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Assessing High-End Climate Change Impacts on Floods in Major Rivers of Bangladesh Using Multi-Model Simulations

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Bangladesh is highly vulnerable to climate change impacts due to its geographical location, low topography, monsoonal climate and proximity to the sea. Both frequency and intensity of floods are predicted to be increased due to climate change. However, readily useful information on flood risks along the rivers of Bangladesh is not available. In this study, we have applied a multi-model approach to simulate the flood risks in the major rivers of Bangladesh due to increased rainfall and sea level under a high-end climate scenario. The models used include SWAT hydrological model for basin-scale rainfall-runoff modeling, HEC-RAS hydrodynamic model for flood routing, and Delft3D coastal model for sea level rise induced tidal forcing in the Bangladesh coast. These models together simulate flood hydrographs at different locations under climate change. The Ganges, Brahmaputra and Meghna rivers and their major distributaries and tributaries, the Bay of Bengal and the coastal region of Bangladesh are included in the different model setups. This is probably the largest complex river networks in which the models have been applied. The models are calibrated and validated using observed water level and discharge data of BWDB and BIWTA for different years. It was found that the models could simulate the observed variation in flood hydrographs quite well. To assess the impact of climate change on flood, the flood hydrographs under the base condition and the high-end climatic condition were simulated and compared. The findings reveal that the peak flood levels in the three major rivers within Bangladesh may increase by 25-72 cm, depending on location. This increase is anticipated by the end of this century due to increased river flows from upstream areas and higher coastal and estuarine water levels due to rise in sea levels under a high-end climate change scenario. The findings would be useful in future infrastructural planning and design of the country as well as climate change and disaster risk reduction measures.

Field of Research: Climate change, sea level rise, flood, deterministic simulation, SWAT model, HEC-RAS model, Delft3D model, Ganges-Brahmaputra-Meghna rivers.

1. Introduction

Bangladesh is considered to be among the most vulnerable countries to climate change in the world. The country has a huge population in a small geographical area, and is located mostly in a deltaic setting of the world's great rivers – the

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Ganges, the Brahmaputra and the Meghna. Low relief, proximity to the sea and monsoonal climate also add to its vulnerability. Floods, cyclones, storm surges, tornadoes, landslides and river erosion are among the major hydro-climatic hazards that intensify the struggle for Bangladesh to elevate itself as a middle-income country. Among the hydro-climatic hazards, flood is a recurrent natural occurrence in the country. About one-fifth of the country gets inundated in a normal year and two-thirds in an extreme flood year.

Both frequency and intensity of floods are predicted to be increased due to climate change. For example, Mirza (1997) assessed possible changes in annual runoffs in nine sub-basins of the Ganges River under a doubling of CO_2 scenario. He found an area-weighted average increase of about 69% in annual flow of the Ganges River at Farakka. Mirza (2002) studied the changes in mean annual maximum discharge of the Ganges, Brahmaputra and Meghna rivers due to climate change by using a series of empirical relations between the annual precipitation and river discharge, and then between the annual average and peak discharges. He found that the frequency of large floods, such as a 20-year flood, would generally increase due to global warming in all the rivers. In another study, Mirza et al. (2003) analyzed the sensitivity of the Ganges mean annual flow at Bangladesh-India border to climate change. There was a large variation in reported increases in annual discharge (2.4% to 63.3%) depending on the general circulation model used for climate projection. Miller and Russel (1992), however, reported a decrease of 1.2% in annual runoff of the Ganges-Brahmaputra for a doubled CO_2 climate. In a recent study, Mohammed et al. (2017) have simulated the impact of climate change under RCP 8.5 scenario on monthly flows of the Brahmaputra River at Bahadurabad. Eleven climate projections have been used in the study and as such a wide variation in discharge is reported depending on the projection. It is difficult to use such information in actual planning process because of this high variability. Moreover, such information is usually available at upstream boundaries of selected major rivers. It is not known the flood risks in downstream locations of these rivers. In this study, we have used a multi-model simulation approach to generate stage hydrographs at different locations on the Ganges, Brahmaputra and Meghna rivers inside Bangladesh. The models we have used include Soil and Water Assessment Tool (SWAT), Hydrologic Engineering Center’s River Analysis System (HEC-RAS) and Delft3D.

SWAT is a basin-scale hydrological model, which can be used to estimate water yield of a large complex watershed with varying soils and land uses (Arnold et al. 1998). It has recently become one of the most commonly used hydrological models around the world for investigating climate change impacts on regional water resources because of its flexibility and robustness (Jha et al. 2006). The model has already been used in a number of studies to assess climate change impacts in the Indian subcontinent (Bharati et al. 2016; Gosain et al. 2011; Mohammed et al. 2017; Narsimlu et al. 2015). In this study, we have used the SWAT model to generate discharge hydrographs of the major rivers close to the Bangladesh-India Border under a high-end climate change scenario.

