cross section ~~used offor~~ the Khaprabhanga River

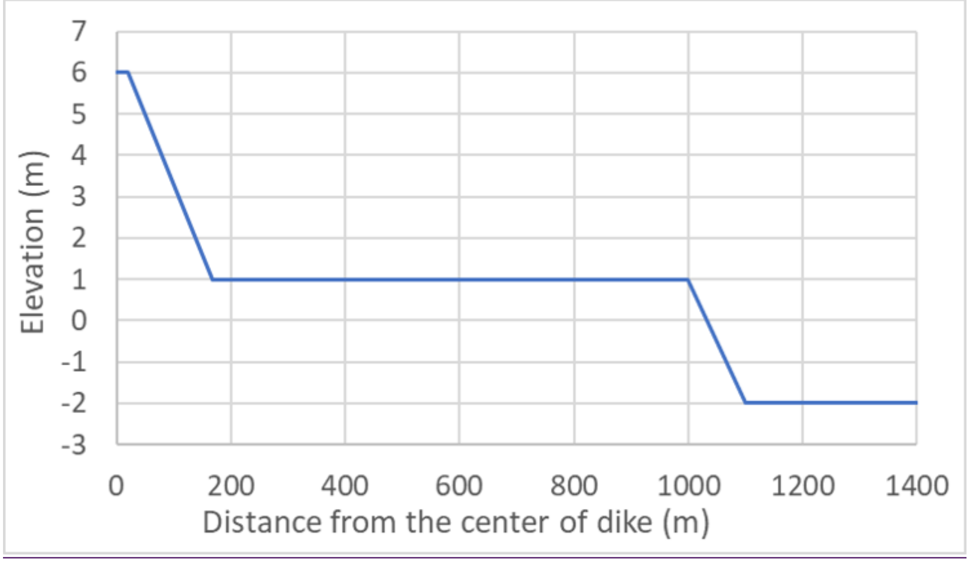

Figure 5: Cross section for the 1D network on the sea side

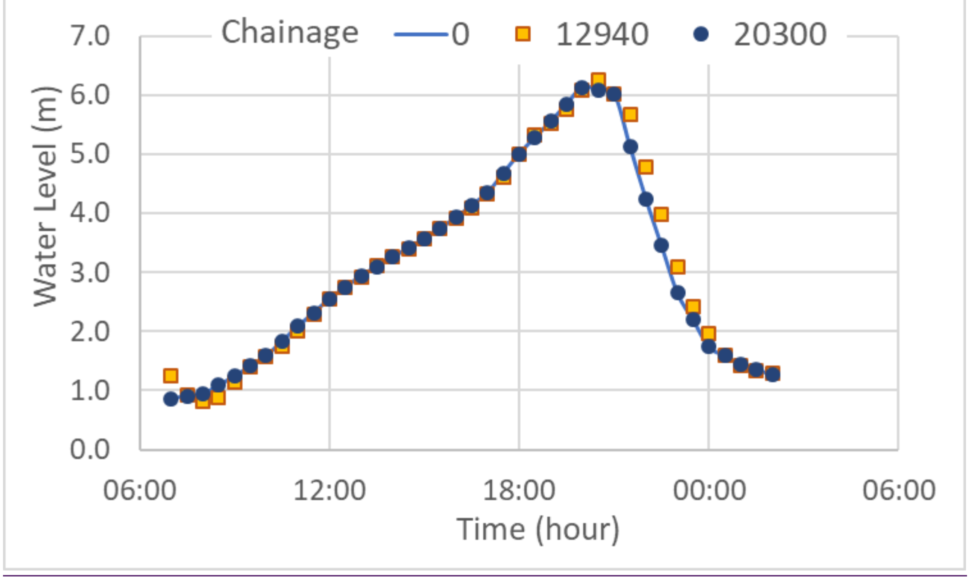

Figure 6: Variation of w~~W~~ater level at three locations (chainage 0, 12940 and 20300) ~~different chainage~~ along the 1D channel~~network~~ on the sea side according to a specific Scenario (out of 72 Scenario).

In order to ensure model stability a maximum spacing between the computational points was imposed and computed using Samuels' formula (1989) presented in Eq. (1):

$$\Delta x \leq 0.15 * D/So \quad (1)$$

where, Δx is the spacing between the computational points, D is the average bank full depth of the channel and S_0 is the average slope of the channel. The maximum spacing between cross sections was calculated as 300 m. The river had steeper bed slope than the long shore slope of the sea bathymetry requiring smaller Δx to ensure stability and same Δx will reduce instability of the foreshore as well.

As suggested by Fromm (1961) the Courant number was kept less than or equal to 1.0 to maintain the stability of the numerical model by controlling the time step. The Courant number was calculated using the following Eq. (2):

$$Cr = V * \Delta t / \Delta x \tag{2}$$

where Cr is Courant number, V is velocity, Δt is the time step and Δx is the spacing between the cross sections.

3.2 Cyclonic s~~S~~cenarios considered

Different ~~S~~scenarios were developed considering the probability of occurrence of cyclones, the angle of landfall, SLR due to climate change, diurnal, semi-diurnal and seasonal variation of tides, locations of breaching of the dike and geometrical properties of the breach.

Frequency of cyclone: A cyclone of 1 in 25 year return period was considered for all the s~~S~~cenarios as this is used as the design criteria for the dikes (BWDB, 2013). Nineteen previous cyclones for different tidal conditions were simulated by IWM using a 2D model for the Bay of Bengal. A statistical analysis was conducted using these model results to generate the storm surge height corresponding to a cyclone of 25 year return period (Islam *et al.*, 2013). Due to lack of data, change in the probability of occurrence of the cyclone in the future was not considered.

Angle of landfall: The angle of landfall affects the height of storm surges. The storm surge height increases with angle of the storm to the coastline (Azam *et al.*, 2004). Angle of attack governs the wind speed which is one of the parameters for the height of cyclone induced storm surges (Azam *et al.*, 2013).

Tides: The difference between the storm surge at high tide and low tide is 1.2m for the study area (Azam *et al.*, 2004). The average seasonal variation of the tidal range is 1.3m.

Sea level rise: The coast of Bangladesh may be severely affected by SLR and one fourth of the land may be lost due to SLR by 2100, which will directly affect 3 million people (Ericson et al., 2005). IPCC published their 5th assessment report (AR5) in 2013. Among the s~~S~~cenarios considered in AR5, RCP (representative concentration pathways) 2.6 is the most optimistic one and RCP 8.5 is the worst considering the carbon emission, rise in temperature and SLR. The mean SLR at the end of 21st century is estimated to be 0.4m, 0.47m, 0.48m and 0.63m for ~~Scenario~~RCP 2.6, RC 4.5, RCP 6.0 and RCO 8.5 respectively (Stocker *et al*., 2013). For this study, ~~Scenario~~RCP 8.5 with SLR of 0.63 m was considered for developing the s~~S~~cenarios.

