



# Effectiveness of water infrastructure for river flood management – Part 1: Flood hazard assessment using hydrological models in Bangladesh

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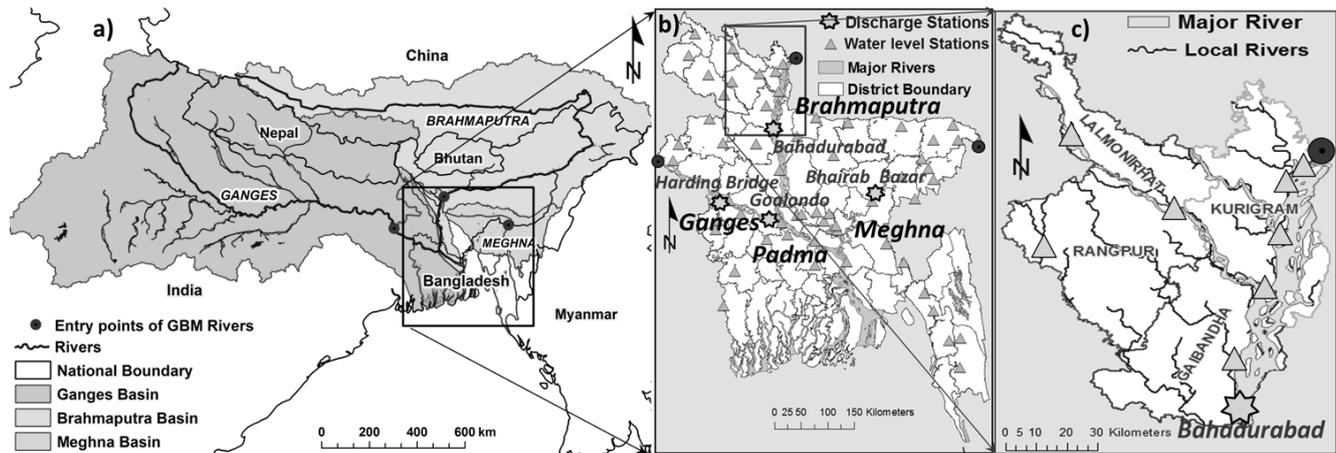
**Abstract.** This study introduces a flood hazard assessment part of the global flood risk assessment (Part 2) conducted with a distributed hydrological Block-wise TOP (BTOP) model and a GIS-based Flood Inundation Depth (FID) model. In this study, the 20 km grid BTOP model was developed with globally available data on and applied for the Ganges, Brahmaputra and Meghna (GBM) river basin. The BTOP model was calibrated with observed river discharges in Bangladesh and was applied for climate change impact assessment to produce flood discharges at each BTOP cell under present and future climates. For Bangladesh, the cumulative flood inundation maps were produced using the FID model with the BTOP simulated flood discharges and allowed us to consider levee effectiveness for reduction of flood inundation. For the climate change impacts, the flood hazard increased both in flood discharge and inundation area for the 50- and 100-year floods. From these preliminary results, the proposed methodology can partly overcome the limitation of the data unavailability and produces flood maps that can be used for the nationwide flood risk assessment, which is presented in Part 2 of this study.

## 1 Introduction

Bangladesh is flood prone and densely populated country that is located at the confluence of the Ganges, Brahmaputra and Meghna (GBM) rivers (FAO, 2012). In Bangladesh, the frequent floods cause fatalities and economic losses and are due to the combined influence of these rivers. Among these floods, the 1998 flood affected 53 out of 64 districts in Bangladesh and was considered the most devastating flood (BWDB, 2014). Despite these frequent floods, embankments are only available means for the flood hazard reduction in Bangladesh while the forecasting of flood peaks in Bangladesh is complicated due to lack of hydro-meteorological and water use data outside of Bangladesh. For example, a special version of MIKE11 Flood Fore-

casting (FF) model simulates flood river discharges in Bangladesh by assuming fixed boundary river discharge at Bangladesh's border (BWDB, 2014). Therefore, the existing levee infrastructure in Bangladesh needs to be considered with GBM flood flows in the flood hazard assessment to investigate its effectiveness due to climate change impacts.

