IMPORTANCE OF DISTRIBUTED HYDROLOGICAL MODEL FOR PRESENT AND FUTURE FLOOD RISK MANAGEMENT IN BANGLADESH

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In Bangladesh, the lack of upstream basin-wide hydro-meteorological data makes flood risk management challenging in the present and future climates. Under these circumstances, the Distributed Hydrological Model (DHM), forced with globally available hydro-meteorological data, is useful for generating basin-wide river flows. In this study, the Block-wise TOPMODEL with Muskingum-Cunge routing (BTOPMC) model was applied to generate daily river discharge using WATCH Forcing Data (WFD) for model calibration and validation. The calibrated BTOPMC model reproduced important signatures of the Ganges, Brahmaputra and Meghna (GBM) basins hydrology, such as annual, seasonal, flood peak, and low flows, and was applied with the MRI-AGCM3.2S (SRES A1B scenario) Data to obtain 10-, 25-, 50- and 100-year flood discharge for the Present (1979-2003) and Future (2075-2099) climates using flood frequency analysis. The 50- and 100-year flood discharge were used to obtain inundation area and depth using GIS-based Flood Inundation Depth (FID) model and to estimate the number of flood affected people using LandScan 2009 population data. For the flood risk, the estimated flood inundation and affected people increased over the study area of Bangladesh due to the increase of both flood hazard and exposure for both 50- and 100-year floods in the Future climate. From the results of this study, the structural and non-structural adaptation measures should be considered in the future studies for the flood risk management in Bangladesh.

Keywords: GBM, BTOPMC, Climate change, MRI-AGCM, FID, Flood Risk.

INTRODUCTION

Bangladesh is situated in the active delta of the world's three major rivers, the Ganges, Brahmaputra and Meghna (GBM) (Figure 1.A). The Bangladesh area lies under GBM basins area and the four administrative districts of northern Bangladesh were selected as the nationwide (large-scale) and district wise (small-scale) study area respectively (Figure 1.B and 1.C). The GBM River basins are highly heterogeneous in geography and climate settings with a majority of the basins located outside of Bangladesh, which is a disaster prone country to natural hazards and experiences frequent floods causing large inundated area. Among those floods, the 1998 flood was the most devastating to the country, lasted for 63 days and affected 53 districts out of 64 (BWDB, 2014). To make the matter worse, the basin-wide hydro-meteorological data required for the flood risk management in

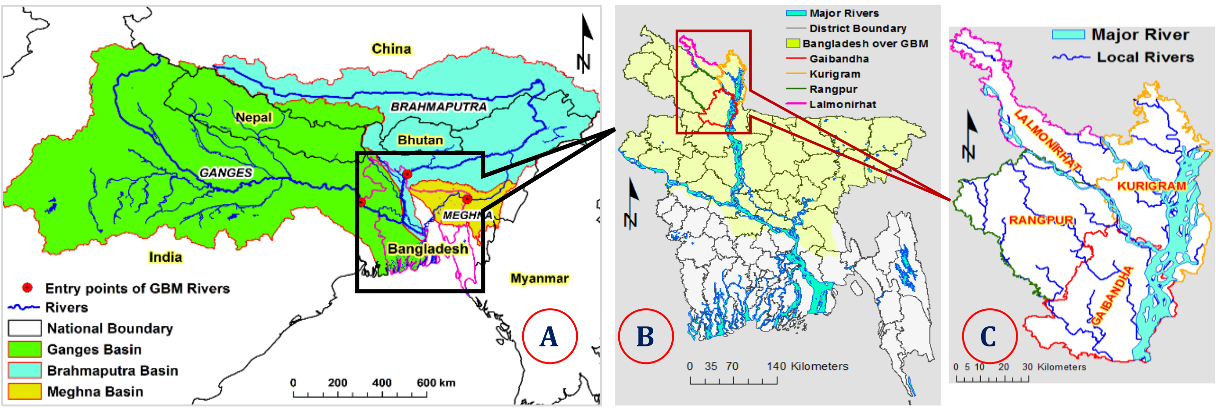

Figure 1. *A) The Ganges-Brahmaputra-Meghna (GBM) basins; B) Nationwide (Large-scale) study area - GBM basins located in Bangladesh; and C) District wise (Small-scale) study area - four districts of northern Bangladesh.*