Location of breach: The sections of the sea facing dike of the study area protected by mangrove forest, sand dunes and wide beach are least likely to be breached due to storm surges. The study considered breach locations with least protection. The considered locations for dike breach as well as the mangrove forest around the study area are shown in Figure 3.

~~The geometry and propagation of the breach of the dike depends primarily on the storm surge height, angle of landfall, soil properties and wave action. The coastal embankments of Bangladesh are usually earthen embankments. The geometrical~~

properties of the breaching of the dike and the time required for breaching were calculated following the instructions of US Bureau of Reclamation. An *S*-curve was used for breach propagation with time (Oumeraci, 2006). As the geometry of the breach is not independent, it was not considered as a parameter for scenario development.

A sScenario matrix consisting of 72 sScenarios were generated by combining different phases of tides, angle of landfall, SLR and breach locations (Table 2). Single breach was considered for each sScenario. The highest storm surge height among all the developed sScenarios was 7.2 mPWD considering the angle of landfall as 230^0, high tidal phase during spring tides, SLR and dike breaching at any of chosen locations. This storm surge height with breaching at the western, central and eastern parts of the dike were considered as the worst case sScenarios and were denoted as Scenario 1, 2 and 3 respectively. Flooding due to overtopping of the dikes was not considered as the crest level (7.36 mPWD) was higher than the highest storm surge height (7.2 mPWD).

Table 2: Storm surge heights corresponding to different Scenarios considered

Angle of Landfall	Tidal Variation		Breach Locations: East, With SLR	East, Without SLR	West, With SLR	West, Without SLR	Central, With SLR	Central, Without SLR
			Storm Surge Heights					
200	High Tide	Spring tide	4.06	3.38	4.06	3.38	4.06	3.38
		Neap tide	2.77	2.09	2.77	2.09	2.77	2.09
	Low Tide	Spring tide	2.83	2.15	2.83	2.15	2.83	2.15
		Neap tide	1.54	0.86	1.54	0.86	1.54	0.86
215	High Tide	Spring tide	6.16	5.48	6.16	5.48	6.16	5.48
		Neap tide	4.86	4.18	4.86	4.18	4.86	4.18
	Low Tide	Spring tide	4.93	4.25	4.93	4.25	4.93	4.25
		Neap tide	3.63	2.95	3.63	2.95	3.63	2.95
230	High Tide	Spring tide	**7.20**	6.52	**7.20**	6.52	**7.20**	6.52
		Neap tide	5.91	5.23	5.91	5.23	5.91	5.23
	Low Tide	Spring tide	5.97	5.29	5.97	5.29	5.97	5.29
		Neap tide	4.68	3.99	4.68	3.99	4.68	3.99

To identify the critical location of breaching simulation results with HEC-RAS corresponding to the three worst case sScenarios were compared based on the total area flooded and estimated damage due to flooding. Using the calculated damage and occurrence probability of the event, a risk map was generated for the critical locations of the sea facing dike. A probabilistic flood map (PFM) was generated from the flood maps of the 72 sScenarios (Table 2).

Different scenarios were developed considering the probability of occurrence of cyclones, the angle of landfall, SLR due to climate change, diurnal, semi-diurnal and seasonal variation of tides, location of breaching of dike and geometrical properties of the breach. A cyclone of 1 in 25 year return period was considered for scenario development as this is used as the design criteria for the dikes (BWDB, 2013). Nineteen previous cyclones for different tidal conditions were simulated by IWM using a 2D model for the Bay of Bengal. A statistical analysis was conducted using these model results to generate the storm surge height corresponding to a cyclone of 25 year return period (Islam *et al.*, 2013). The angle of landfall and the tidal phase affect the height of storm surges. The storm surge height increases with angle of the storm to the coastline (Azam *et al.*, 2004). Angle of attack governs the wind speed which is one of the parameters for the height of cyclone induced storm surges (Azam *et al.*, 2013). The difference between the storm surge at high tide and low tide is 1.2m for the study area (Azam *et al.*, 2004). The average seasonal variation of the tidal range is 1.3m.

The coast of Bangladesh may be severely affected by SLR and one fourth of the land may be lost due to SLR by 2100, which will directly affect 3 million people (Ericson et al., 2005). The land subsidence in the delta will exacerbate the effect of SLR. SLR and sea surface temperature (SST) will affect the cyclone induced storm surge height in the Bay of Bengal (Karim and Mimura, 2008). With increasing SST, the storm surge height can increase from 21% to 49% (Karim and Mimura, 2008) and 20 with SLR, the flood depth due to storm surges may increase by 30-40% (Karim and Mimura, 2008). The Intergovernmental Panel on Climate Change (IPCC) published their 5th assessment report (AR5) in 2013. Among the scenarios considered in AR5, RCP (representative concentration pathways) 2.6 is the most optimistic one and RCP 8.5 is the worst considering the carbon emission, rise in temperature and SLR. The mean SLR at the end of 21st century is predicted to be 0.4m, 0.47m, 0.48m and 0.63m for scenario RCP 2.6, RC 4.5, RCP 6.0 and RCO 8.5 respectively (Stocker *et al.*, 2013). For this study, the 25 worst case scenario RCP 8.5 with SLR of 0.63 m was considered for developing the scenarios.

The sections of the sea facing dike of the study area protected by mangrove forest, sand dunes and wide beach are least likely to be breached due to storm surges. The study considered breach locations with least protection. The considered locations for dike breach as well as the mangrove forest around the study area are shown in Figure 3.

The geometry and propagation of the breach of the dike depends primarily on the storm surge height, angle of landfall, soil properties and wave action. The coastal embankments of Bangladesh are usually earthen embankments. The geometrical properties of the breaching of the dike and the time required for breaching were calculated following the instructions of US Bureau of Reclamation. An *S*-curve was used for breach propagation with time (Oumeraci, 2006). As the geometry of the breach is not independent, it was not considered as a parameter for scenario development.

For the generation of the probabilistic flood map (PFM), a scenario matrix consisting of 72 scenarios were generated combining different values of tidal level, angle of landfall, SLR and breach locations (Table 2). Single breach was considered for each scenario. The storm surge height corresponding to a cyclone of 25 year return period (Islam *et al.*, 2013) and the SLR for RCP 8.5 of AR5 by IPCC were considered. Due to lack of data, change in the probability of occurrence of the cyclone in the future was not considered. The highest storm surge height among all the developed scenario was 7.2 mPWD considering the SLR, worst angle of landfall, high tides and spring tide, simultaneously. Due to the worst case of all the parameters, this storm surge height was considered for worst case scenarios. Breaching at west, central and eastern part of the dike with the highest storm surge were considered as the worst case scenarios and were denoted as Scenario 1, 2 and 3 respectively. Flooding due to overtopping of the dikes was not considered as the proposed crest level (7.36 mPWD) was higher than the storm surge height of the worst case scenario (7.2 mPWD). The three locations selected for breaching were considered to present an approach to analyse the effect of dike breach and identify the worst case scenario.