Up to date, a number of hydrological and inundation models have been utilized in the GBM basin and its sub-catchments with limited local observed data (Johnston and Smakhtin, 2014; BWDB, 2014). Kwak et al. (2012) assessed flood inundation depth and area maps in Asia-Pacific region including the GBM river basin using GIS-based flood inundation depth (FID) model with flood peak discharges of the global 20 km BTOP model, which is distributed hydrological model calibrated at the Mekong River basin (Takeuchi et



**Figure 1.** The Ganges, Brahmaputra and Meghna (GBM) river basin in Nepal, India, China, Bhutan and Bangladesh (a). The Bangladesh river water level and discharge gauging stations are demonstrated in zoom-in (b) and the Lalmonirhat, Kurigram, Gaibandha and Rangpur districts in zoom-in (c).

al., 2008). Winsemius et al. (2013) used 50 km hydrological model PCR-GLOBWB globally including the GBM basin to estimate flood discharge and flood inundation, but they also did not conduct model calibration with the observed river discharges. In addition, neither of the studies considers levee infrastructure for the flood inundation simulations. Recently, Masood et al. (2015) investigated the change of hydrologic variables with 10 km hydrologic model H08, which was applied for the GBM basin and calibrated to Bangladesh river discharge data. However, Masood et al. (2015) did not analyze the flood peak river discharges and did not conduct flood inundation simulations. Therefore, a calibrated hydrological model forced with globally available hydro-meteorological data, is useful to simulate Bangladesh flood river inflows and to investigate effectiveness of levees to reduce flood inundation depth and area for the present and future climates.

In this study, we apply the BTOP and FID models for flood hazard assessment in Bangladesh under the present and future climates. Firstly, we utilize existing 20 km BTOP model with available WATCH Forcing Data (WFD) for the GBM basin (Weedon et al., 2011) and calibrate the BTOP model with the Bangladesh observed river discharge data (BWDB, 2014). Secondly, the calibrated BTOP model is applied with the forcing data of the Meteorological Research Institute atmospheric general circulation model (MRI-AGCM) 3.2S for the present and future climates for the SRES A1B scenario (Mizuta et al., 2012). The simulated BTOP discharges are utilized for the flood frequency analysis to produce flood peak discharges of 10-, 25-, 50- and 100-year return period. Next, the FID model is used in the Bangladesh portion of the GBM basin to produce flood water levels and inundation area considering height of levees in Bangladesh (BWDB, 2014). Finally, the potential flood inundation depth and area maps of 50- and 100-year flood peak discharges are compared for the

present and future climates and used to estimate flood risks in Part 2 of this study.

## 2 Study area

In this study, we selected the entire GBM basin to simulate river discharge and only the Bangladesh portion of the GBM basin for the flood inundation simulations. In Fig. 1a, the GBM basin has a total drainage area of 1 712 700 km<sup>2</sup> that consists of 1 087 300 km<sup>2</sup> for the Ganges River, 543 400 km<sup>2</sup> for the Brahmaputra River and 82 000 km<sup>2</sup> for the Meghna River (FAO, 2012). The GBM basin is located in India, China, Bhutan, Nepal, and Bangladesh and has a wide range of climatic conditions from high altitude at the Himalayan and Vindhya ranges to low elevation areas at the Bay of Bengal (FAO, 2012). In Bangladesh, the Ganges and Brahmaputra rivers confluence at the Padma River and the Meghna River, which originates in the north-east of Bangladesh, joins the Padma River near the mouth of the GBM basin (Fig. 1b). FAO (2012) reports that the Bangladesh portion of the GBM basin has an area of 120 400 km<sup>2</sup> with 46 300 km<sup>2</sup> of the Ganges basin, 39 100 km<sup>2</sup> of the Brahmaputra basin and 35 000 km<sup>2</sup> of the Meghna basin (Fig. 1b). In northern part of Bangladesh, four flood prone administrative districts with an area of 8008 km<sup>2</sup> are located in the Bangladesh portion of the Brahmaputra basin (see Fig. 1c).

