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Flood Hazard Mapping of the Floodplain of the Jamuna River

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ABSTRACT

Bangladesh is located in the deltaic plain. It is very vulnerable to floods. Flood causes enormous losses to crops, lives, settlements and others. Jamuna river is prone to monsoon floods and is located in the North-central part of Bangladesh. Flood Hazard Mapping is a cost-effective and non-structural measure to mitigate floods. The study area is about 75 km. Flood hazard maps were generated using the RIVERFLOW2D model in conjunction with ArcMap. Calibration and validation were done for the years 2014 and 2017. Then steady simulation was done for 2, 25 and 100-year return periods and inundation areas were found at 40, 55 and 58 km^2 respectively. The flood hazard maps were generated based on depth, velocity and the product of maximum velocity and depth. Then these flood hazard maps were superimposed on different land uses such as crops, settlements & others for the assessment of the flood hazard areas. These hazard maps for different land use will be useful for future planning and management to mitigate floods.

1. Introduction

Bangladesh is a deltaic country where floodplains cover about 80% of the area. By properly utilizing the floodplain for fisheries, agricultural and manufacturing production, this deltaic floodplain can be used to improve the livelihood of rural people [1]. Bangladesh faces floods

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almost every year and in every monsoon period, about 20-30% of the land is inundated [2]. Generally, a flood is categorized as catastrophic if the flood inundates 33% or more of the land. Bangladesh experienced this kind of catastrophic flood in the following year such as in 1988,1998, 2004, 2007 & 2017 [3,4]. There are both structural and non-structural measures that can be taken to prevent natural disasters including floods, cyclones, and storm surges. Along with structural measures, non-structural measures are becoming increasingly popular as a low-cost and effective alternative. The non-structural measure includes flood forecasting warnings, flood zoning, flood hazard mapping and assessment [5]. For flood hazard assessment, mathematical modelling and remote sensing techniques are commonly used. Due to the limitations of the 1D hydraulic model, the 2d hydraulic model is preferred for flood hazard mapping as the 2d model can estimate variations in longitudinal and lateral directions [6]. In this study area, Jamuna River is selected with a width varying from 6 km to 12 km. Rahman et al (2021) coupled a 2D hydrodynamic model with a Machine learning algorithm to develop Flood hazard mapping for the Surma river which is located northeast of Bangladesh [7]. Rangari et al (2021) developed flood risk maps based on inundation depth and velocity using the 1D-2D urban flood model. They considered the effects of climate change and urbanization [8]. Tyrna et al (2016) used high-resolution Terrain for a large-scale study area to prepare flood hazard maps with the 2D model High-Performance Computing version of FloodArea (FloodAreaHPC) [9]. Baky et al (2020) assessed flood risk GIS and 2D hydraulic model. He found that the flood risk level did not increase with the increase in flood depth [10]. Vasconcellos et al (2021) generated flood hazard maps for an alluvial river with the combination of three models such as Hydrological Engineering Center – River Analysis System 2D (HEC-RAS), FAN Model and Height Above the Nearest Drainage (HAND). As the alluvial river changes its position year to year, these three combinations of models will be helpful to prepare flood hazard mapping more precisely [11]. Khaing et al 2021 use the Rainfall-Runoff model to generate flood hazard mapping in the data-scarce Nyaungdon area, Myanmar. Then they validated their results with some remote sensing images such as Moderate Resolution Imaging Spectroradiometer (MODIS) and the Phased Array type L-band Synthetic Aperture Radar-2 onboard Advanced Land Observing Satellite-2 (ALOS-2 ALOS-2/PALSAR-2) and they found very good results comparing with this satellite images. The output results of the flood 2d model also depend on the accuracy of data such as resolution and accuracy of the DEM [12]. Farooq et al (2019) used four DEMs such as 12-m World DEM, 30-m SRTM, 30-m ALOS and 30-m ASTER DEMs and then analyze model sensitivity. They found that the flood depth varied significantly with a different kind of DEM. He found that 12-WorldDEM gives accurate depth compared with the other three DEMs. In this study area, Cross-section derivate DEM is used for the flood hazard mapping and assessment [13]. Flood hazard assessment is also useful to determine the impact of floods in different locations and for this several research, works have been carried out such as Ernst et al. 2010, de Kok and Grossmann 2009 [14,15]. In this study. Flood hazard mapping is prepared using RIVERFLOW2D, HEC-RAS & cross-section derivate DEM based on different variables such as depth, velocity, and the product of velocity and depth for the different return periods. Then these hazard maps are expressed in terms of different land use such as Crops & settlements.

2. Research significance

The floodplain of the Jamuna River has flooded almost every year. Flood causes huge losses to crops, settlements & others. These hazard mapping can be useful to select a suitable place for crops and settlements according to the separate or combined magnitude of the velocity and depth during the monsoon period. The results of this study will be helpful for the National Agency to mitigate the flood vulnerability in the study area.

3. Methods

3.1. Study area

The bank full discharge of the Jamuna River is 48000 m3/sec. Jamuna River exceeds its bank full discharge almost every year and the floodplain of the Jamuna River experience flood. The location of this study area is started from Bhadurabadh station and ends at Sirajganj station which is about 75 Kms.