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Bangladesh, are not available from the upstream countries and Bangladesh has no management control over transboundary rivers that cause floods with large inflows during rainy seasons. Localized heavy rainfall may also contribute the Bangladesh floods. In addition, the magnitude of flood hazard is expected to increase under climate change. Under these circumstances, the DHM, forced with globally available hydro-meteorological data, is useful for generating basin-wide river flows for the purpose of flood risk management. Such hydrological modelling might mitigate the data sharing issues of transboundary river basins and provide Banalgadesh with the information of how much water would enter from the upstream countries and of what the extent of flood inundated area would be. Several studies such as Kwak *et al.* (2012) assessed flood risk under climate change scenario in Asia-Pacific region globally using non-calibrated BTOPMC model. Winsemius *et al.* (2013) proposed a framework for global river flood risk assessments in current conditions as well as in future conditions due to climate and socio-economic changes. In contrast to the above studies, the BTOPMC model was set up for the entire GBM basins at a spatial scale of 20-km resolution to generate daily river discharge and a GIS-based Flood Inundation Depth (FID) model was used to estimate inundation area and depth over Bangladesh. In this study, the BTOPMC model simulation was calibrated (1981-1990) and validated (1991-2000) based on a long-term observed discharge data at four gauging stations located near the area of interest and the flood risk calculations were performed regionally rather than globally. Therefore, the key objectives of this study are (1) to demonstrate how a DHM is applied for the GBM basin-scale discharge simulation, (2) to assess climate change impact on flood discharge, inundation area and depth over Bangladesh, and (3) to assess flood risk in terms of the exposed people over Bangladesh both in nation and district wise areas (Figure 1.B and 1.C).

THEORY AND METHODOLOGY

In this study, the flood risk assessment methodology was divided into three major steps, see Figure 2. These steps consist of daily river discharge simulation by BTOPMC model, flood frequency analysis of the simulated discharge, the hazard analysis with FID model, and risk assessment in terms of the exposed people over Bangladesh. The detailed description of three steps is provided in the following sections.

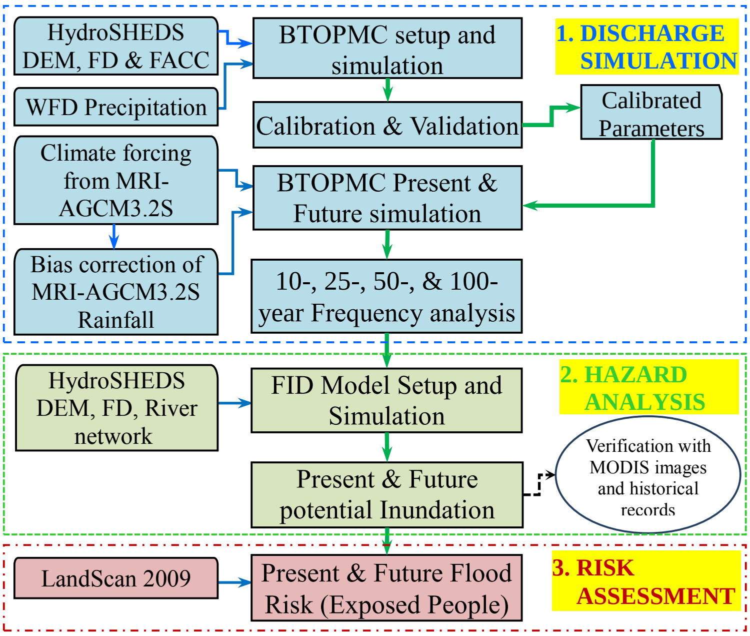

Figure 2. *Schematic of methodology for Present and Future flood risk assessment with BTOP and FID models.*