For the Bangladesh data, the Hydrology Division of the Bangladesh Water Development Board (BWDB) measures river water levels 5 times per day at observation gauging stations (see Fig. 1b). In BWDB, these observed water levels are converted to daily river discharges using rating curves (IWM, 2006) constructed for the four gauging stations (Fig. 1b). In addition, BWDB measures river discharges weekly by the velocity-area method at four river gauging stations (BWDB, 2014). For the Goolondo station, the river discharge is con-

sidered as a sum of the Ganges and Brahmaputra discharges in this study due to lack of the river water level and discharge observation data during the flood season. For the flood water levels, BWDB distinguishes between rivers with and without an embankment. In an embanked river, BWDB selects the danger water level (DWL) above which flood inundation occurs to be below a design flood level of the embankment while a river channel without embankment has DWLs equal to the annual average flood water level (BWDB, 2014).

### 3 Methodology

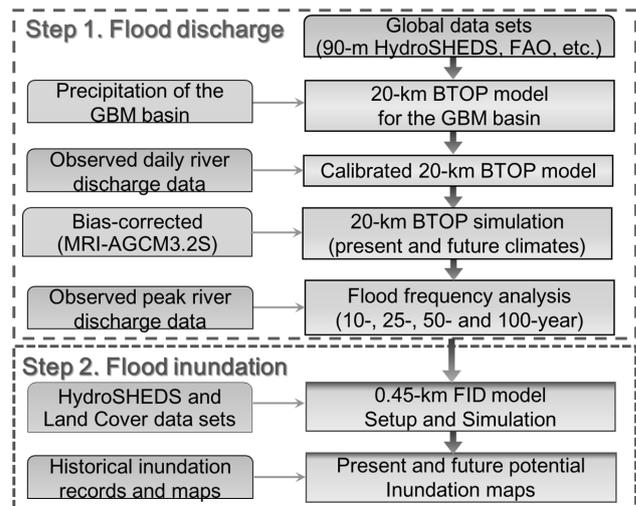
#### 3.1 Flood hazard assessment

In our flood hazard methodology, we simulate flood peak discharges (Step 1) and flood inundation depth maps with river embankments (Step 2) to quantify the effectiveness the existing infrastructure under climate change (Fig. 2). For the flood discharge step, the existing 20 km BTOP model, which is developed from global data sets and utilized for discharge generation globally, is run with daily forcing data and is calibrated with the daily available discharge data at river gauging stations. From the river discharges simulated with the calibrated model, the flood peaks of the selected return periods such as 10-, 25-, 50- and 100-year are estimated with the flood frequency analysis and compared to the historical observations. For the climate change impacts, the calibrated 20 km BTOP model is run with General Circulation Model daily forcing data for the present (1979–2003) and future (2075–2099) climates to generate river discharges, which are utilized in the flood frequency analysis.

In the flood inundation step, the 0.45 km FID model, which is constructed using globally available data sets, estimates flood water levels considering height of river embankments from flood peak discharges estimated in step 1 and produces potential flood inundation area and depth maps. In the FID model, flood water levels are generated using synthetic rating curves and are calibrated with measured river flood water level and river cross-section data. The potential inundation maps simulated with the FID model are compared with the available record of historical inundation area and depth maps. For the climate change impact assessment, the change of potential flood inundation depth between present and future climates is demonstrated to evaluate the effectiveness of existing river infrastructure in the future.

#### 3.2 20 km BTOP model in the GBM basin

For the discharge simulations in the GBM basin, we utilized the 20 km BTOP model, which was developed from the globally available datasets for the global river discharge generation. The BTOP model is a distributed hydrological model that uses a modified topographical index to simulate rainfall-runoff processes including snowmelt, overland flow, soil moisture in the root and unsaturated zones, sub-