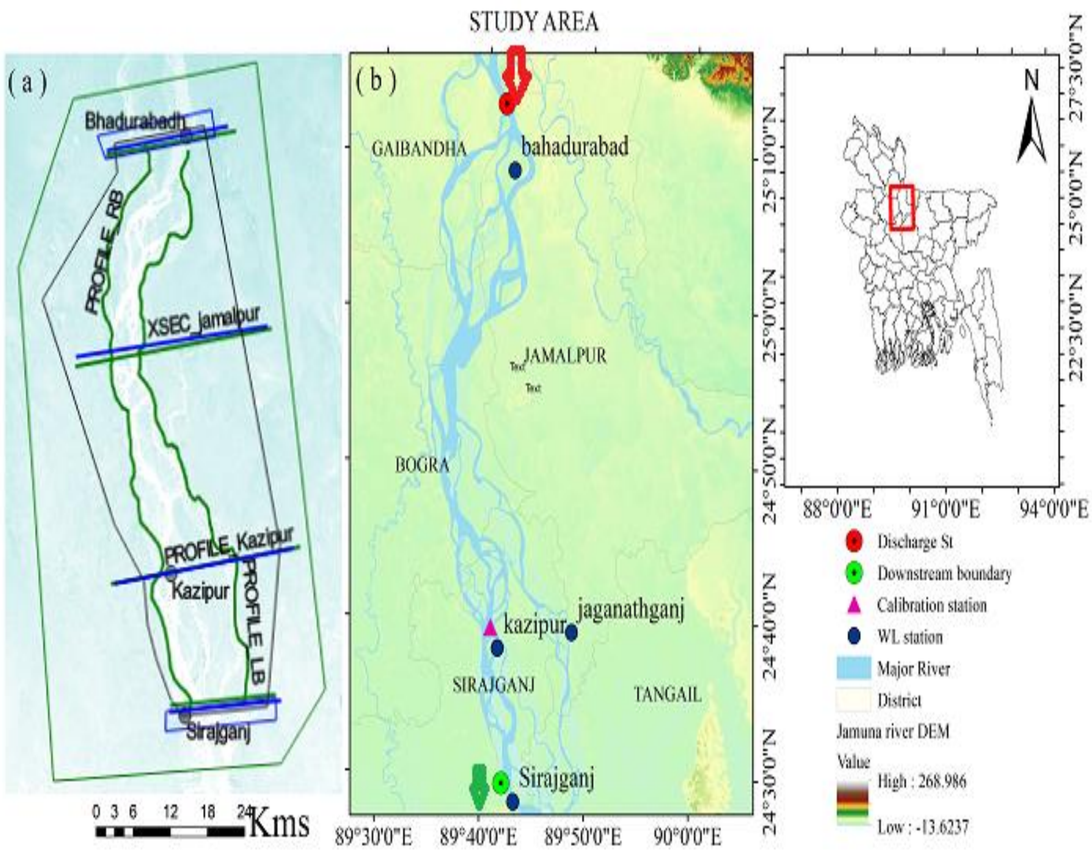

Fig. 1. Study area showing Jamuna river reach.

3.2. Data collection

15 cross-sections of Jamuna river between Bahaduranadh station and Sirajganj station were collected from the Bangladesh water Development Board (BWDB) for the year 2018. Merit DEM

was downloaded from the free access website. Discharge data for the Bhadurabadh station (SW 46.7L) was collected from BWDB for the year 2014 to 2019. Water level data for three stations such as Bhadurabadh, Kazipur and Sirajganj stations were also collected from BWDB for the same year.

Table 1
Data collection.

Data type	Source	Data collection	Period
Discharge	BWDB	Bahadurabad	2014-2019
Water level	BWDB	SW49A,SW49, SW46.9	2014-2019
Cross-section	BWDB	RMJ #13-#7	2018
MERIT DEM	http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/	Jamuna River	

3.3. Hydraulic model

RIVERFLOW 2D uses the Navier-stokes equation and the model does not consider turbulence terms. The assumption about bed shear stress is that it follows the depth average velocity directions.

Depth averaged mass and momentum conservation equations are used to describe shallow water flows. Partial differential equations of the shallow water flows will be expressed here. The conservative form of these equations is as follows:

$$\partial U/\partial t + \partial F(U)/ \partial x + \partial G(U) /\partial y = S(U, x, y) \quad (1)$$

where $U = (h, q_x, q_y)^T$ is the vector of preserved variables and h is representing the water depth, $q_x = uh$ and $q_y = vh$ the unit discharges, (u, v) represents the depth-averaged components of the velocity of vector u along with the x and y coordinates respectively. The flux vectors are given by:

$$F = (q_x , q^2{}_y/h + 0.5gh^2 , q_x q_y/h)^T , G = q_y , q_x q_y/h , (q^2/yh + 0.5gh^2)^T \quad (2)$$

where g is the acceleration due to gravity. After assuming a hydrostatic pressure distribution, the term $0.5gh^2$ in the fluxes has been found in every water column. The source term vector (S) combines the effect of pressure force over the bed and the tangential forces generated by the bed stress

$$S = (0, gh(S_{0x} – S_{fx}), gh(S_{0y} – S_{fy}))^T \quad (3)$$

where the bed slopes of the bottom level z_b are

$$S_{0x} = - \partial z_b/\partial x , S_{0y} = - \partial z_b/\partial y \quad (4)$$

and the bed stress contribution is modeled using the Manning friction law so that:

$$S_{fx} = n^2u \sqrt{(u^2 + v^2)}/ h^{4/3}, S_{fy} = n^2v\sqrt{(u^2 + v^2)}/ h^{4/3} \quad (5)$$

with n the roughness coefficient.