Delft3D is a three-dimensional modeling suite, which is used to investigate hydrodynamics, sediment transport and morphology for fluvial, estuarine and coastal environments (Deltares 2011). The model has been developed by Deltares, a Dutch-based research institute. It has flow, morphology and wave modules, and solves the respective governing equations by the finite difference technique on a curvilinear, boundary fitted grid. The vertical grid, when necessary, is defined using a sigma-coordinate approach. The model has been found useful in many countries including the Netherlands, Bangladesh, USA, Hong Kong, Singapore and Australia (Elahi et al. 2015; Haque et al. 2016; Nihal et al. 2015; Nihal et al. 2016; Sakib et al. 2015; Sakib et al. 2016; Sumaiya et al. 2015). In this study, we have used the Delft3D model to generate stage hydrographs of the Lower Meghna and the Arial Khan rivers after a potential rise in sea level.

HEC-RAS is widely used to perform one-dimensional steady/unsteady flow and two-dimensional unsteady flow calculations. It solves the unsteady equations of motion, derived by Barkau (1982) in computationally convenient forms, using an implicit finite difference solution algorithm, called Skyline Matrix Solver (USACE 2016). Moreover, the original algorithm of Bathe and Wilson (1976) with two pointers into skyline storage was modified with seven pointers to improve its efficiency. The unsteady flow routine of HEC-RAS has been applied for flood forecasting in the Peace River in Alberta, Canada (Hicks and Peacock 2005), San Antonio River in Texas, USA (Knebl et al. 2005) and Lower Tapi River in India (Timbadiya et al. 2011), generating water surface profiles from design storm events for the South Nation River in Ontario, Canada (Yang et al. 2006), assessing flood hazard and risk in the eastern part of Dhaka City in Bangladesh (Masood and Takeuchi 2012), and estimating Manning's roughness coefficient in the Hilla River in Iraq (Hamid and Ali 2013). An accuracy level, which is comparable to more sophisticated hydraulic models, is obtained in the above studies (for example, see Hicks and Peacock 2005). In this study, we have used the HEC-RAS model to generate discharge and stage hydrographs in the major rivers of Bangladesh using the upstream boundary conditions from the SWAT model and the downstream boundary conditions from the Delft3D model.

The paper is organized such that Section 1 provides background and importance of the study along with a review of relevant literatures. Section 2 describes how the three models used in this study have been setup, their data sources and boundary conditions. The calibration and validation of the models are discussed in Section 3. The impact of climate change on flood levels in major rivers is assessed in Section 4. The paper ends in Section 5 with some conclusions.

2. Model Setup

Three SWAT setups were prepared for the three basins – the Ganges, the Brahmaputra and the Meghna. In each setup, a digital elevation model (DEM), a land use/cover map, a soil map, and gridded precipitation and temperature data were required. A hydrologically conditioned version of the Shuttle Radar Topography Mission (SRTM) DEM of 90 m resolution was collected from the Hydro SHEDS database of the United States Geological Survey. A global land use/cover map of 300 m resolution called Glob Cover prepared by the European Space Agency for the year 2009 was collected and its legend was reclassified to match with the land classes in the SWAT database. For using as a soil map in SWAT, the Digital Soil Map of the World prepared by the Food and Agriculture Organization of the United Nations in 1995 was collected. For using as weather inputs to SWAT, daily time series of observed precipitation and maximum/minimum temperature were collected. Version 7 of the 3B42 product of Tropical Rainfall Measuring Mission (TRMM) was collected as daily observed precipitation for grid points over the study area. The

TRMM grid points have a resolution of 0.25°. As for the daily maximum and minimum temperature required in SWAT, atmospheric reanalysis products from ERA-Interim database was collected for grid points over the study area. ERA-Interim grid points also have a resolution of 0.25°. The automatic watershed delineation command of SWAT was initially used to define the stream network given a minimum drainage area threshold and later delineated the outline of the complete basin given the location of the basin outlet. The outlets of the whole Ganges, Brahmaputra and Meghna river basins were considered at the Hardinge Bridge, Bahadurabad and Bhairab Bazar gaging stations of Bangladesh Water Development Board (BWDB), respectively, so that the observed discharge data from these locations can be compared with the SWAT generated discharges in order to calibrate and validate the model. Later, the Hydrologic Response Unit (HRU) analysis command was performed to divide each whole basin into a number of sub-basins and to create a number of HRUs. The Hargreaves method was selected for estimating potential evapotranspiration, the Soil Conservation Service (SCS) curve number method for estimating surface runoff volume and the variable storage coefficient method for channel routing. The SWAT model was run at a daily time-step for all purposes, i.e. for calibration, validation and simulation of future discharges.