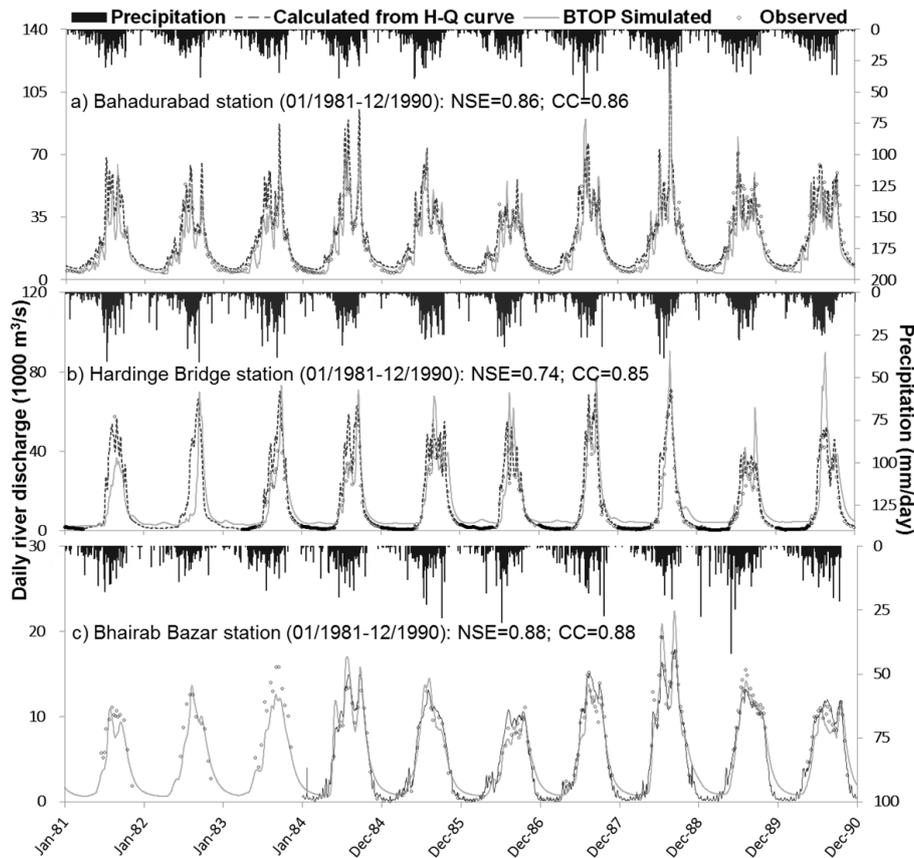


**Figure 2.** Flood hazard assessment methodology implemented in our study.

surface flow, and river flow routing (Takeuchi et al., 2008). The 20 km BTOP model was constructed from 90 m HydroSHEDS Digital Elevation Model (DEM) (Lehner et al., 2008) using river network upscaling algorithm (Masutani and Magome, 2008). From the existing 20 km BTOP model, we introduced four blocks with the outlets at the four river gauging stations in Bangladesh to represent the Ganges, Brahmaputra, Meghna and Padma river basins by each BTOP model block (Takeuchi et al., 2008).

In this study, we utilized WFD and MRI-AGCM3.2S (SRES A1B scenario) forcing data sets with daily values on 20 km resolution in the GBM basin. For the WFD data set, we selected a range between 1980 and 2001 of the WFD daily precipitation and temperature data developed by Weedon et al. (2011) to match available river discharge data in Bangladesh (BWDB, 2014). For the MRI-AGCM3.2S data set, the daily precipitation data were used for the present (1979–2003) and future (2075–2099) climates (Mizuta et al., 2012). For the MRI-AGCM3.2S precipitation, we applied a bias-correction factor, which was estimated as each sub-basin averaged long term (22 years) monthly mean rainfall of the WFD data (Masood et al., 2015). The long term seasonal potential evapotranspiration (PET) within BTOP model was estimated by the Shuttleworth–Wallace (SW) model using climate forcing data Climatic Research Unit (CRU) TS3.1 (UEA CRU, 2008) and a fortnightly Normalized Difference Vegetation Index (NDVI) (Tucker et al., 1994).

The BTOP model performance was evaluated with Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) and correlation coefficient (CC) for the calibration period of 1981–1990 and the validation period of 1991–2000. To estimate flood peak discharges beyond the existing record, we applied flood frequency analysis using L-moment ratio dia-



**Figure 3.** Daily river discharges for the BTOP model calibration at Bahadurabad (a), Hardinge Bridge (b), and Bhairab Bazar (c) stations.

gram with the Gumbel distribution to obtain 10-, 25-, 50- and 100-year return period flood peak discharges.