3.4. Model setup

The Merit DEM was originally in the Geographic co-ordinate (Lat-Long) system. In ARC-GIS 'Define Projection' Tool was used for the transformation of the coordinate system. The coordinate system was set to WGS 1984 UTM 46N projection. According to the BWDB cross-section shapefile, the cross-section was drawn in RAS Mapper and the cross-section was inserted. Then new terrain was created from a cross-section in the RAS-Mapper. The terrain was saved in a definite folder. The overall methodology is shown in Fig.02

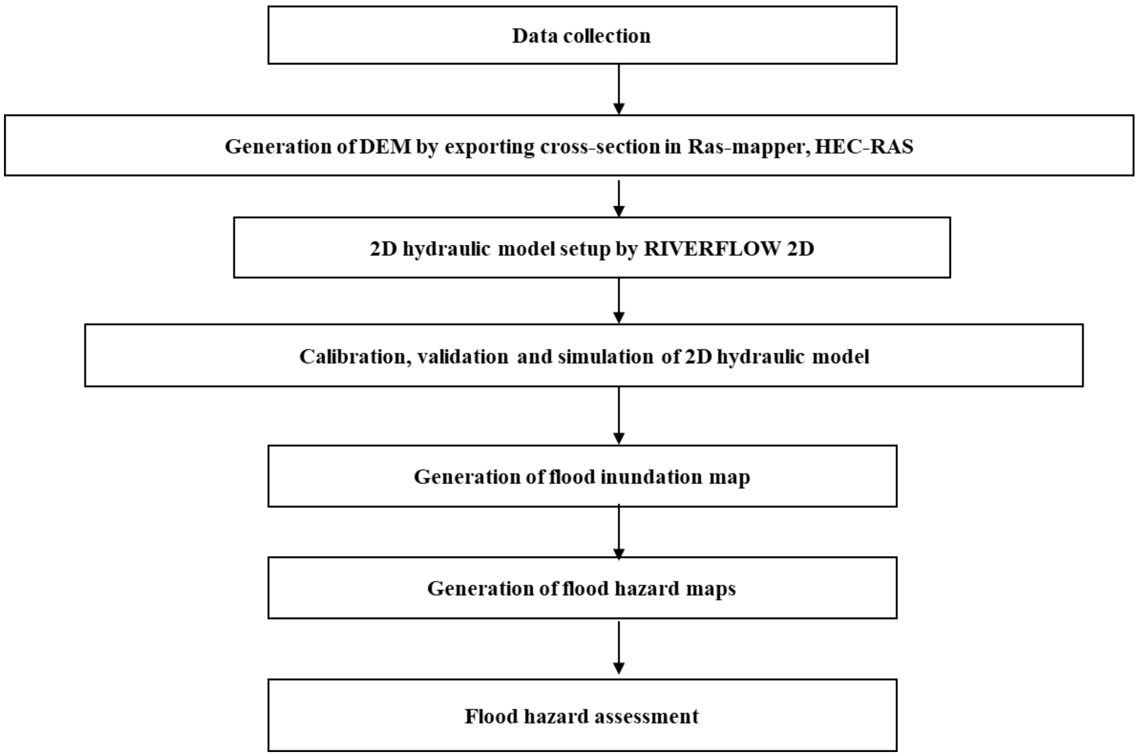

Fig. 2. Flow chart.

After that, the RIVERFLOW2D model was used for 2D hydraulic modelling. First, Terrain was added. Then, a Domain outline was created which represents the study area. Trish was generated and the cell size was 300 meters. The upstream and downstream boundary was given. The outline was created for man's n. The file was exported to the RIVERFLOW 2D simulation model. The computational interval was given as 10 minutes and the output computational time interval was given as 24 hours. After, flood hazard maps were generated based on different conditions and finally flood hazard assessment was done.

4. Results and discussions:

4.1. Simulation, calibration and validation

The hydrodynamic model was calibrated and validated for the years 2014 and 2017 at the Kazipur station for the monsoon period with the water level which is shown in Fig.03. The manning's roughness coefficient was adjusted to calibrate the hydrodynamic model. Model simulated water level showed a very good agreement with the observed water level for the manning's roughness as 0.029. For the 2D hydrodynamic model, the coefficient of correlation(R^2) was found 0.98 for calibration and validation (Fig.03).