The Delft3D setup was prepared covering the coastal region of Bangladesh. The downstream boundary of the model was far into the sea and the upstream boundary was at non-tidal, freshwater gages. Bathymetric data for the sea part of the model was obtained from an open source database of General Bathymetric Chart of the Oceans and that of the estuaries and rivers was measured under the Ecosystem Services for Poverty Alleviation-Deltas project of the Institute. The inland ground elevations of the coastal region were available from the National Water Resources Database. A curvilinear grid of size 500 m × 600 m in the sea and 200 m × 300 m in the estuaries was used in domain discretization. Discharge time series was used as upstream boundary condition and water level as downstream boundary condition. The river discharge data was collected from BWDB and the sea water level data was generated as tide by using Nao 99b tidal prediction system (Matsumoto 2000). In this study, the Delft3D model was used to generate stage hydrographs at desired locations under future potential sea level rise scenarios. These hydrographs were used as inputs in another hydrodynamic model (HEC-RAS).

A setup of the HEC-RAS model was also prepared to simulate water surface profiles along the major rivers of Bangladesh. A schematic showing the river network used in the model is given in Figure 1. In the network, the major rivers (the Ganges, the Brahmaputra and the Meghna) as well as their distributaries (the Gorai, the Arial Khan and the Dhaleswari) and tributaries (the Atrai, the Karotoya, the Shitalakhya and the Buriganga) were included. Altogether, the current model set-up covers a river network length of 1267 km. Of these, major rivers cover 521 km. Also, there are 18 river junctions in the model setup. The total length of these junctions is about 80 km. This is probably the largest complex river network in which the model has been applied. For the HEC-RAS model setup, the river network was properly delineated using the Google Earth and ArcGIS softwares. After delineation of the river network, the bathymetry of the rivers was entered into the HEC-RAS Geometry. Most of the bathymetries were available from our own measurements under different projects over the last few years and some were collected from BWDB. Under the 'airport project', some bathymetries of the Padma, Upper Meghna and Lower Meghna rivers have also been obtained very recently.

Bangladesh has a relatively flat topography. Its rivers have floodplains in which water can get into during rising high river stages and come out during falling river stages. These floodplains act as storage reservoirs and play an important role in determining the peak, shape and base of the flood hydrograph. However, the floodplains in many places are now obstructed by highways, roads and flood control embankments. So, only the unobstructed parts of the floodplain act as storage areas. These unobstructed floodplains of the major rivers were identified from the Google Earth image, digitized, georeferenced and finally imported into the HEC-RAS setup. The total area included as storage was about 5700 km^2. A storage capacity versus land elevation relation was developed for each of these storage areas using a 500 m digital elevation model and also used in HEC-RAS to account for their roles in flood routing.

For unsteady flow simulation, the model requires boundary and initial conditions. At the seven upstream boundaries, such as Hardinge Bridge on the Ganges, Bahadurabad on the Brahmaputra, Bhairab Bazar on the Meghna, Demra on the Shitalakhya, Mirpur on the Buriganga, Ullapara on the Karotoya and Baghabari on the Atrai, discharge was used as boundary condition. At the three downstream boundaries, such as Nilkamal on the Lower Meghna, Gorai Railway Bridge on the Gorai and Madaripur on the Arial Khan, water level was used as boundary condition. Since two of the three downstream boundaries experience tidal influence, sub-daily water level was used as downstream boundary condition. Observed discharge and water level for each river and each reach were used as initial condition.

3. Calibration and Validation of the Models

The three SWAT models were calibrated against the measured daily discharges of the Ganges at Hardinge Bridge, the Brahmaputra at Bahadurabad and the Meghna at Bhairab Bazar. The calibration period was 2000-2006 and the validation period was 2007-2013. The soil curve number, bulk density, hydraulic conductivity, Manning’s roughness coefficient, depth of water required in shallow aquifer to initiate return flow, and base flow alpha factor for bank storage were found to be among the most sensitive model parameters. A comparison of observed and simulated hydrographs for the Brahmaputra at Bahadurabad is given in Figure 2. The figure shows that the fitted SWAT model of the Brahmaputra captures the daily variation in discharge reasonably well. A further comparison with the statistical indicators revealed that the Nash-Sutcliffe efficiency was very high (0.83-0.84), and the bias in the simulated flows was very low (0.3-0.6%). Similar results were also obtained with the SWAT models of the Ganges and Meghna basins. Further details on the fitted SWAT models can be found in Mohammed et al. (2017) and IWFM (2018).