### 3.3 FID model in Bangladesh

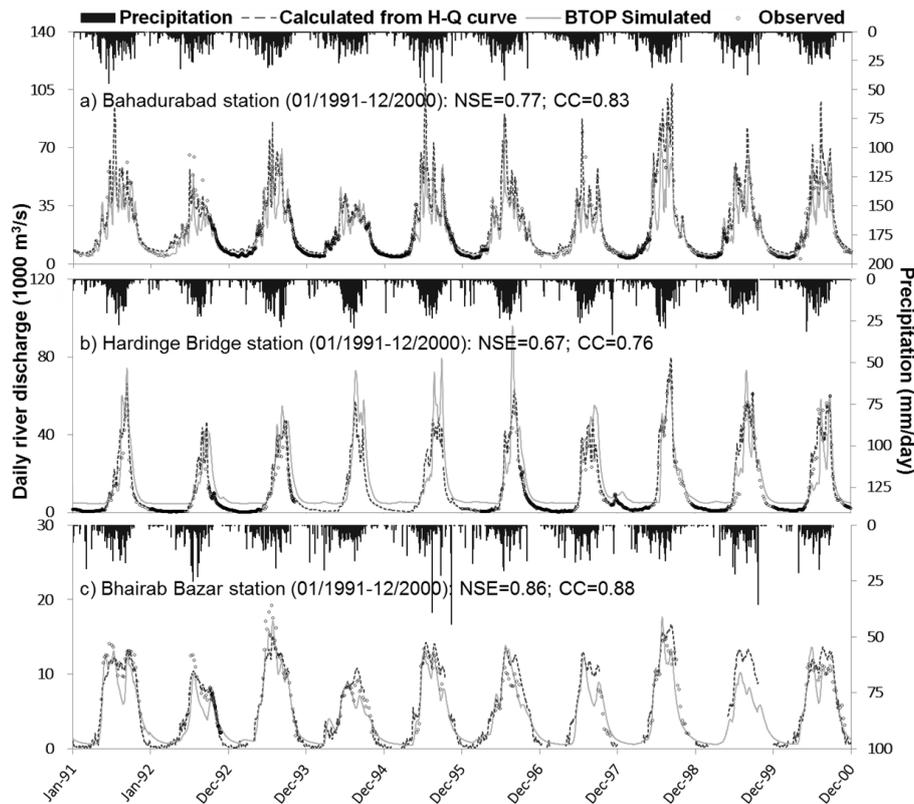
In the Bangladesh portion of the GBM basin, the 0.45 km FID model simulated the flood water level and estimated potential flood inundation depth and area using flood peak discharges of a selected return period produced at each BTOP grid (Kwak et al., 2012). The FID model is a GIS-based model developed from about 0.5 km HydroSHEDS data set (Lehner et al., 2008) and converts flood peak discharges to flood river water levels using a synthetic rating curve developed with Manning's equation (Kwak et al., 2012). The FID simulated flood water levels of the 10-year return period discharge were considered as DWLs, which include height of embankments. The FID simulated flood water levels of the 50-year return period were calibrated with the recorded highest water level (RHWL) data selected at the 40 gauging stations in the study area (Fig. 1b). In addition, these flood peak water levels of the 50-year return period were verified with three cross-sections of the Brahmaputra River (Fig. 1c). From the optimized FID flood water levels, the potential flood inundation maps produced with 25- and 100-year flood

peak discharges were compared with the MODIS images of 2004 Bangladesh flood and the historical flooded district area of 1998 Bangladesh flood, respectively (BWDB, 2014). For the climate change impacts, we analyzed the change of potential flood inundation depth between future and present climates.

## 4 Results and discussion

### 4.1 Simulated flood discharges in the GBM basin

The BTOP simulated river discharges with WFD forcing data are shown in Fig. 3 for the calibration period (1981–1990) and for the validation period (1991–2000) in Fig. 4. In both figures, the BWDB measured river discharges are shown by circle and discharges calculated based on the rating curves by dashed line. The BTOP river discharge simulations are found in good statistical agreement with the historical discharges at four stations, see demonstrated statistics in Figs. 3 and 4 (Goalondo station is not shown). For the Goalondo station, the BTOP simulated discharges follow a combined influence of the Ganges and Brahmaputra Rivers and the NSE equals to 0.88 for the calibration period and to 0.86 for the validation period. In the BTOP model, the Farakka barrage operation,