Table 21: Storm surge heights corresponding to different scenarios considered.

Angle of Landfall	Tidal Variation		Breach Locations: East, With SLR	East, Without SLR	West, With SLR	West, Without SLR	Central, With SLR	Central, Without SLR
			Storm Surge Heights					
200	High Tide	Spring tide	4.06	3.38	4.06	3.38	4.06	3.38
		Neap tide	2.77	2.09	2.77	2.09	2.77	2.09
	Low Tide	Spring tide	2.83	2.15	2.83	2.15	2.83	2.15
		Neap tide	1.54	0.86	1.54	0.86	1.54	0.86
215	High Tide	Spring tide	6.16	5.48	6.16	5.48	6.16	5.48
		Neap tide	4.86	4.18	4.86	4.18	4.86	4.18
	Low Tide	Spring tide	4.93	4.25	4.93	4.25	4.93	4.25
		Neap tide	3.63	2.95	3.63	2.95	3.63	2.95
230	High Tide	Spring tide	**7.20**	6.52	**7.20**	6.52	**7.20**	6.52
		Neap tide	5.91	5.23	5.91	5.23	5.91	5.23
	Low Tide	Spring tide	5.97	5.29	5.97	5.29	5.97	5.29
		Neap tide	4.68	3.99	4.68	3.99	4.68	3.99

To identify the critical location for breaching of the dike results of the three worst case scenarios were compared using the total area flooded and estimated damage due to flooding. Using the calculated damage and occurrence probability of the event, a risk map was generated for the critical locations of the sea facing dike. A probabilistic flood map (PFM) was generated from the flood maps of the 72 scenarios (Table 2).

3.3 Estimation of damage due to floods

A comprehensive damage calculation should involve both direct and indirect damages due to floods (Büchele *et al.*, 2006). Direct damage is caused by physical contact of properties and human beings with flood water. Indirect damage is caused by interruption of services, production and transportation and, degradation of health etc. due to floods. Due to lack of data, only the direct damage to properties were calculated for the study area. The damage was considered as a function of flood depth.

Depth-damage curves for different land classes for the study area were developed by adapting existing depth-damage curves from elsewhere (Figure 3). The land use of the study area was classified by the Ministry of Land of Bangladesh in residential areas (settlements), rice fields, shrimp ponds and water bodies (rivers/canals) by the Ministry of Land of Bangladesh. Only the tangible damage was considered and no environmental damage was calculated. Damages to the canal network was not considered. The damage in a flood event was calculated using the following Eq. (3).

$$D = \left(\sum_{i=0}^{n} x_i \times f\,(x_i)\right) \times A_i \qquad (3)$$

Where, D = total direct tangible damage in a flood event, n = total number of computational cells within the flooded area, x_i = flood depth of cell i, $f\,(x_i)$ = damage function for the land use of the flooded cell i and A_i = area of cell i.

Depth-damage curves for different land classes for the study area were developed by adapting existing depth-damage curves found in the literatureprovided by different studies for similar land usesfrom elsewhere (Figure 7Figure 7Figure 3). Reese *et al*. (2010) calculated flood damage as a percentage of the value of the property value offor different buildings categorised based on types according to the construction material. The buildings of the study area are primarily built of timber due to its low cost and easy availability. The depth-damage ratio curve suggested by Reese *et al.* (2010) for buildings made of timber was used as a basis for generating the depth-damage curve for the settlements (residential area). Simple Action for the Environment (SAFE) carried out a research on the average value of properties in rural areas of Bangladesh (SAFE, 2011). This property values were used to update the damage values used by Reese *et al.* (2010)develop the depth-damage curve for the settlements of the study area. As the rural houses in Bangladesh usually have a lot of open and unoccupied spaces, 50% of the area of a settlement was considered areas with no damages. Muktadir and Hasan, (-1985) reported stated in their study that the rural houseshold of Bangladesh usually are built with around a large cournttry yard and as a result houses have a lot of open and unoccupied space around buildings. The land classification by the Ministry of Land defines the whole house hold including the country yard as residential area. TBut the damage curve considered for the residential area was used for the damage to the buildingshouse and not for the cournttry yard will not have significant damage if flooded. Moreover, the satellite image of the area also indicated that about half of the settlement area of residential complex (house hold) wais without buildingsusually empty. Therefore, 50% of the settlement area was considered with no damages-.

The cultivation of rice involves flooding the rice field with water up to a few of several cm. However, But if the height of water increases and the rice plant goes under water then, the productivity decreases. The damage to rice plants also depends upon the flood duration. If the rice plant is continuously under water for more than 2-3 days then the damage can be up to 80% (Chau *et al*., 2014). The depth-damage curve for rice fields suggested by Chau *et al*. (2014) was used in thisfor the study area (Figure 7).

Based on the practices in the study area the banks of the shrimp ponds were considered as 2 meter above the adjacent land. Shrimp ponds are surrounded by embankments so Therefore, it was assumed that there iswill be no damage to shrimp ponds till the flood leveldepth crosses the embankment levelreaches 2 meter. However, after the flood level is higher than the embankment levelgoes above the banks of the shrimp ponds the shrimps will escape to the flooded area and causeing a loss of the total investment. To take this into account, the investment made by farmers was assessed using a study conducted by Fatema *et al.* (2011). According to the study the investment for shrimp pond in the study area was about € 0.09/ m^2 ~~Euros per square meter~~. Based on the practices in the study area the banks of the shrimp ponds were considered as 2 meter above the adjacent land and the depth-damage curve (Figure 7~~Figure 7~~Fig. 7) was modified accordingly. ~~.~~The adapted depth-damage curves are obviously simplistic ones. Further research is needed for improving them.