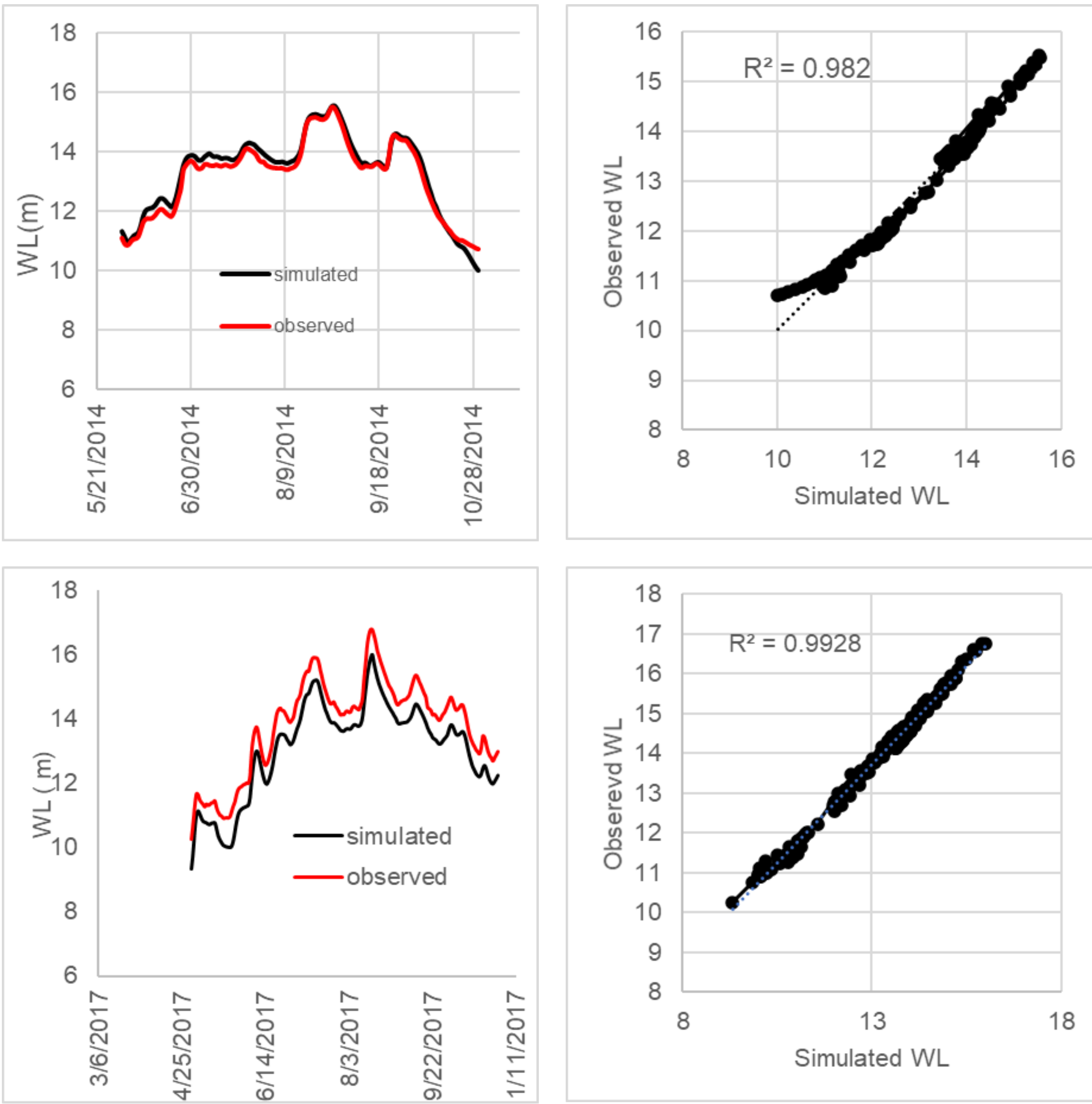

Fig. 3. Calibration and validation graph.

4.2. Analysis of land-use map

Among total modelled area of 8329.311 km2 , waterbody, island, bare soil, agriculture, settlements & others cover almost 2.52%,1.68% 8.39%, 37.68% & 49.71%. respectively. The land use map is shown in figure.04 where the area of water body, island, bare soil, agriculture, settlements & others are 225.02 km^2, 150 km^2, 749.17 km^2, 3364.56 km^2, 4260.174278 km^2.