Figure 1: The River Network That has been Considered in Setting the HEC-RAS Model

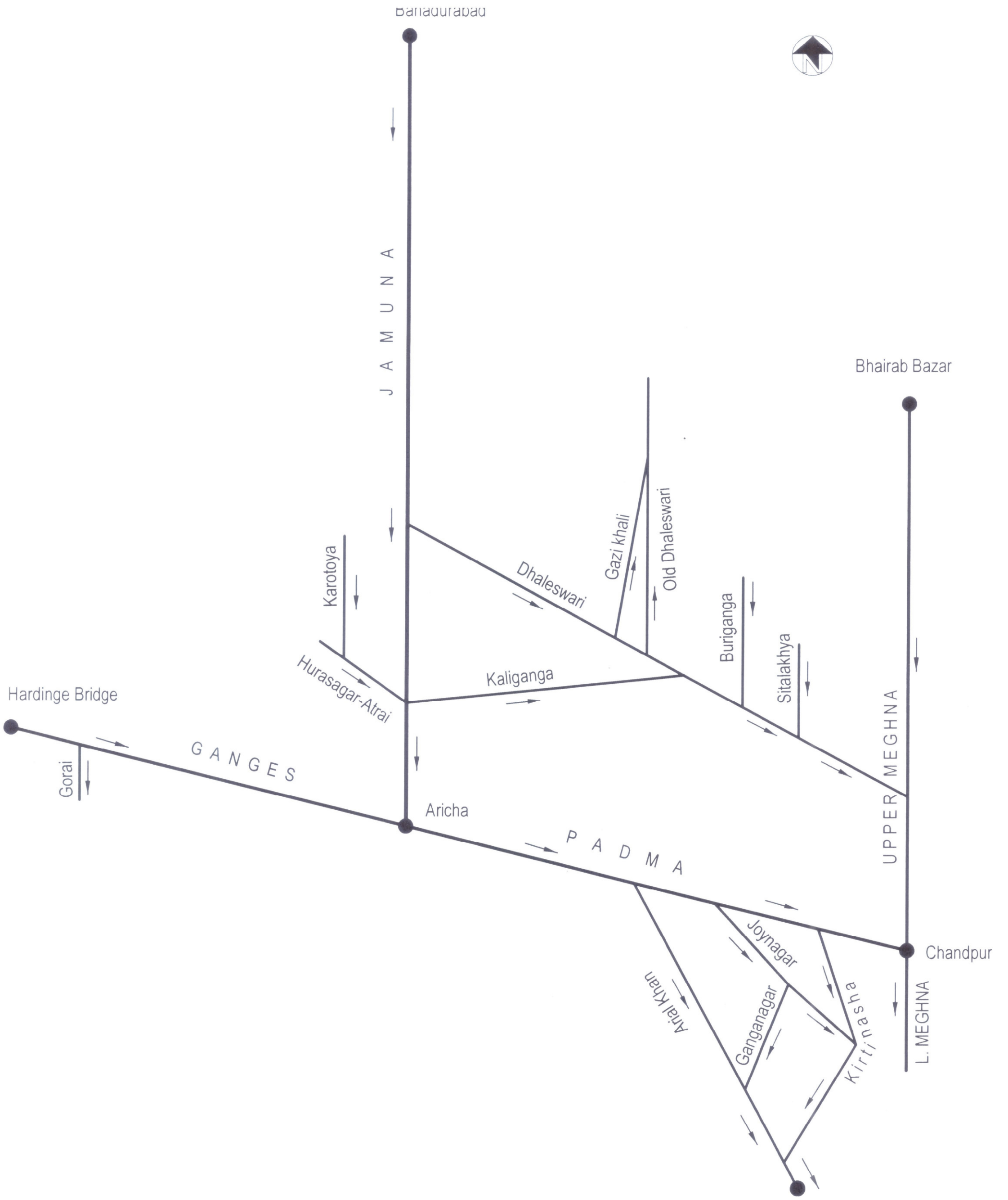
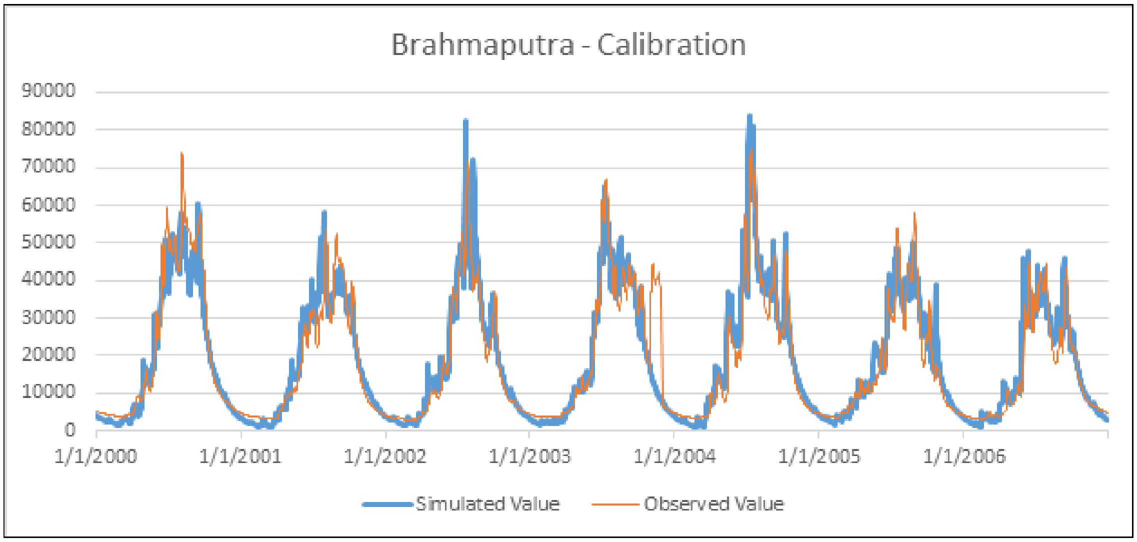