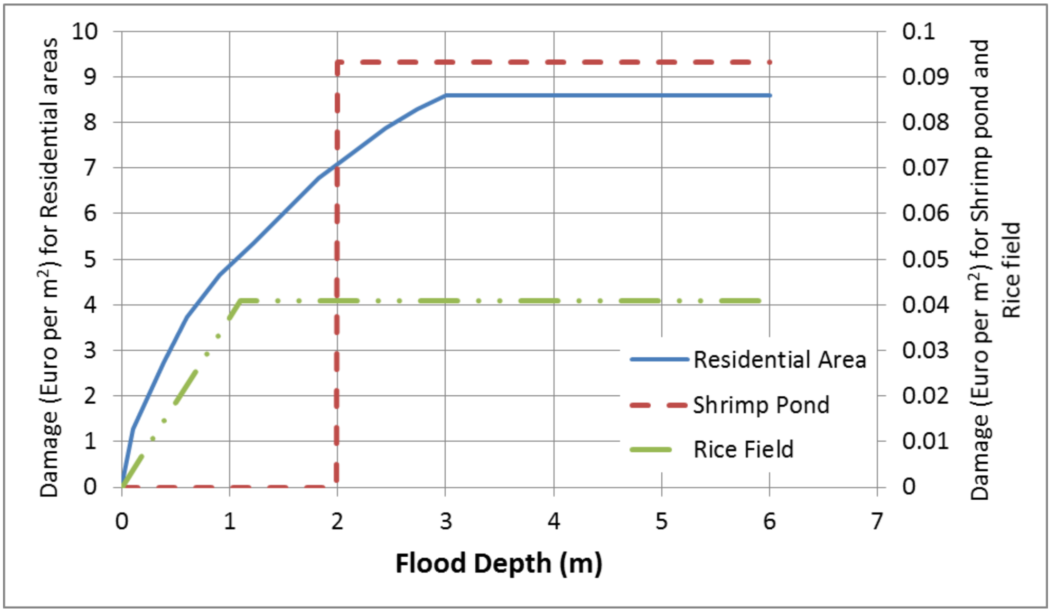

Figure 7: Depth-damage curves for different land use classes.

The~~For carrying out~~ damage calculations were carried out using ~~, a simple tool was developed in~~ ArcGIS. The simulated flood depth and landuse for each grid cell ~~The tool~~was used~~s simulated inundation map and landuse map~~ as the input and the damage ~~, calculates damage~~ in each grid cell~~s~~ was computed by using the ~~identifying landuse class and flood depth, and by applying the appropriate~~ depth-damage curve corresponding to that landuse. The damage for each s~~S~~cenario was estimated using this procedure~~tool~~. ~~The critical location of breaching was selected by considering maximum flooded area and estimated flood damage. The developed depth-damage curve obviously is a simple one, which was built by updating the existing ones. More research is needed to improve the depth-damage curve.~~

3.4 Calculation of flood risk and generation of risk map

Flood risk assessment is an essential part of risk management. Spatial distribution of risk and areas requiring mitigation measures can be identified from flood risk maps (~~Meyer *et al.*, 2009~~Helm, 1996). To examine the spatial variation of risk, flood risk analysis was carried out and a risk map was generated considering dike breaching at the critical location. Van Manen and Brinkhuis (2005) and Klijn (2009) under FLOOD*site* project carried out research to quantify the flood risk for the polders in The Netherlands for dike failure defining the risk as a product of the occurrence probability of the event and the consequences. ~~The following~~ Eq. (4) ~~developed from FLOOD*site* definition~~ was used to calculate the risk due to flooding:

$$R = P_F * S \qquad (4)$$

Where, R = risk, P_F = probability of occurrence of the flood hazard and S = consequences

The exceedance probability (return period) of the cyclone induced storm surge was used as the probability of occurrence of the hazard. The probability of flooding within a protected area is not the same as the probability of the hazard and depends also upon the probability of failure of the dike. It is a difficult probability to compute as the probability of dike failure also depends upon the dike maintenance, information about which were not available ~~and we did not have information about dike maintenance~~. ~~As a simplistic approach~~ ~~H~~here we have assumed that the probability of occurrence of the hazard and the probability of failure of dike ares~~s~~ the same.

3.5 Probabilistic flood map

Purvis *et al.* (2008) stated that the risk assessment for the most probable s~~S~~cenario cannot take into account the impact of the s~~S~~cenario of low probability stressing the necessity of a probabilistic risk analysis. The equation ~~used~~ suggested by Purvis *et al.* (2008) for probabilistic risk analysis was adjusted and used for this research to calculate the probability of flooding of each cell and is presented below in Eq. (5):

$$P_{i(i=1\ to N)} = \frac{\sum_{j=1}^{M} F_{ij} \times P_{fj} \cancel{\sum_j Fij \times P_{fj}}}{\sum_{j=1}^{M} P_{fj} \cancel{\sum_j P_{fj}}} \ and\ F_{ij} = \begin{cases} 1, & if\ flooded \\ 0, & if\ dry \end{cases} \qquad (5)$$

Where, P_i is probability of flooding at cell i, P_{fj} is the probability of reaching a certain storm surge level in simulation number j, F_{ij} is the binary value indicating if the cell i is flooded or not in simulation j, j =1,2,3, .., M where M is the number of Scenarios considered (=72), i =1,2,3,…, N are the computational grid cells on the polder area and N is the number of cells. Equation (5) was used in this study~~paper~~ to calculate the probability of flooding at each cell. The probabilistic flood map (PFM) was calculated using the results of all the scanerios~~scenarios of the developed scenario matrix~~.

4. Results and discussion

~~A 1D-2D model was developed and simulated for different scenarios in this study.~~ The developed 1D-2D modelled for the present study was calibrated for the 1D part ~~1D part of the model was calibrated~~ by comparing the observed and simulated values for ~~-~~discharge and water level ~~and discharge~~. The corresponding performance indicators used for evaluation were coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE) for which values of ~~were~~ 0.98, 2.15 m^3/s and 1.68 m^3/s respectively were obtained for discharge; and 0.98, 0.09 m and 0.08 m respectively for water level. The average value of the discharge and water level for the considered simulation period was 5.68 m^3/s and 0.82 m respectively ~~for the simulation period~~. The period of simulation for calibrat~~ed~~ion ~~model was simulated~~ coincide~~d~~s with ~~for~~ the

~~storm~~ surges corresponding to cyclone Sidr (from November 14 to November 17, 2007). The simulation results indicates~~d~~ that the ~~sea facing~~ dike facing the seaside ~~of the study area~~ was overtopped and the area inside the polder was inundated. This conclusion is in line with t~~T~~he survey conducted by Japan Society of Civil Engineers (JSCE) ~~after cyclone Sidr had similar findings~~ (Hasegawa, 2008).

The coupled 1D-2D -model has not been calibrated because ~~N~~there we~~a~~re no~~o~~ flood maps~~,~~ showing flood extents available for recent cyclones ~~were available for the study area to calibrate the 1D-2D model~~. However, the 2D part of the model was pseudo-calibrated -considering MODIS reflectance data. Such data -was used in order to analyse~~d~~ ~~for~~ the -inundation extent, though ~~.~~ ~~The availability of MODIS data~~this also posed considerable ~~-was~~ challenge~~d~~s due to the cloud coverage during the cyclones. The survey conducted by JSCE after cyclone Sidr was collected to investigate the flood extent and depth, which provided ~~.~~ ~~F~~flood depth for only one location inside the study area ~~was provided by JSCE~~. This location was used for the calibration of 2D model. The error in the simulated flood depth was 4.5%. Prior to the calibration of the 2D model, sensitivity analysis was carried out~~r~~ regarding the roughness coefficient (Manning's *n*). The analysis indicated that the inundation model is not highly sensitive to the roughness coefficient and the areas of low flows (locations furthest from the dike breach) are most sensitive. The sensitivity analysis was done for the breaching on the western part of the dike only. It was considered that the breaching at other locations will have similar effects as the area inside the polder is flat and low lying with mostly farmlands near the dike.