1. Discharge Simulation

The BTOPMC model was developed by Takeuchi *et al.* (1999) and is an extension of TOPMODEL concepts (Beven and Kirkby, 1979). The model is developed in order to overcome the limitations of using the TOPMODEL for large river basins. The block-wise concept is used for the runoff generation from each grid cell to include local parameters in the BTOPMC model (Takeuchi et al., 2008), and the Muskingum-Cunge routing method is used for flow routing (Cunge, 1969).From the simulated BTOPMC discharge, the flood frequency analysis was applied to estimate 10-, 25-, 50- and 100-year flood discharge at each BTOPMC grid cell.

2. Hazard Analysis

Hazard analysis was performed in terms of flood inundation extent (areas) and depth with the use of Flood Inundation Depth (FID) model, which utilizes a topography based inundation analysis method and is used to determine potential flood inundation depth around river channels for any basin size globally (Kwak *et al.*, 2012). In the FID model, the inundation areas and depth are calculated as:

$$FID = H_{max} - REM \quad \textbf{(1)}$$

where $FID\ (m)$ is the flood inundation depth, $H_{max}\ (m)$ is the maximum river water level, and $REM\ (m)$ is the Relative Elevation Model from DEM. The REM of an individual cell is calculated as the elevation difference between the cell and its nearest downstream river channel cell. FID indicates the potential flood inundation depth of a given cell when H_{max} is greater than the REM of that cell $(REM < H_{max})$. In the case of $REM \geq H_{max}$, FID has not been calculated because it means that no flooding occurs over such cells (Kwak *et al.*, 2012).

3. Risk (Exposure) Assessment

Flood risk has been studied as one of the major impacts of climate changes. In this study, the flood risk indicator in a given area ($RISK_{flood}$) is defined as:

$$RISK_{flood} = function\ (\ Hazard_{flood},\ EXP_{population},\ Vul\ ) \qquad \textbf{(2)}$$

where $Hazard_{flood}$ is the potential occurrence of flood inundation under the selected return period, $EXP_{population}$ is the number affected people i.e. people living in the hazardous (potential inundation) area, and Vul is the maximum vulnerability, which was not considered in this study.

DATA

The HydroSHEDS (Lehner *et al.*, 2006) Digital Elevation Model (DEM), flow direction (FD) and flow accumulation (FACC) data were used to set up the BTOPMC model (Figure 2). HydroSHEDS along with the Global Land Cover data by National Mapping Organization (Tateishi *et al.*, 2014) was used to set up the FID model. The WATCH Forcing (WFD) precipitation data was used for the BTOPMC model calibration and validation at four stations with a long term (1981-2000) observed discharge (BWDB, 2014), see circles in Figure 3. Internal validation of BTOPMC was also performed at three stations (Figure 3) using monthly average discharge data collected from Global Runoff Data Centre (GRDC, 2013). The corrected MRI-AGCM3.2S (SRES A1B scenario) precipitation was used to assess climate change impact on flood discharge using BTOPMC and the flood inundation area and depth over Bangladesh using the FID model. On the other hand, observed water levels at 40 gauge stations inside the study area, representative cross-section data in Bangladesh (BWDB, 2014), and MODIS satellite images were used to verify the inundation depth and area produced by FID model. Finally, the LandScan 2009 global population data was used in the flood risk assessment to find the number of affected people (Budhendra *et al.*, 2007).