Figure 2: Comparison of Observed and SWAT-Simulated Discharge Hydrographs of the Brahmaputra at Bahadurabad



The Delft3D model was calibrated against the measured water levels at the Hiron Point gage station for the year of 2000, which is an average flood year. Manning's roughness coefficient, horizontal eddy viscosity and horizontal eddy diffusivity were the principal calibration parameters. The calibrated roughness coefficient was spatially variable, viscosity had a constant value of 100 m^2/s and diffusivity also had a constant value of 1000 m^2/s. Figure 3 shows a comparison between the observed and simulated stage hydrographs. It is seen from the figure that the model could capture the semi-diurnal variation in tidal water level reasonably well. Further details on calibration of the model can be found in Sumaiya et al. (2015) and IWFM (2018). The calibrated model was then validated for a wet year of 1998. Almost similar performance of the model was found for the validation period. Overall, the model was found to be reliable to simulate the tidal water level in the Bangladesh coast.

Since most of the bathymetries used in the HEC-RAS model were relatively recent, a recent year (2014) was chosen to calibrate the model. Further reasons for selecting 2014 were that all the required data for this year was available and there was a moderate flood in this year. Using the boundary and initial conditions of 2014, the model was run. Model simulated stage hydrographs were compared with the observed stage hydrographs to judge the performance of the model. Intermediate gage stations, which were neither used as upstream boundary condition nor downstream boundary condition, such as Mawa and Baruria Transit on the Padma River, were used in this process. Manning's roughness coefficients for the main channel and floodplain were the principal calibration parameters of the model. The calibrated roughness coefficients for different rivers and reaches can be found in IWFM (2018). The roughness parameters were found to be higher, as expected, for smaller rivers and lower for larger rivers. Also, the values were higher for upper non-tidal rivers compared to those of lower tidal rivers. The model simulated hydrograph for Baruria Transit on the Padma River is shown in Figure 4 along with the observed hydrograph. It is seen from the figure that the model follows the observed pattern in water level variation quite well.

Figure 3: Comparison of Observed and Delft 3D-Simulated Stage Hydrographs for the Year 2000 at Hiron Point

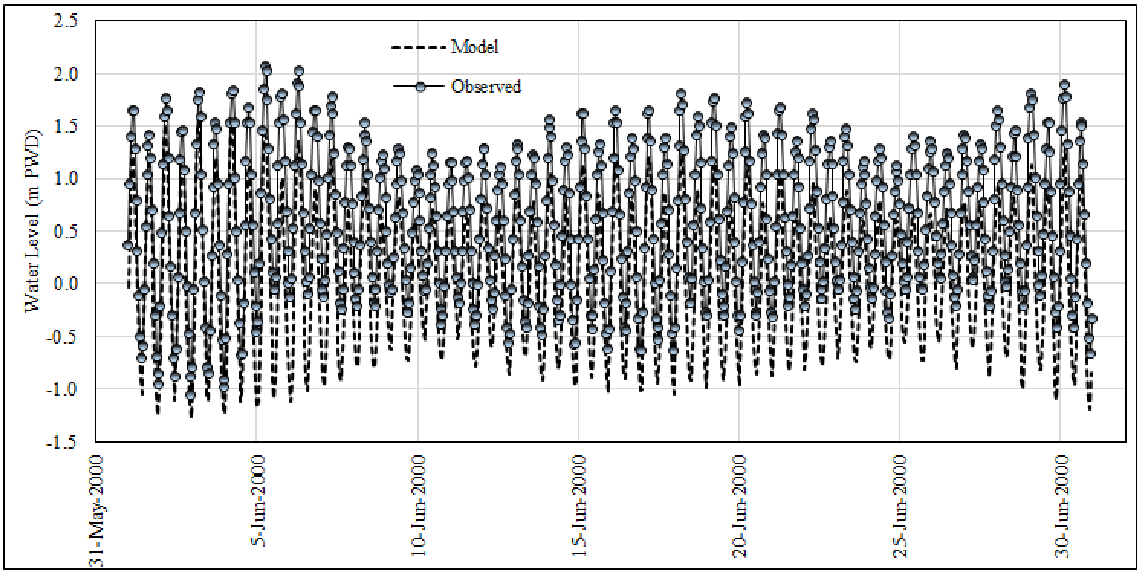
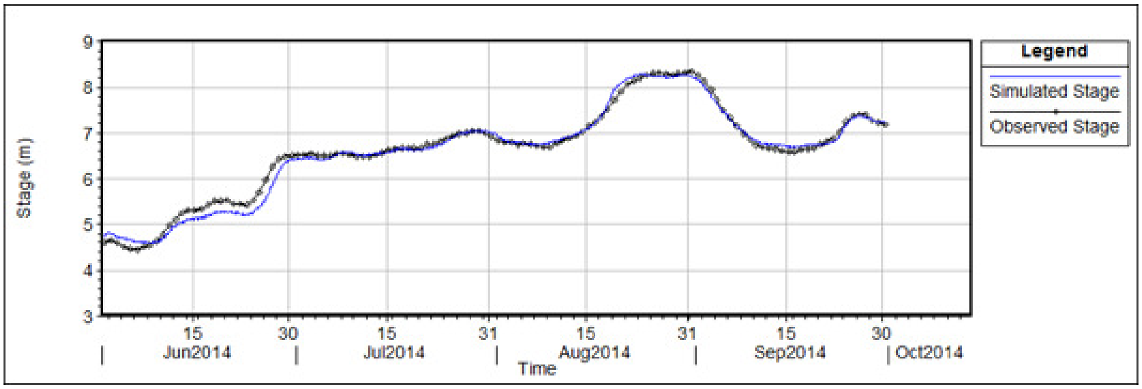