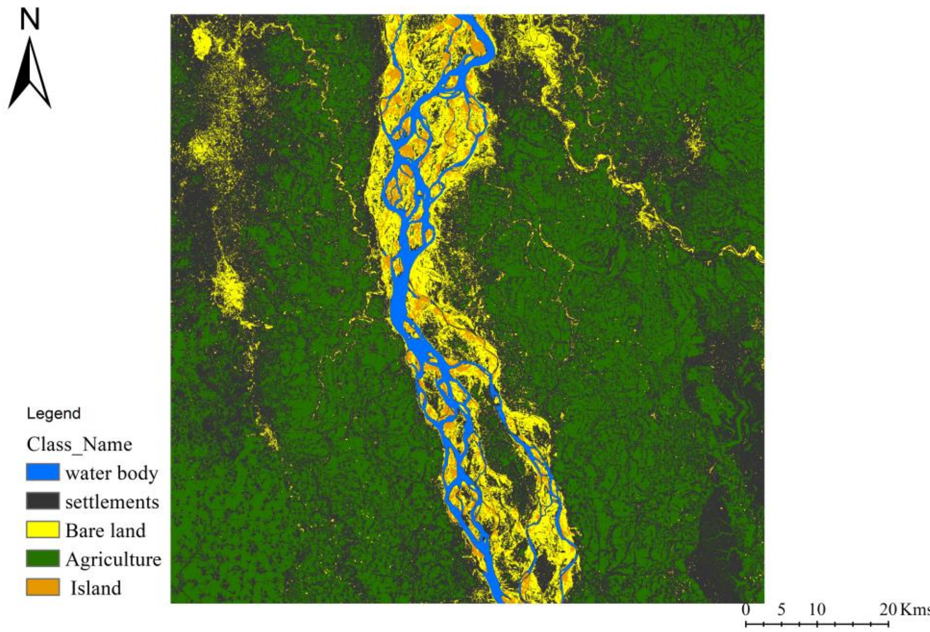

Fig. 4. land use map of the study area.

4.3. Flood extent map

The flooded area was found at around 4043.52 km^2 , 5504.97 km^2 and 5854.48 km^2 for the return period of 2, 25 and 100 years respectively. (figure.5).

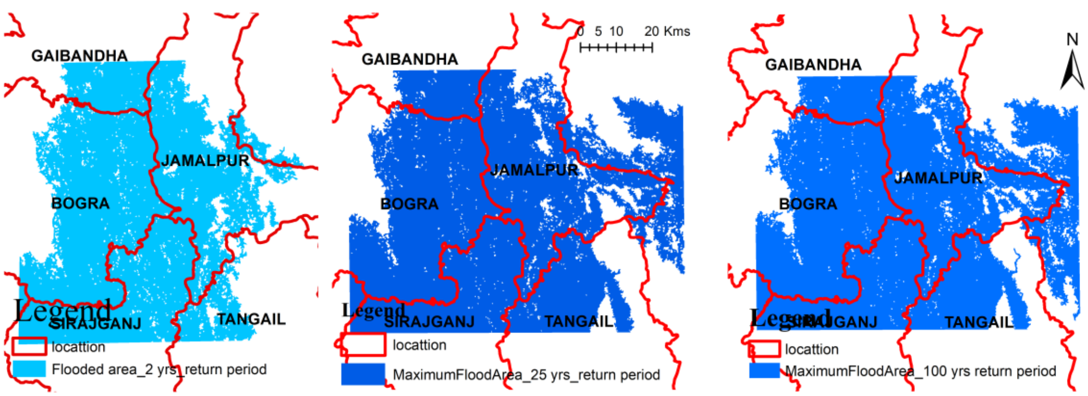

Fig.5. Flood extent map.

4.4. Hazard mapping based on depth

According to water depth, the floodplain is classified into three categories. The right floodplain of the river locates in the high danger zone. The red colour represents that the depth over the floodplain is greater than 3 meters. The water depth in Sirajganj, Bogra & Gaibandha districts varies between 1.5 and greater than 3 meters, except in some areas which are located 25-35 km from the right bank of the Jamuna River for a 100-year return period (Fig. 06). Jamalpur is located in a medium danger zone near the bank but Tangail is located in a high danger zone which is shown in fig.06.

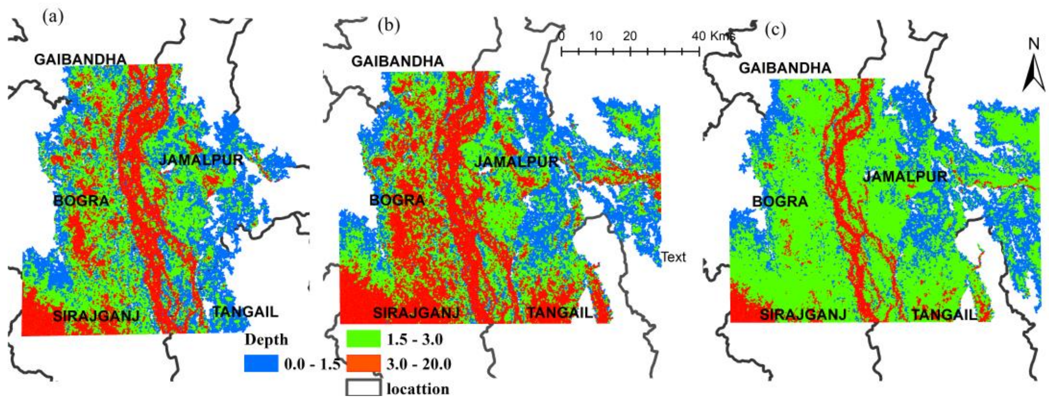

Fig. 6. Flood hazard mapping based on depth, (a) for 2 yrs return period, (b) for 25 yrs return period, (c) for 50 yrs return period.