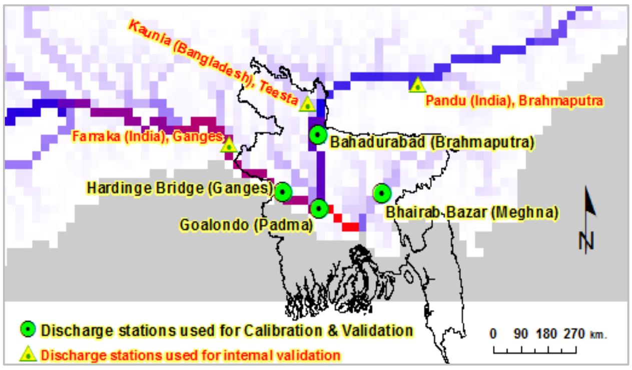

Figure 3. *Location map of seven discharge stations used for calibration & validation.*

RESULTS AND DISCUSSION

Discharge Simulation: The BTOPMC daily discharge hydrographs plotted for calibration and validation periods (Figure 4.A-B) at the Ganges and Brahmaputra discharge gauge stations shown in Figure 3 and three internal validation points as monthly averages (Figure 4.C-E) The BTOPMC model simulated the timing and runoff volumes reasonably well for the GBM basins and the performance indices (NSE, CD, VB) in each of GBM basins were found quite satisfactory at seven stations. For the low flows, the match between simulated and observed hydrographs in the Brahmaputra, Padma and Meghna basins was satisfactory while the Ganges basin simulated flows were slightly overestimated (Figure 4.B). This was likely due to the considerable upstream water use (FAO-AQUASTAT, 2014), which was not accounted in model simulations due to data unavailability. Therefore, the long-term calibration and validation along with internal validation of BTOPMC model reproduced the important signatures of GBM hydrology such as annual runoff, seasonal runoff, flood flows, and low flows (Figure 4). The calibrated BTOPMC model was used with the bias corrected MRI-AGCM3.2S data for Present (1979-2003) and Future (2075-2099) climates to simulated river discharges. The flood frequency analysis was performed to obtain the 10-, 25-, 50- and 100-year flood discharge at each BTOPMC cell, which compared well with the observed values at four stations.