Figure 4: Comparison of Simulated and Observed Stage Hydrographs at Baruria Transit on the Padma River for the Year 2014



The calibrated HEC-RAS model was then validated against the floods of 1998 and 1988. These two floods have so far been the historical highest floods in the country. The upstream and downstream boundary conditions and the initial conditions of the model were changed according to the observed data of BWDB for the years of 1998 and 1988. The other conditions and parameters were kept the same. It was found that the model captures the variation in stage hydrograph at Mawa and Baruria Transit reasonably well during both the validation years as well. For example, the highest measured water level at Mawa was found to be 7.12 m PWD on the 10th of September and the highest simulated water level was 7.14 m PWD on the same day. However, a closer view of the simulated hydrograph revealed that there was some positive bias in the hydrograph at Mawa, though the bias was small. There was no such bias in the simulated stage hydrograph at Baruria Transit.

4. Impact of Climate Change on Floods

Flooding in Bangladesh can be exacerbated by increased rainfall and its consequent increased runoff. It is generally expected that, due to climate change, the future streamflow would change. Using the SWAT models, daily streamflow time series were generated for the three major transboundary rivers. Eleven different streamflow time series, based on 11 climate projections, were generated for 1980-2099. As greenhouse gas concentration trajectory, RCP 8.5, which provides maximum possible radiative forcing and assumes that emissions would continue to rise throughout the 21st century, was adopted as a high-end climate change scenario. Since the SWAT-simulated stream flows varied greatly from one projection to another projection, and it was not possible to run the one-dimensional HEC-RAS model for all the projections due to time and resource constraints, a representative projection had to be identified first. This was done by comparing the highest observed and modeled flows during the base period (1980-2009), as the highest flow was a major concern for this study. For the Brahmaputra River, the projection based on REMO 2009 RCM coupled with MPI-M-MPI-ESM-LR GCM (hereinafter referred to as Model 7) provided the best match between the observed and modeled flows. For the Ganges River, the best match was with the RCA4 RCM coupled with IPSL-CM5A-MR GCM (Model 10), and for the Meghna River, it was with the RCA4 RCM coupled with NOAA-GFDL-GFDL-ESM2m (Model 9). For the Meghna River, the Model 10 agreement with the observed flows was also good though it was not the best. The Model 10 resulted in 20.3% higher maximum flow during the base period for the Brahmaputra River, and the Model 7 resulted in 33.3% higher maximum flow during the base period for the Ganges River. Thus, it appeared that the highest flows were better simulated as a whole with the Model 10. However, there was a positive bias in the model results for the Brahmaputra which needed to be corrected. A comparison of the highest flow of 2080s (1970-2099) with that of the base condition (1980-2009) indicated that the peak flow would increase by 29% in the Ganges, 10% in the Brahmaputra and 22% in the Meghna under a changed climate. However, there was no indication of synchronization of peak flows in these rivers. The upstream boundary conditions of the HEC-RAS model on the Ganges at Hardinge Bridge, Brahmaputra at Bahadurabad and Meghna at Bhairab Bazar were then changed according to these projected future flows due to climate change. A discharge hydrograph thus prepared for the high-end flood extreme for the Ganges at Hardinge Bridge is given in Figure 5.