4.5. Hazard mapping based on velocity

Based on velocity magnitude, the inundated areas are classified into four qualitative hazard classes which are shown in fig. 07 such as Very low hazard (0-.664m/s), low hazard (0.664-1.54m/s), medium hazard (1.54-3.313m/s), high hazard (3.13-4.5m/s). The maximum velocity varied between 0-1.53 m/sec in the floodplain. In Sirajganj district, the sloping topography might be below as well as a different kind of settlement for which the velocity is low compared to upstream of Bogra, Ghaibandha area for a 100-year return period (Fig. 07)

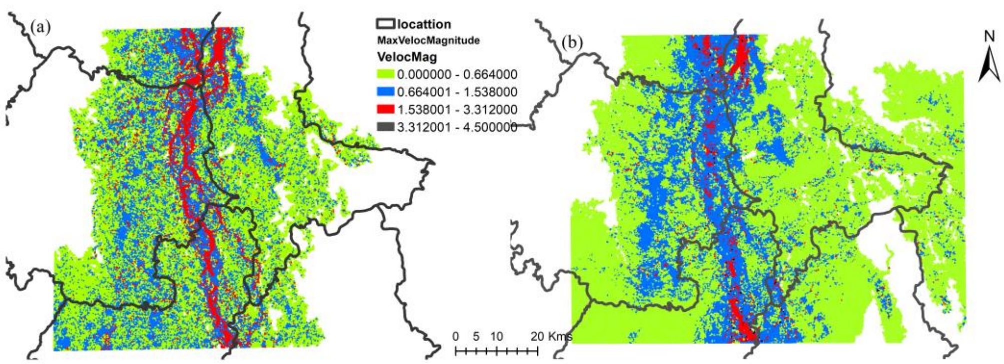

Fig. 7. Flood hazard mapping based on velocity, (a) for 2 yrs return period, (b) for 100 yrs return period.

4.6. Hazard mapping based on the product of velocity & depth

The product of velocity and depth is more realistic for the quantification of crops and settlement hazards which is shown in fig. 08. For a return period of 100 years, the right floodplain of the river is more vulnerable to crops and settlements than the left floodplain. Both floodplains are vulnerable near the river. As the distance from the river increases, the magnitude of the product of velocity and depth decreases which represents a low vulnerability to crops, lives and infrastructure. For 2 years return period, the magnitude is low except in some locations such as a small portion of the Ghaibandha & Sirajganj district(Figure 08).

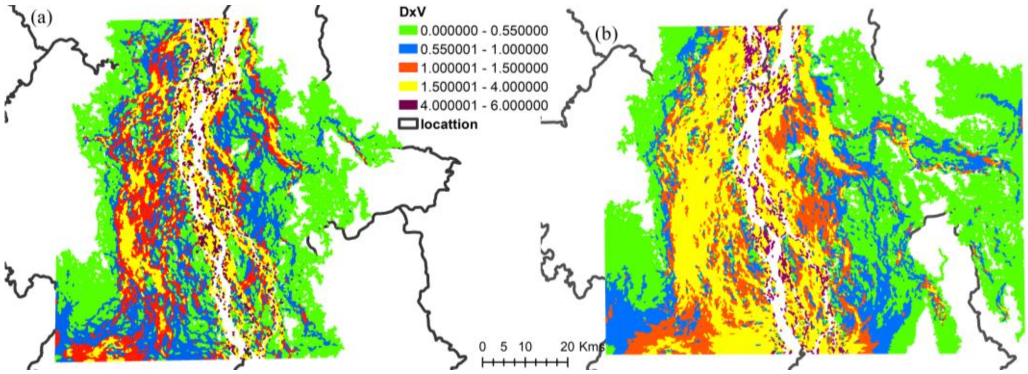

Fig. 8. Flood hazard mapping based on the product of maximum velocity and depth, (a) for 2 yrs return period, (b) for 100 yrs return period.

4.7. Hazard mapping for crops

2 years return period flood hazard mapping for crops is more important than 100 years return period to select a suitable area and to select crop types. The Sirajganj district is located in low(0.5-1.0), medium(1.0-1.5) hazard zone (Fig.09).Some portion of the Gaibandha district which is situated 1-10 km from the right bank is located in a low to medium zone but the area located at a far distance from 12 km can be classified as a very low to no hazard zone. The Jamalpur and Tangail districts can be classified as low (0.5-1.0) to very low (0.0-0.5) hazard zone which is shown in fig.09. Several areas within the floodplain are located in the high danger zone which can be very vulnerable to settlements.