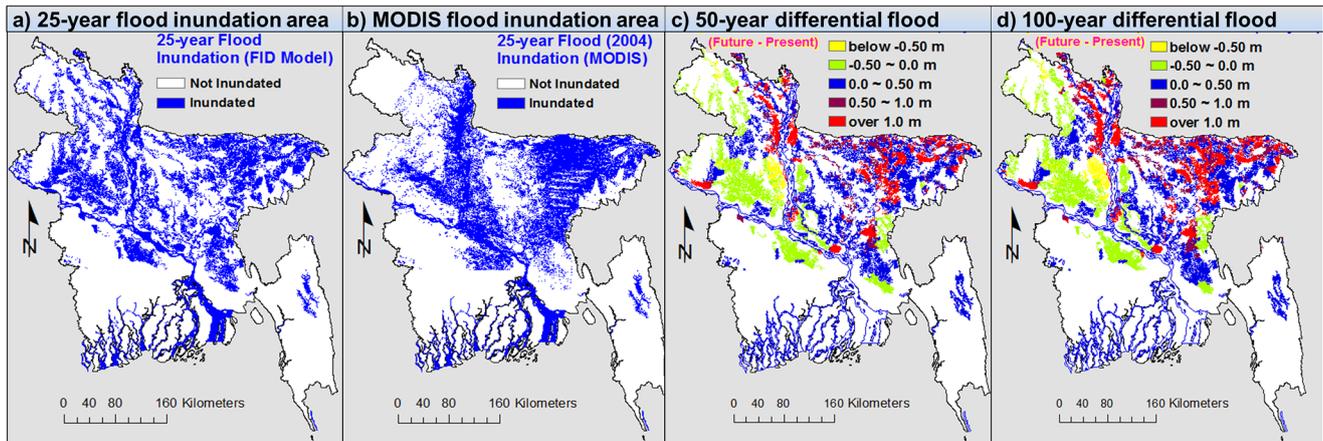
**Figure 4.** Daily river discharges for the BTOP model validation at Bahadurabad (a), Hardinge Bridge (b), and Bhairab Bazar (c) stations.

which is located near Bangladesh border and diverts Ganges river water for irrigation in India during dry season, was not considered and may be attributed to the overestimation of the low flows (FAO, 2012). For the historical flood peak discharges, the 1988 and 1998 floods are considered 50- and 100-year return period floods, respectively (BWDB, 2014). These historical discharges are comparable to the flood peak discharges estimated with the flood frequency analysis and simulated BTOP discharges in Figs. 3 and 4. The 50-year return period flood peak discharges are about 104 000 cms at the Hardinge Bridge station and about 86 000 cms at the Bahadurabad station. For the 100-year return period, the flood discharges are 110 000 cms at the Hardinge Bridge station and 92 000 cms at the Bahadurabad station. For the Goalondo station, the BTOP simulated river discharges are about 205 000 cms in 1988 and about 215 000 cms in 1998. For the climate change impact analysis, the simulated BTOP discharges for present and future climates with the bias-corrected MRI-AGCM3.2S forcing data demonstrate an increasing trend of the flood peak discharges at all stations. For example, both 50- and 100-year flood peak discharges of the future climates increased by about 2.1 times at the Bahadurabad station, by about 1.4 times at the Hardinge Bridge station and by about 1.7 times at the Bhairab Bazar station.

#### 4.2 Simulated flood inundation in Bangladesh

In Bangladesh, historical flood inundation maps are not available to make a direct comparison between simulated and actual flood inundation depth (BWDB, 2014). For the flood water level calibration, the FID flood water levels of the 50-year peak discharge shows a good correlation with the RHWL data ( $R^2 = 0.79$ ) and are used to produce potential flood inundation maps. For the 25-year return period flood, the FID model map resulted in inundated area of 41 523 km<sup>2</sup> (Fig. 5a) and is considered to represent the 2004 flood in Bangladesh with the inundation area of 40 704 km<sup>2</sup> (BWDB, 2014). In Fig. 5b, the 2004 flood inundation area is verified by the 8-day composite of Terra sensor MODIS satellite image collected for 27 July 2004–3 August 2004 (EOS, 2006) and has inundation area of about 40 000 km<sup>2</sup> detected from the MODIS satellite image. The potential inundation map of the 50-year flood discharge indicates an inundation area of 47 600 km<sup>2</sup> (35.9 %) and the 1988 flood inundated 61 % of Bangladesh (BWDB, 2014). For the 100-year flood, the potential inundation area produced with the FID model covered an area of 52 149 km<sup>2</sup> (43.4 %) while the historical 1998 flood inundated 68 % of Bangladesh based on district level information (BWDB, 2014).