This ~~The~~ 1D-2D model, which had ~~with~~ limited calibration points, was further used in simulating the developed s~~S~~cenarios. The simulated results were used ~~in~~to analys~~ing~~e flood depth, ~~flood~~ extent and damages due to flood. The FRM and the PFM were generated based on flood results of the model~~from the results~~.

4.1 Inundation corresponding to three worst case Scenarios

Among the simulated s~~S~~cenarios, the results of three worst case s~~S~~cenarios (Scenario 1, 2 and 3) were compared for identifying the critical location of breaching~~. The flood maps were created from the simulated results~~. The corresponding flood maps for the worst case s~~S~~cenarios are presented in Figure 8.

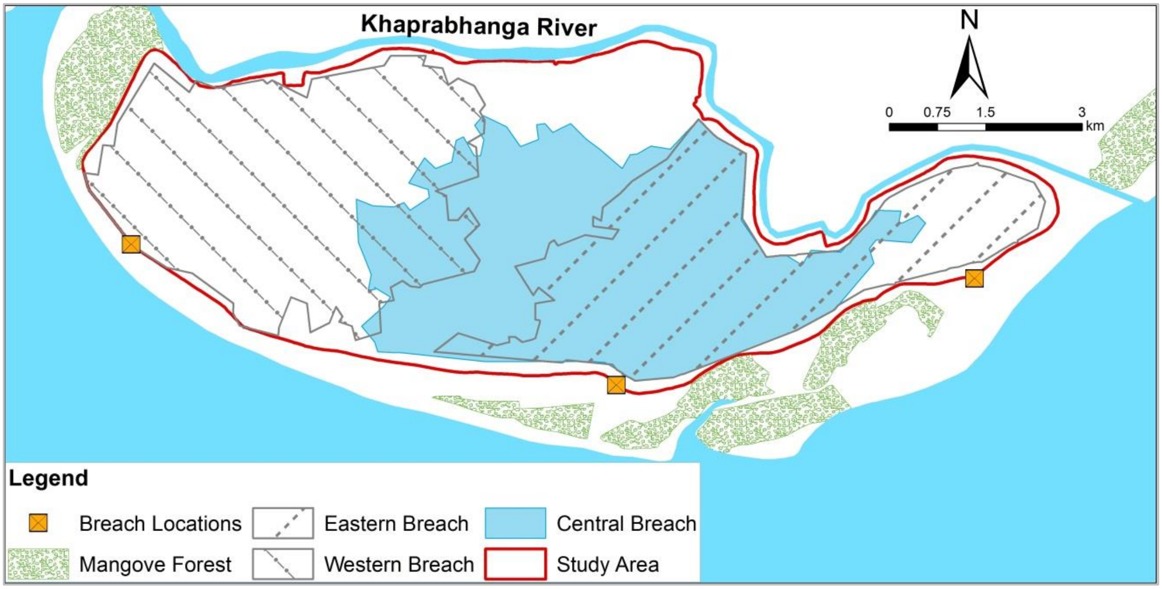

Figure 8: Flood extent corresponding to three worst case s~~S~~cenarios of dike breaching in the central, eastern and western section of the dike.

Flood extents corresponding to all different s~~S~~cenarios presented in Table 1 were compared to understand the effect of SLR, diurnal and seasonal tidal variation and angle of cyclone at landfall. The flood extent~~d~~s of different s~~S~~cenarios considering the breaching at central part of the sea facing dike is presented in Figure 9.

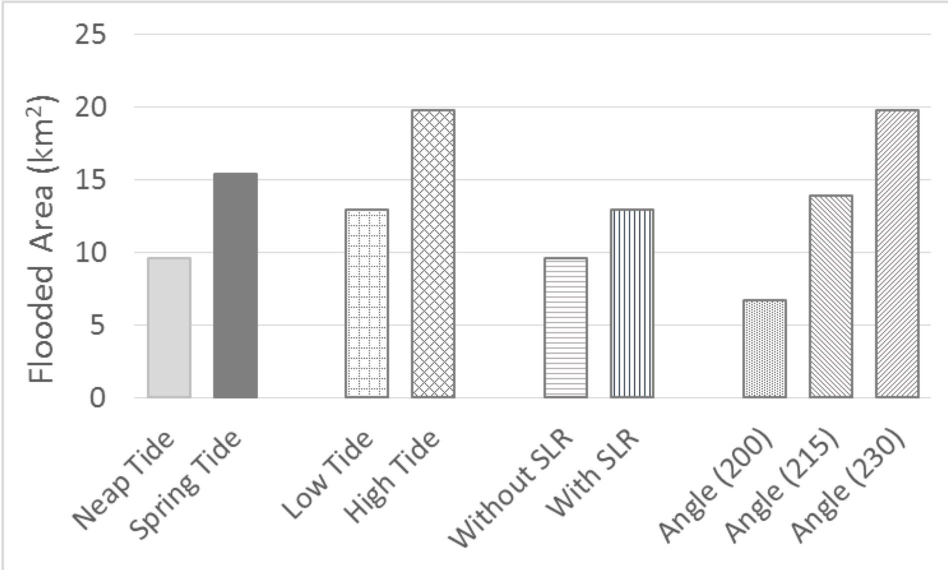

Figure 9: Comparison of flooded areas corresponding to different Scenarios.

Moreover different The flooded areas for different land classes were considered calculated while computing the flood extent for the three worst case sScenarios (Table 3). The analysis of the flooded area extents for different flood depths, based on the considered land uses are presented ranges were also analysed in (Figure 10).

Table 3: Flooded areas of different land classes corresponding to the three worst case Scenarios.