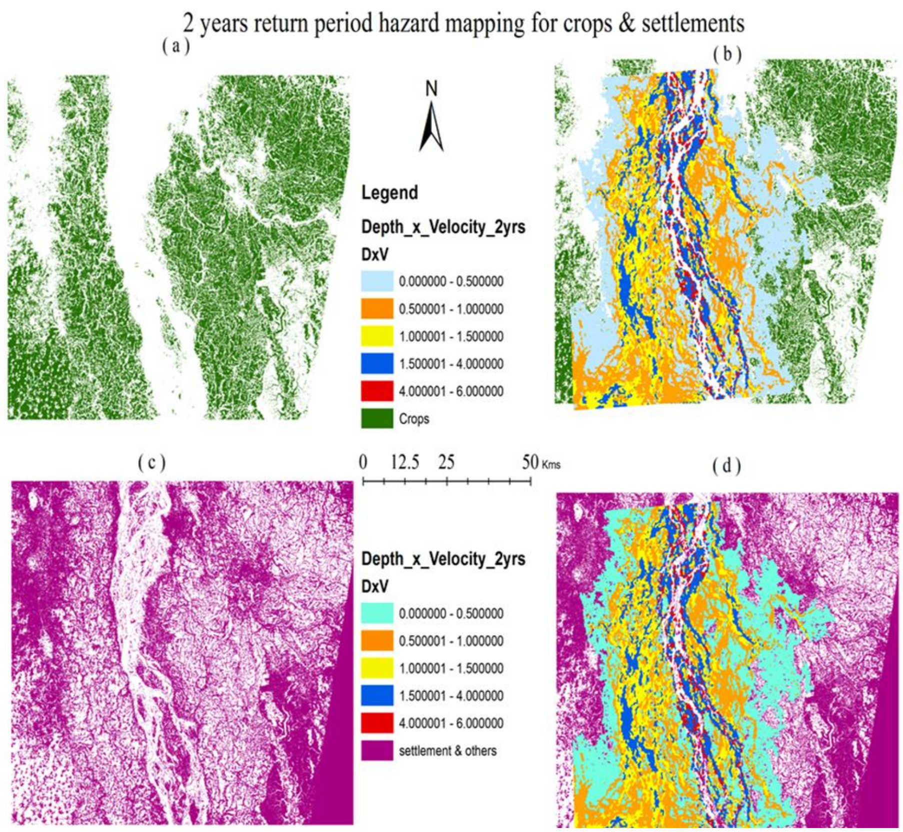

Fig. 9. Flood hazard mapping for crops.

4.8. Hazard mapping for settlements and others

100 years return period hazard mapping for settlements is more important than 2 years return period to select suitable areas for different kinds of interventions. The upper part of the Sirajganj district is located in a high hazard (1.5-4 m^2/s) zone near the bank up to a distance of about 12.5 km and gradually the zonation shift to medium & low hazard (Fig. 10). The Jamalpur and Tangail district can be classified as low to medium hazard zone except some portion is located in high hazard zone near the bank. Near Bankline in Bogra, some area is located in the low to medium hazard zone but the middle portion of Bogra and Gaibandha is located in the high hazard zone.

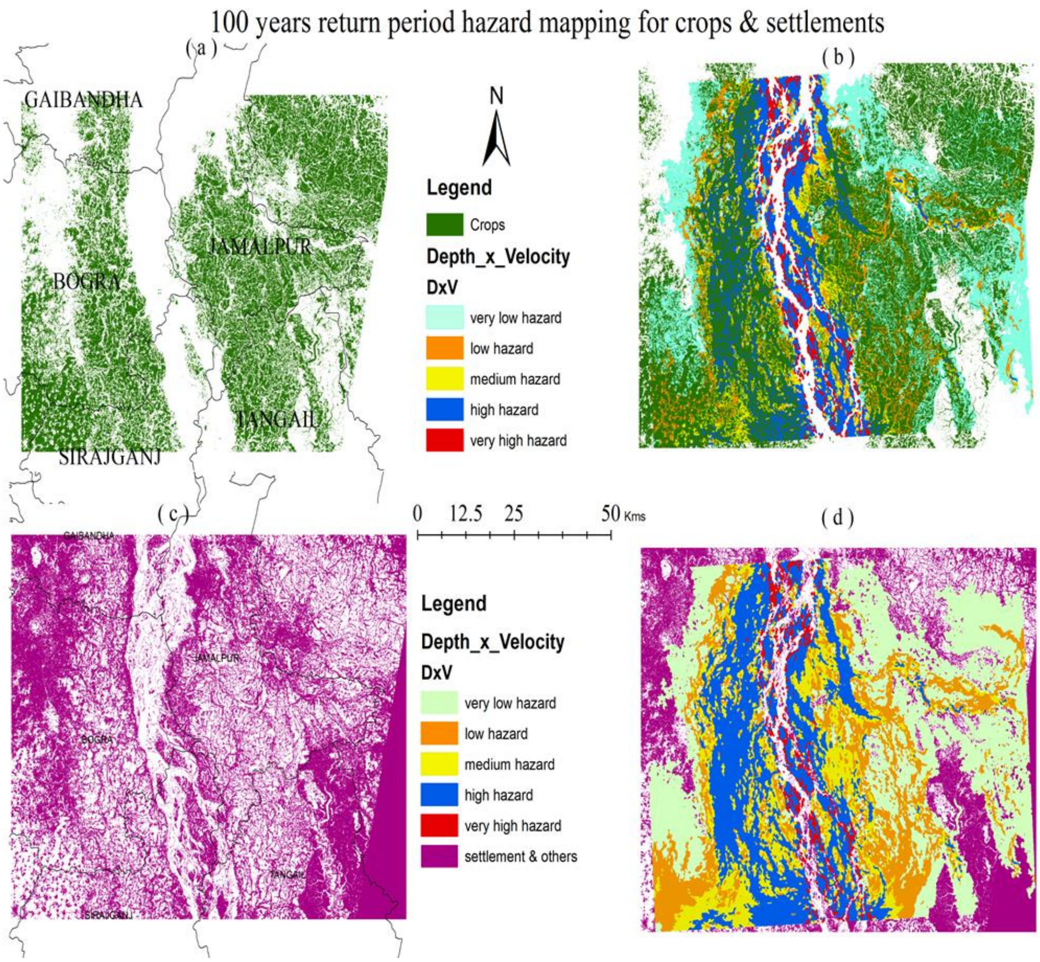

Fig. 10. Flood hazard mapping for settlements and others.