For the climate change impact assessment, the change of the flood inundation depth is presented in Fig. 5c for the 50-



**Figure 5.** The 25-year flood inundation area produced with FID model (a) and MODIS image (b) data. The change between future and present flood inundation depth for 50-year flood (c) and 100-year flood (d) with existing levee infrastructure.

year flood and for the 100-year flood in Fig. 5d. In Fig. 5c, the potential flood inundation area increases by 2639 km<sup>2</sup> from 47 600 km<sup>2</sup> in the present to 50 239 km<sup>2</sup> in the future for the 50-year flood and by 2518 km<sup>2</sup> from 52 149 km<sup>2</sup> in the present to 54 667 km<sup>2</sup> in the future for the 100-year flood in Fig. 5d. However, the spatial distribution of flood depth change in the Bangladesh portion of the GBM basin is not uniform with a decreasing trend for the Ganges and Padma basins and an increasing trend for the Brahmaputra and Meghna basins. For the 50-year flood, the flood inundation area of 33 151 km<sup>2</sup> has an increase of flood inundation depth by more than 50 cm in the area of 12 929 km<sup>2</sup> and by more than 100 cm—8951 km<sup>2</sup> between future and present climates. For the 100-year flood, the flood inundation area of 39 040 km<sup>2</sup> has an increase of flood inundation depth by more than 50 cm in the area of 17 568 km<sup>2</sup> and by more than 100 cm—12 883 km<sup>2</sup>. These preliminary inundation area and depth maps indicate potential flood hazard hotspots in the Bangladesh portion of the Brahmaputra and the Meghna river basins, where height of the existing embankment may be insufficient to reduce the future flood hazard.

## 5 Concluding remarks

In this study, the 0.45 km FID model was developed in the Bangladesh portion of the GBM basin to produce flood inundation maps using simulated river discharges with the 20 km BTOP model applied for the entire GBM basin. In the GBM basin, the 20 km BTOP model was run with WFD forcing data from 1980 to 2000 and with bias-corrected MRI-AGCM3.2S for the present (1979–2003) and future (2075–2099) climates. The BTOP model with WFD forcing data was calibrated with river discharge data at four stations in Bangladesh and represented river flows in the GBM basin. For the flood frequency analysis, the Gumbel distribution with L-moments was selected to produce 10-, 25-,

50- and 100-year return period flood discharges from simulated BTOP discharges for the present and future climates. For the climate change impacts, the magnitude of the flood discharges increases under the future climates in Bangladesh area. For 50- and 100-year the flood peak discharges, the future discharge increased by about 2.1 times at the Bahadurabad station, by about 1.4 times at the Hardinge Bridge station and by about 1.7 times at the Bhairab Bazar station.

The potential flood inundation maps were produced with the FID model for the Bangladesh portion of the GBM basin. For the past Bangladesh floods, historical flood inundation maps are not available for the detailed comparison of inundation extent and depth. The total inundation area of 100-year historical flood reported by BWDB (2014) was comparable to the inundation areas simulated with the FID model. For the 25-year flood inundation map, the 2004 flood inundation area of the MODIS image and of the BWDB (2014) historical data was similar to the potential flood inundation maps simulated with the FID model. For the climate change impacts, the potential flood inundation area increases by 4.83 % for the 50-year flood and by 5.54 % from present to future for the 100-year flood. In both cases, the spatial distribution of flood depth change had a similar pattern: increased near the Brahmaputra and Meghna rivers and decreased near the Ganges and Padma rivers. These preliminary inundation area and depth maps indicate potential flood hazard hotspots, where height of the existing embankment may be insufficient to reduce the future flood hazard. In Part 2 of this study, we utilize these potential flood inundation hotspots to produce flood risk in terms of affected people and agricultural damages. The results of this study provide essential flood hazard and risk information to implement the Integrated Flood Management concept in Bangladesh.

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