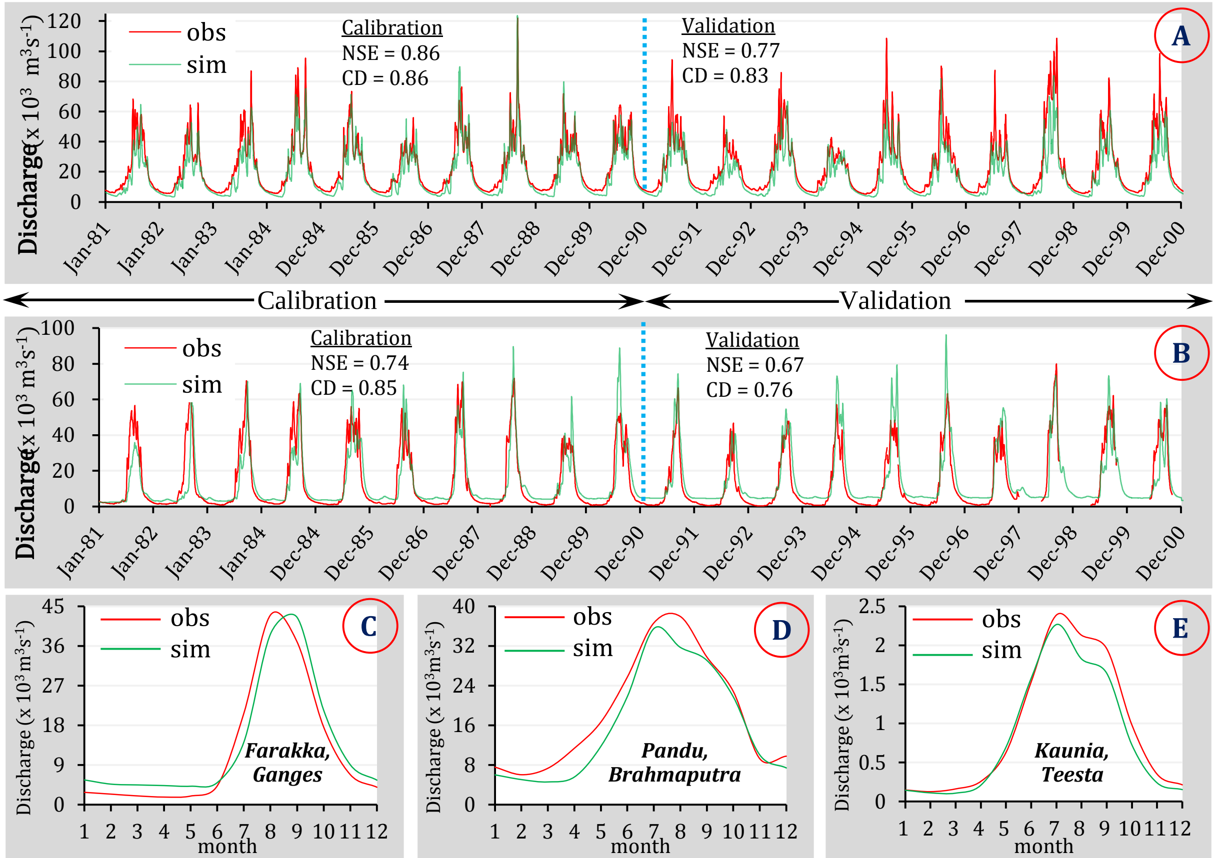

Figure 4. *A) Calibration and Validation hydrographs of Brahmaputra River at Bahadurabad station; B) Ganges River at Hardinge Bridge station; and C), D), E) Monthly mean discharge hydrographs at three discharge gauge stations used for internal validation.*

Hazard Analysis: In each BTOPMC grid cell, the estimated 10-, 25-, 50- and 100-year flood discharge of MRI-AGCM3.2S was applied in the FID model to produce potential flood inundation maps. For the FID calibration, the simulated river water heights above the danger level ($\Delta H'_{max}$) were verified with the recorded water heights (ΔRH) along the river channels at the 40 gauge stations located inside the study site of Bangladesh and corresponded with ΔRH. The $\Delta H'_{max}$ data sets were also verified with representative cross-section data of Brahmaputra and Ganges Rivers. The potential inundation extent of 25-year frequency flood for the Present climate compared well with MODIS images and actual Bangladesh inundation data of the 2004 flood, which roughly corresponded to the 25-year flood. The potential inundation area of 50- and 100-year return period floods for the Present climate was also comparable with the actual inundation data provided by BWDB (BWDB, 2014). After validating the Present climate (1979-2003) potential inundation maps, the 50- and 100-year Future climate (2075-2099) potential inundation maps were produced for Bangladesh. From the climate change impact assessment, it was found that the projected 50-year flood inundation area would increase from Present to Future by 2639 km^2 (from 47 600 km^2 to 50 239 km^2) (Figure 5). Locally, the potential flood hotspots would increase in the Future by 39 per cent and 27 per cent where FID increases more than 50 cm and 100 cm respectively. In case of the 100-year flood, inundation extent may increase from the Present to the Future by 2518 km^2 (from 52 149 km^2 to 54 667 km^2). The potential flood hotspots may increase in the Future by 45 per cent and 33 per cent where the FID increases more than 50 cm and 100 cm respectively for the 100-year flood.