Land Classes	Flooded Area (km^2)		
	Scenario 1	Scenario 2	Scenario3
Rice fFields	15.3	16.4	12.3
Settlements	3.1	3.1	2.1
Shrimp pPonds	0.2	0.1	0.1
Canals	1.2	1.7	1.2
Total	19.8	21.2	15.8

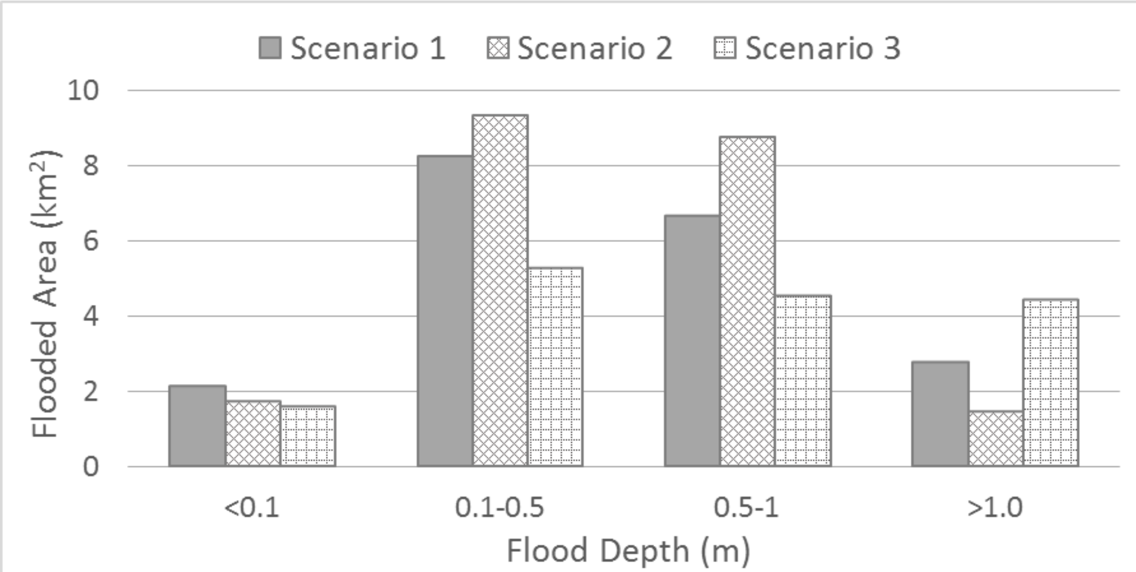

Figure 10: Flooded areas for different ranges of flood depths corresponding to different Scenarios.

4.2 Comparison of calculated damages

The damage due to flooding was calculated using the depth-damage curves for different land classes~~ and the tool developed in ArcGIS~~. The calculated damages for different land classes and damages for different flood depths corresponding to the three worst case s~~S~~cenarios are presented in Table 4 and Figure 11.

Table 4: Calculated flood damages for different land classes corresponding to different s~~S~~cenarios.

Land Classes	Estimated flood damage (million Euros)		
	Scenario 1	Scenario 2	Scenario 3
Rice Fields	0.4	0.4	0.3
Settlements	10.3	10.3	8.3
Shrimp Ponds	0.0	0.0	0.0
Total	10.7	10.7	8.7

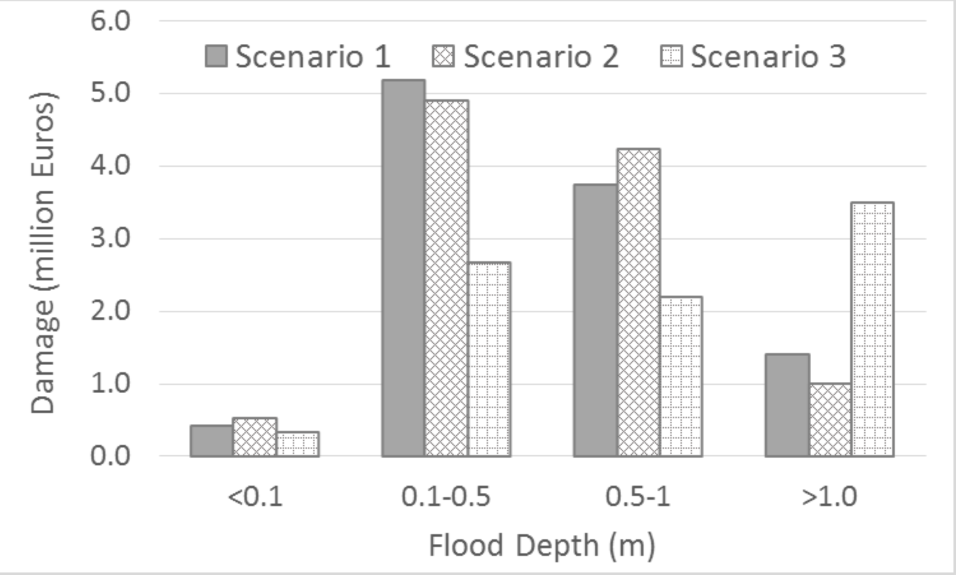

Figure 11: Variation of estimated flood damages with varying ranges of flood depths corresponding to Scenario 1, 2 and 3.

4.3 Risk map for the worst case s~~S~~cenario

The flood risk map for the s~~S~~cenario with the critical location of breaching of dike is presented in Figure 12. ~~The risk maps were generated using the process explained in the previous section (Methodology).~~ The risk map presents the assessed risk of flooding due to breaching at critical locations of the dike. The identification of the critical location of breaching is described in ~~the following~~ section 4.5.

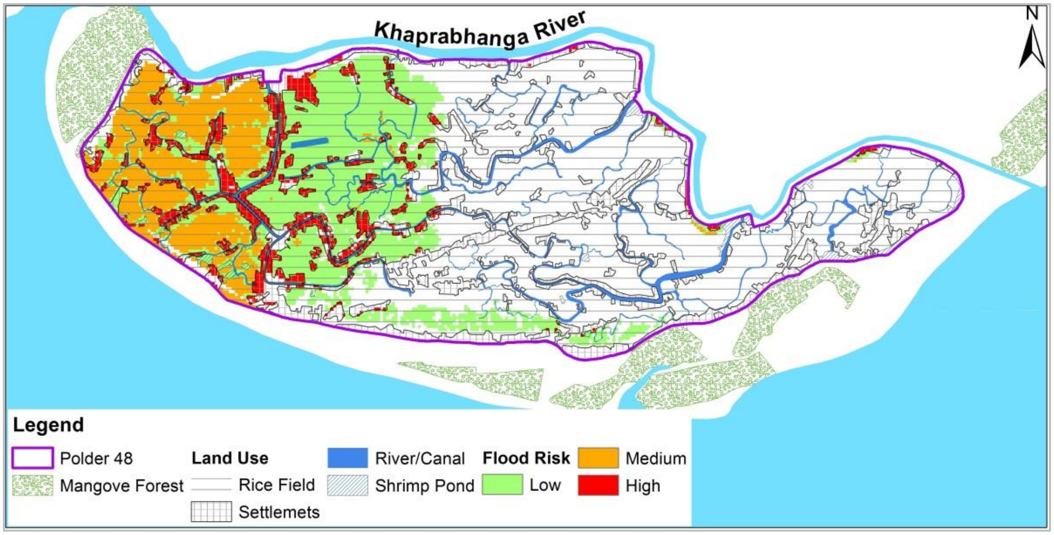

Figure 12: Flood risk map corresponding to the dike breach at the critical location of the dike. The following three classes of risk are shown: high, medium and low. The considered four landuses are shown as well.