Climate change would also impact flooding in Bangladesh through a potential rise in sea level and an increase in river flow. Sea level would rise due to thermal expansion of sea water, reduction of glacier volume and melting of land ice mass. In the fifth assessment report of IPCC (IPCC, 2013), a global mean sea level rise of 52-98 cm by the year of 2100 under a very high emission scenario of RCP 8.5 and 36-71 cm under a moderate emission scenario of RCP 4.5 are projected. For the Bay of Bengal, the IPCC projection is little wider (25-73 cm under RCP 4.5). Based on IPCC's projections of global and local (Bay of Bengal) sea level rise, a maximum sea level rise of 1 m by 2100 and 0.31 m by 2050 is anticipated for the Bay of Bengal (IWFM, 2018). The downstream sea boundary of the Delft3D based coastal model was then changed according to these projections of sea level rise, and the model was rerun. The model generated stage hydrograph at Nilkamal on the Lower Meghna River for 1998 flow condition, as an example, is given in Figure 6. Such hydrographs on the Lower Meghna and Arial Khan rivers were used as downstream boundary conditions in the HEC-RAS model to simulate the effect of sea level rise on flooding along the major rivers.

Figure 5: Projected High-End Extreme Dicharge Hydrograph for the Ganges at Hardinge Bridge

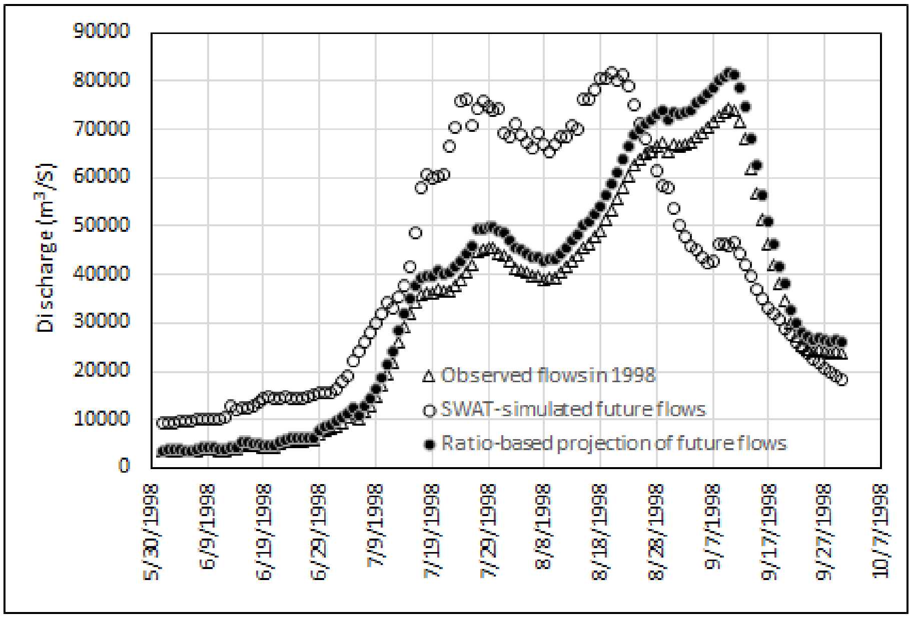
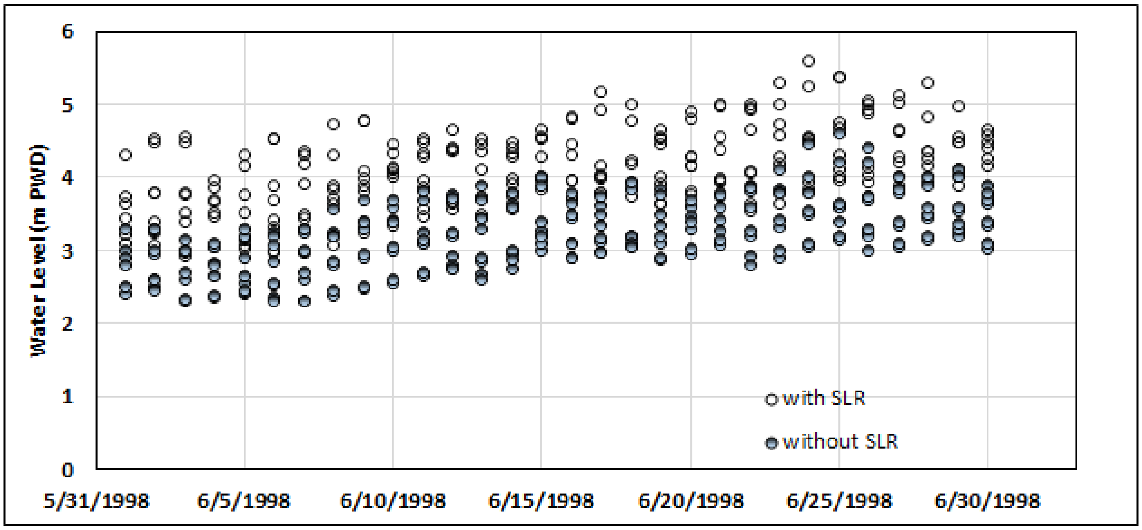


Figure 6: A Partial Plot of the Delft 3D-Model Generated Water Level at Nilkamal on the Lower Meghna River with a Potential Sea Level Rise Scenario