Risk (Exposure) Assessment: For the nationwide flood risk assessment, analyses were conducted on flood-risk area, affected population and their rate of change. As both inundation extent (area and depth) and affected people would increase in the Future, the flood risk may increase as well even if the hazard does not increase. The results showed an upward trend which means that the increased rainfall is likely to contribute to higher flood risk. For example, it was found that approximately 11.5 million people may experience new inundation in the Future by a 50-year flood. In addition, 89 per cent

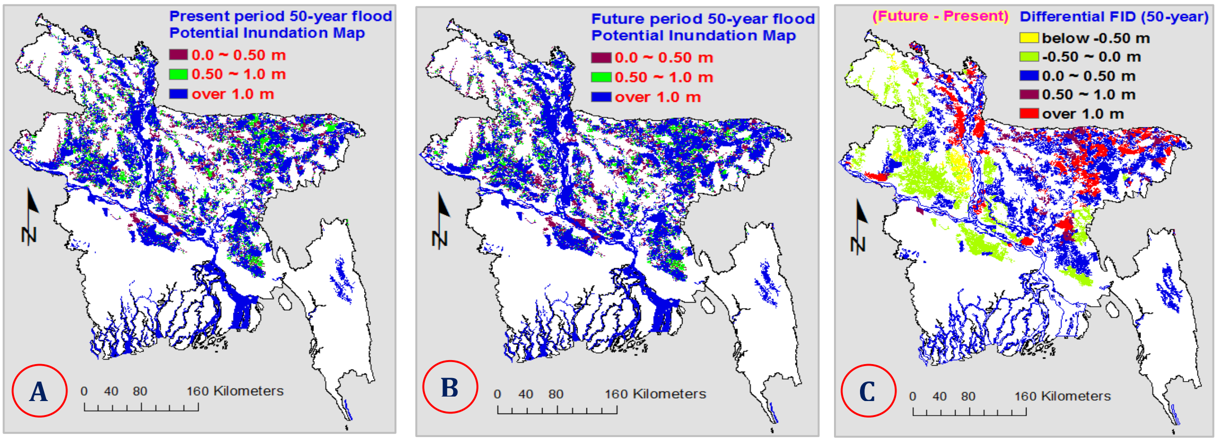

Figure 5. *A) 50-year potential inundation map using MRI-AGCM3.2S simulated discharge for the Present climate (1979-2003); B) for the Future climate (2075-2099); and C) Changes of Potential inundation depths showing the difference in FID from Present to Future inundation.*

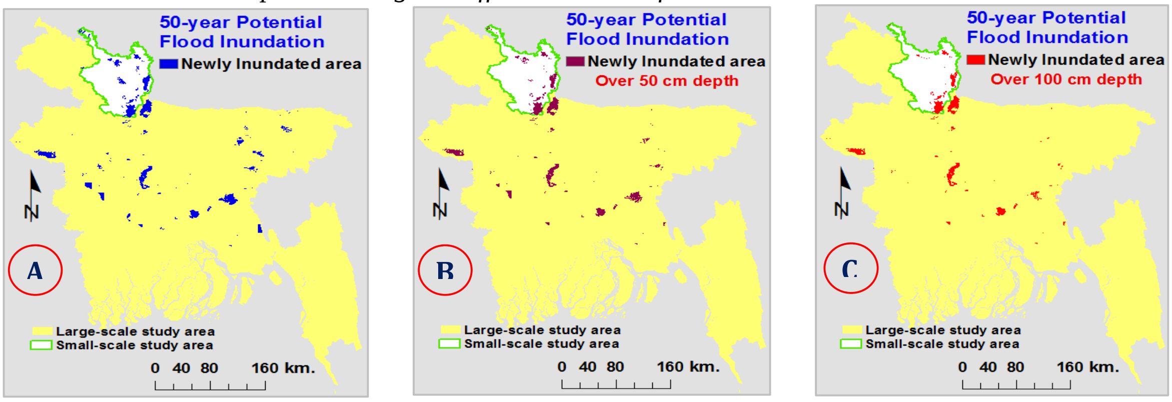

Figure 6. *A) 50-year flood potential inundation map showing the newly inundated area in the Future climate; B) newly inundated area over 50 cm; and C) over 100 cm.*