4.4 Probabilistic flood map

Although the inundation maps are widely used for spatial planning and flood mitigation measures, the uncertainty of mathematical modelling~~ tool~~ affects the output of inundation maps (Alfonso *et al.*, 2016). ~~To take the~~In order to account for uncertainty~~ into account~~, probabilistic flood maps are suggested to be used (Domeneghetti *et. al.*, 2013). The probabilistic flood map was calculated from the inundation maps corresponding to the 72 s~~S~~cenarios considered in the study. Probabilistic flood maps were calculated for a threshold of flood depth greater than 0.5 m. The developed damage curves suggest that the damage for flood depth below 0.5 m is minimal. Moreover, considering the widely accepted ´~~To explore the effect of ~~living with floods´ philosophy in Bangladesh a threshold of 0.5m was adopted. ~~concept and to take the uncertainty of the DEM and the 2D inundation model into account, this depth as~~the 0.5 m inundation depth ~~was considered. For a country where flood is a recurrent phenomenon, and where with larger depths of inundation occurs, living with flood might be already adopted by the local people.~~ T~~Moreover, t~~his arbitrary threshold~~depth~~ was used in developing the~~for~~ PMFs and the estimation of damage due to flood was not affected. The calculated probabilistic flood maps are presented in Figure 13. The probabilistic flood map indicates the likelihood of being flooded. This will assist the planning for future land use zoning, which can be used to restrict further developments in the floodplains.

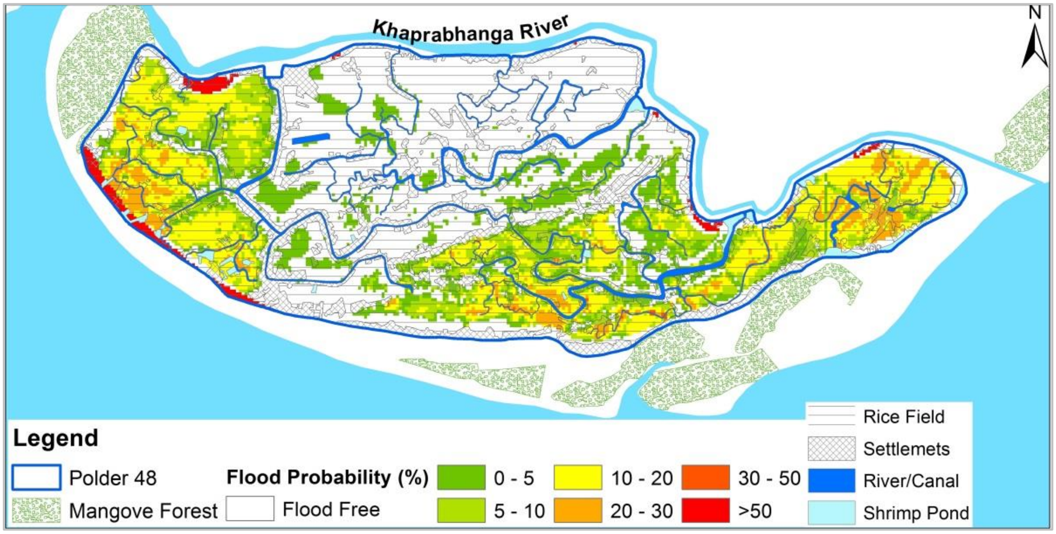

Figure 13: Probabilistic flood map of the study area. Varying colours indicate probabilities of obtaining flood depths more than 0.5m.

4.5 Discussion on the results

Among the scenarios developed, the results of tThree worst case sScenarios (Scenario 1, 2 and 3) were compared by generating flood maps, calculating total flooded areas and total damages. The flood maps for Scenario 1, 2 and 3 (Figure 8) demonstrate that large area is flooded for all the breach locations. However, Figure 9Figure 9 indicates that the flood extent is different for different sScenarios. More than 25% of the total area of Polder 48 was inundated for all the three worst case Sscenarios (Table 3). With In the case of all 3three considered sScenarios, the inundation area withhaving flood depths from 0.5 to 1.0 m, was larger than the inundation areas with other flood depths (Figure 10). The inundation area with flood depths more than 1m was largest for Scenario 3, due to the depressions close to the dikes (Figure 10). The rice fields were flooded- mostre in all three Scenarios, while- most and the shrimp ponds were flooded least in all the sfor all the Scenarioss (Table 3).

Flood risk was quantified with damage due to floods (negative consequences) and probability of occurrence. The total estimated damages due to flooding for Scenario 1, 2 and 3 were 10.71, 10.67 and 8.61 million Euros, respectively (Table 4). For all the sScenarios, a 1--in--25 year cyclone event was considered. The damage to the settlements was greater than other land classes for all the sScenarios (Table 4). Rice fields were flooded most but they did not experience the highest damage compared to other landuse classes (Table 3 and Table 4). This can be explained by the high damages in settlements compared to rice fields (Table 4). The damage to crops depends on the flood depth, duration and overland flow velocity. For simplification, only the damage related to flood depth was used. As the probability of cyclones were considered the same for all the sScenarios, the calculated damage governed the estimated flood risk, i.e., . Hhigher damage to the settlements translated as higher risk of flooding. The primary economic activity of the inhabitants of the study area is farming and most of the inhabitants are poor. Even though the estimated damage and risk of flooding to crops are were much less compared to other land uses, it will affect the people living in the study area most as they depend on the farming of rice for their livelihood (Nasreen *et al.*, 2013). Hasan *et al.* (2004) found out that the dependence on fishing (in the sea) by the inhabitants of Polder 48 are increasing due to loss of crops by flood, loss of productivity, lack of jobs and poverty. Fishing in the sea is a risky profession for the coastal region of Bangladesh as it yields lower economic returns leading to enhanced poverty (Hasan *et al.*, 2004).

The damage was maximum with flood depths 0.1 to 0.5m for all the s~~S~~cenarios (Figure 11). The damage due to inundation less than 0.1m was small and insignificant. The damage is a function of flood depth but the unit is per unit area(per m^2).Therefore, if the flood extent for higher depth is lower, the damage due to flood might be lower even though the flood damage increases significantly for inundation more than 0.5m according to the developed depth damage curves (Figure 7).

Generated PFM indicated that the areas adjacent to the ~~sea facing~~ dike facing the seaside, have higher probability of flooding and the rice fields are more prone to flooding (Figure 13). Moreover, the areas protected by mangrove forest might also be flooded due to breaching of unprotected location of the dike (Figure 13), stressing the importance of proper maintenance of the dike everywhere.

Scenario 1 had higher risk of flooding as the damage due to flooding was maximum for Scenario 1. Total flooded area for settlements of Scenario 1 was lower than Scenario 2 (Table 3) but the estimated damage for settlements of Scenario 1 was more than Scenario 2 (Table 4). This indicates that the settlements for Scenario 1 were exposed to greater flood depth and higher risk of flooding than Scenario 2. Furthermore, ~~the total flooded area was higher for scenario 2 than scenario 1, but the estimated total damage was higher for scenario 1scenario~~Scenario 1 had similar total damage due to flood with lower flood extent than Scenario 2 (Table 3 and Table 4). Considering these facts, Scenario 1 was selected as the worst case Scenario and breaching at the western part of the sea facing dike was identified as the critical location for breaching during cyclone.