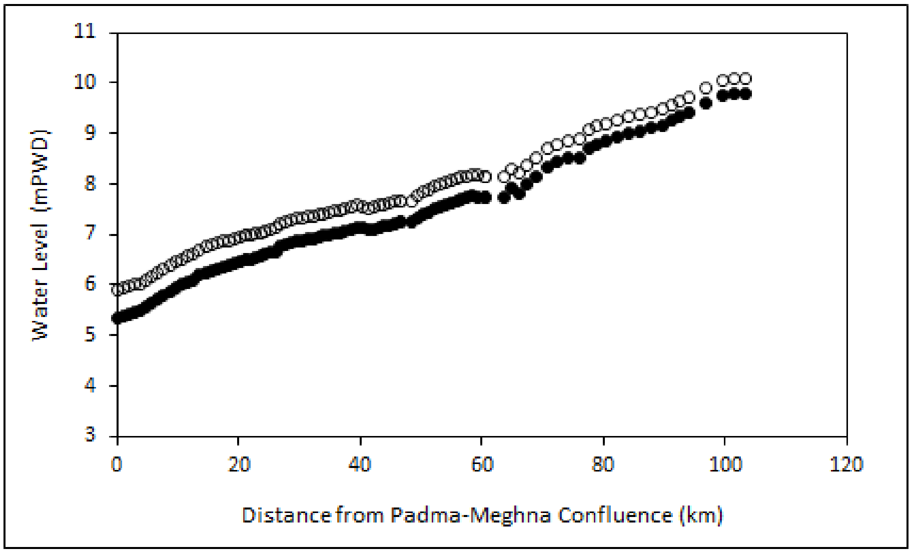


After making the above changes in the upstream and downstream boundaries, the HEC-RAS model was rerun for the years of 1998 and 1988 to generate stage hydrographs along the major rivers. The peak water levels that were generated by the model at different locations of the rivers were noted and compared with the corresponding observed water levels in 1998 and 1988. The peaks were found to be increased due to climate change impacts. They are summarized in Table 1. It is seen from the table that the historical peak flood level may increase by 25-72 cm, depending on the river and the location on it, by the end of this century due to climate change in the major rivers of Bangladesh. The higher increase in the upstream of the Ganges and Meghna is due to an increased freshwater flow from upstream under a changed climate. The higher increase in the lower reach of the Meghna is due to the impact of sea level rise. As there is potential for spillover and floodplain storage of surface water in the central part of the country, and as there is less backwater effect of the sea level, the impact of climate change is likely to be less on the Padma flood peaks. Figure 7 depicts the changes in peak water level along the Padma River (the Ganges River after the confluence of the Ganges and the Brahmaputra) due to the impacts of climate change. It shows that with the increase in distance from the Padma-Meghna confluence at Chandpur, the impact of climate change on flood peak would decrease. Among the three major rivers, the Brahmaputra is found to be least impacted as far as flood peak is concerned. This could be due to the large width and slope of the river. The Brahmaputra has the largest width and bed slope among the three rivers.

Table 1: Changes in Peak Water Levels due to Changes in Upstream Flows and Sea Levels under Potential Climate Change by the End of This Century

River	Location	Increase in Peak Discharge (%)	Increase in Peak Stage (cm)
Ganges	Gorai Offtake	29	62
Brahmaputra	Dhaleswari	13	38
Brahmaputra	Kaliganga Offtake	14	32
Upper Meghna	Near Narsingdi	22	69
Ganges	Baruria Transit	11	25
Ganges	Mawa	6	54
Meghna	Chandpur	5	72

Figure 7: Simulated Peak Water Levels under the 1998 Flow Condition along the Padma River for Both 'Base' (Lower Solid Dots) and 'Climate Change' (Upper Hollow Dots) Conditions



5. Conclusions

Changes in flood peaks along the Ganges, Brahmaputra and Meghna rivers within Bangladesh due to potential impacts of climate change have been evaluated by using a novel multi-model simulation approach. The approach is unique in that it uses hydrologic, hydrodynamic and tidal models of different spatial and temporal resolutions to capture land, soil, river, estuary and sea influences on floods. The models used are SWAT, Delft3D and HEC-RAS. The simulations reveal that the flood peaks might increase by 25-72 cm by the end of this century in the major rivers, depending on the river and the location on the river, due to increase in rainfall in the upstream areas and rise in sea level in the Bay of Bengal under a potential high-end climate change scenario. The upper reaches of the Ganges and the Meghna, and the lower reach of the Meghna are expected to be impacted more than the central part of the country due to climate change. The findings of this study would be useful in infrastructural planning and design, such as airport, bridge, Olympic village, flood control embankment, river training work and road, in the vicinity of the major rivers modeled. This study has investigated only the high-end climate change impact. In future studies, more climate change scenarios should be included to get a wider perspective on flood.

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