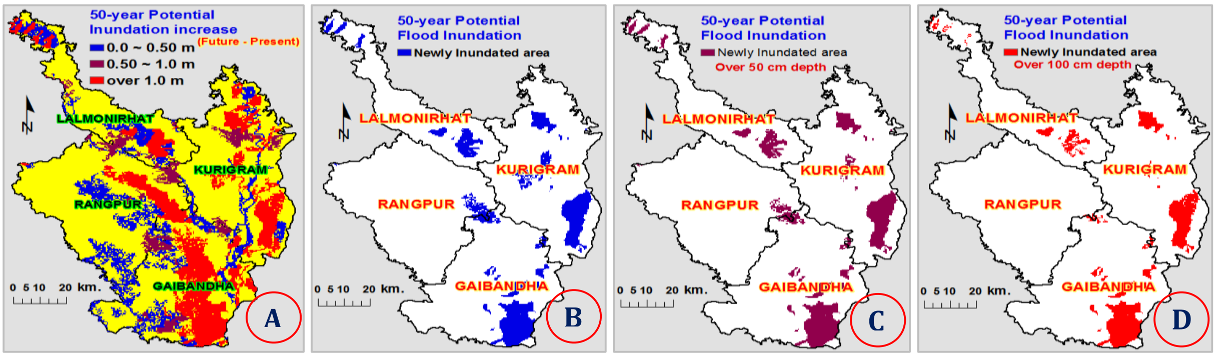

Figure 7. *A) The increase of inundation from Present to Future climate; B) newly inundated area in the Future by a 50-year flood; C) newly inundated area over 50 cm; and D) over 100 cm for the four administrative districts of northern Bangladesh;.*

(10.2 million) and 76 per cent (8.7 million) of the newly affected people (11.5 million) may experience over 50 cm and 100 cm deep of inundation respectively by a 50-year flood. In case of 100-year flood, the number of affected people living in the newly inundated area is 12.6 million of which 92 per cent (11.6 million) and 81 per cent (10.2 million) may experience over 50 cm and 100 cm deep of inundation, respectively. Therefore in the Future, as climate change results in more extreme rainfall, flood risk may show a greater increase from the Present to the Future climate. Figure 6 shows newly inundated area by a 50-year flood in the Future.

From the district wise flood risk analysis, flood inundation depth, extent and exposure increases in the Gaibandha, Kurigram, Rangpur, and Lalmonirhat districts of northern Bangladesh (Figure 7). In the Future climate, approximately 1.61 million people of the four districts will be living in the newly inundated area (Figure 7.B) and 95 per cent (1.53 million) of these people may experience over 100 cm deep of inundation by the 50-year flood (Figure 7.D). For the 100-year flood, approximately 1.68

million people will experience new inundation in the Future and 93 per cent (1.56 million) of these newly affected people may experience over 100 cm deep of inundation.

CONCLUSIONS AND RECOMMENDATION

This study focused on the importance of DHM for the flood risk assessment under climate change. The flood risk in terms of affected people was assessed over the GBM basins located in Bangladesh as well as the most vulnerable four districts of northern Bangladesh. The results of this study demonstrated an increase of flood hazard and risk in Future climates. The BTOPMC model applied with globally available data allowed us to overcome data unavailability in the GBM basins and to simulate flood discharge inflowing into Bangladesh. In future studies, BTOPMC simulation should be performed with satellite precipitation data to generate flood flows with a sufficient lead time for the effective flood management in Bangladesh. Though BTOPMC model performed well, nested calibration and more internal validations with truly optimal and representative grid size at locations midstream and upstream of the GBM basins are recommended to carry out for the improvement of the model's predictability and achieve a better representation of the physical parameters over GBM basin. FID model improvement is necessary, such as ground truthing of the DEM elevation needs to be checked, and FID results should be validated by collecting flood inundation depth of past floods not only along the river channels but in the areas outside of the channels. In addition, the prospective change of flood risk to the population should be examined more closely under various climate change scenarios other than the MRI-AGCM3.2S (SRES A1B scenario) used in this study.

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