The probability of occurrence of the storm surge and damage caused by inundation were taken into account consideration for the risk calculation. In case of breaching of the dike, the probability of flooding was considered the same as the probability of occurrence of storm surge. The depicted risk map (Figure 12) shows the areas adjacent to the dike breach is at higher risk and the risk reduces as the flood propagates towards east.

Canals are used as a mode of transportation by the inhabitants of the area. Most of the economic activities and residential areas are by the canals. The risk analysis show that the areas at highest risk are the settlements by the canals (Figure 12~~Figure 12~~). Therefore, although canals plays a crucial role in the economy and social life of the area, they also increase the risk of flooding and probability of higher damage to the adjacent areas.~~increase the risk of flooding.~~

Land use plan plays an important role in reduction of vulnerability to disasters (Burby, 1998). Probabilistic flood maps (PFM) can be used for land use planning (Alfonso *et al.*, 2016). For better understanding of the area at risk of flooding due to breaching of dike, probabilistic flood maps (PFM) were generated for the study area (Figure 12~~Figure 12~~ and Figure 13~~Figure 13~~). The results of 72 Scenarios from Scenario matrix was used for calculation of PFM. The areas adjacent to the sea dikes had higher probability of flooding due to breaching of dike for both PFMs. The areas inland had lower probability of flooding. Existing land use indicates that the areas with lower probability of flooding are mostly rice fields (Figure 12~~Figure 12~~ and Figure 13~~Figure 13~~). Land use zoning and management using the PMF can reduce the vulnerably~~ and if used properly can lead to economic growth~~.

5. Conclusions

A 1D-2D coupled model was developed to investigate inundation pattern in a polder ~~behind the dike~~ due to breaching of a dike by cyclone induced storm surges. Different Scenarios were developed and the results of these Scenarios were compared using total flooded area and estimated damage. Estimated damage and flood extent were compared to identify the critical location of dike breach during a cyclone. Flood risk map and probabilistic flood map were generated for the dike breach during a storm surge using the results of the developed Scenarios to identify the areas at higher risk and higher probability of flooding.
Inundation for three worst case Scenarios indicated that maximum flooded area occurs during the breaching of central part of the sea facing dike. Most flooded area had flood depth of 0.1 to 0.5 m for all three breaching locations, witch Scenario 2 (~~with~~when breaching is in ~~at~~ the central part) having ~~had~~ the highest depth. Damage for Scenario 1 (breaching at western part) and Scenario 2 (breaching at central part) were equal, whereas Scenario 1 had higher damage for flood depth of 0.1m to 0.5 m and Scenario 2 had higher damage for flood depth of 0.5m to 1.0m. From these findings it can be concluded that the flood extents, flood depth and damage due to flood in case of breaching of the dike depends on breach location. Moreover, the comparison of the flood damages and flood extent led to identification of Scenario 1 as the worst case Scenario and western part of the sea facing dike as the critical location for breaching.
The generated flood risk maps indicated that for all the Scenarios areas adjacent to the dike and canals inside the polder had higher risk of flooding. For better access to the canals, for transportation and livelihood, development of infrastructure and households nearby the canals ~~consequently~~ increases vulnerability. Similarly, developing land for infrastructure and household on the country side of the dikes increases vulnerability. Combining effect of increased vulnerability and higher flood depth results in elevated risk of flooding due to dike breach during a cyclone.
Probabilistic flood maps generated by considering all the Scenarios indicated that the rice fields and settlements are least and most probable land use respectively. Although the inhabitants are mostly dependent on agriculture, the flooding of settlements will cause most damage and forced relocation.
Measured storm surge level for previous cyclones were unavailable. Therefore, for this research synthetic water level time series were generated considering the storm surge height presented by Islam *et al.*, 2013, for a cyclone of 25 year return period. Furthermore, it was assumed that the cyclone will always cause breaching which resulted in storm surge and breaching having the same probability of occurrence. Due to limited field observations, the 2D model was calibrated with few points only. This stresses the importance of field observation pre, post and during event. As the future land use data were not available, current landuse has been used for the future Scenarios as well. The primary objective of the research was to present a methodology

for generating FRM and PFM for the breaching of dike during a cyclone. Due to lack of data on the existing condition and previous history of breaching of the dike, the probability of the dike breaching could not be determined. Comprehensive survey should be conducted to determine the physical condition of the existing embankments and their breach history. Using this data, a join probability of flooding due to storm surges and breaching should be considered for future studies. As the sea beach outside the dike on the sea side was not included in the 2D model, the effect of mangrove forest could not be determined. Single breach was considered for all the developed Scenarios. The probability of multiple dike breaching for a polder should be studies as well. Moreover, due to lack data, the storm surge height for present Scenario was used for future Scenarios as well. As the sea surface temperature will change in the future due CC, the height and the intensity of the storm surges will be effected as well. Research on the change of storm surge height and intensity due to CC should be conducted in the future. As the measured bathymetric data for the sea was not available, the data provided by GEBCO was used which has coarse grids. Furthermore, the study relied on the previous literatures for developing depth damage curves. Conducting field survey to generate these curves will provide more reliable damages due to flood. The developed and simulated model depended on the field measurements and logical assumptions which might be the source of errors. For damages, only direct damages were included. Inclusion of indirect damages will provide more realistic estimates.

Bangladesh is a hazard prone country and cyclone induced storm surge is one of many natural disasters experienced by the coast of Bangladesh. The storm surges cause severe damage to the earthen embankment/dikes protecting the coastal polders and flood the area inside the coastal polders. The methodology presented in this paper to develop 1D-2D inundation model, PFM, risk maps and identify the critical location for breaching can assist in better preparedness by improved flood risk assessment, damage reduction by land use zoning and management, improved monitoring and maintenance of the dike at the critical location and flood forecasting. ~~and flood risk and damage reduction by land use zoning and management. Flood forecasting and warning system using the developed coastal inundation model can provide valuable information to the farmers which could lead to early harvesting, construction of temporary barriers etc.~~ Land use zoning using the risk maps and PFM can ~~indicate~~ lead the settlements, growing tourism and dry fish industry of the study area to safe or flood free zone for future development and relocation. At present, the PFM and FRM due to storm surges and breaching of the dikes are not available for the coastal polders. The methodology to generate PFM and FRM presented in this research has the potential to provide the PFM and FRM for coastal polders of the Bangladesh.~~The economic development and employment opportunity as results of will end the problem of poverty and provide hope of better life to the inhabitants.~~

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