4.9. Flood hazard assessment

The modeled area covers total area of 8329.311 km^2 where water body, island, bare soil, agriculture, settlements & others covers respectively 2.52%,1.68% 8.39%, 37.68% & 49.71% (Fig.11). The most affected land-use type is agriculture. About 88% of the agricultural area is affected by a 100-year return period flood during the monsoon period but for settlements & others around 80% area of total settlements & others get inundated (Fig.11).

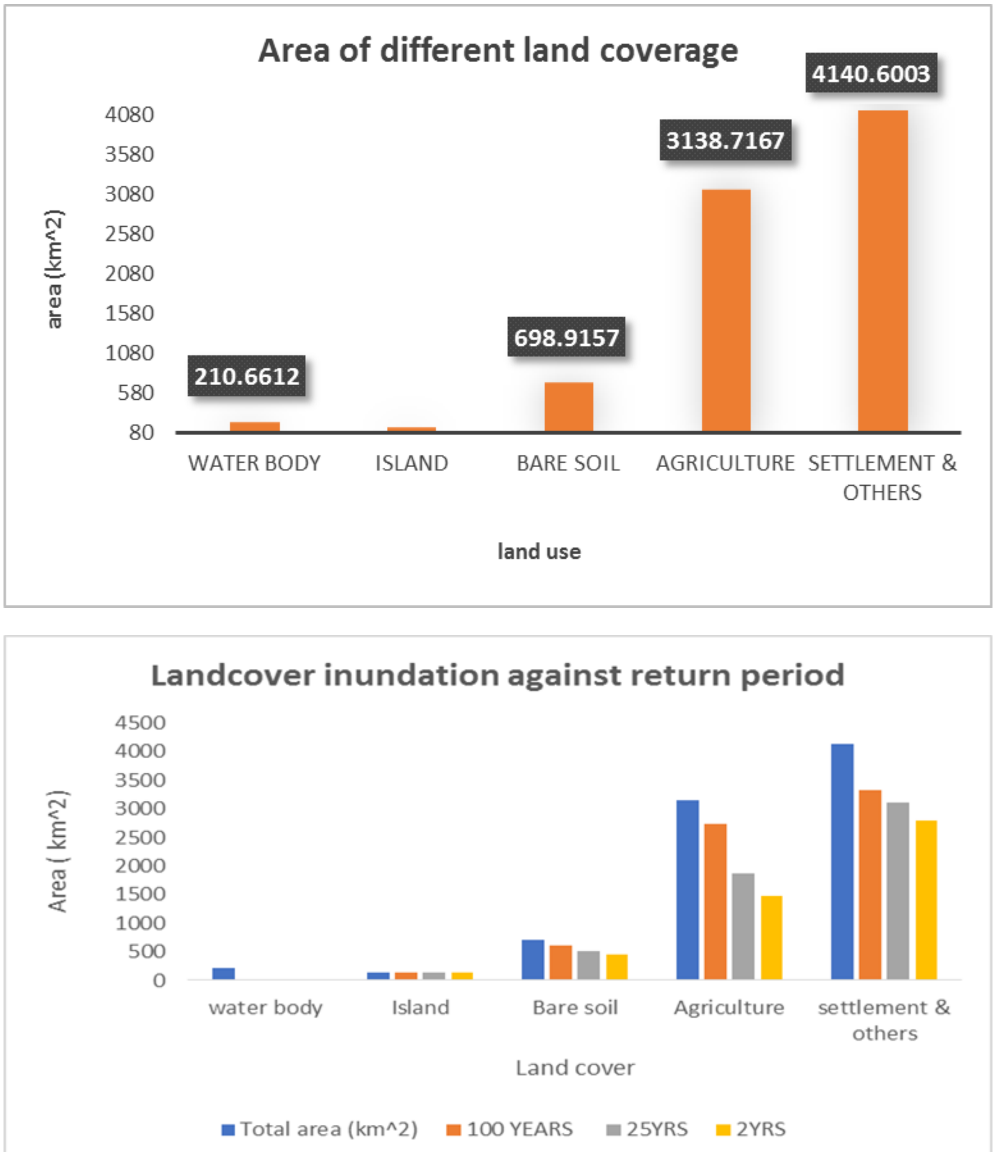

Fig. 11. area of inundation for land use for the different return periods.

5. Conclusions

The hydrodynamic model was calibrated for the monsoon period of the year 2014 at Kazipur station. Then this model was validated for the monsoon period of the year 2017 for the same station. Model simulated values showed a satisfactory agreement with the observed values for Manning's roughness coefficient ranging from 0.025-.035 as R^2 was found around 0.98 for calibration and validation. The flood extent was found 4043.52 km^2, 5504.97 km^2, 5854.48 km^2 for 2,25 & 100 years return period. The flood extent area increases with the increase in the magnitude of the flood. For the 100-year return period, the hazard mapping based on flood depth over the study area showed maximum water depths over several spots in the floodplain such as the middle portion of Ghaibandha, Bogra and the whole portion of the Sirajganj district of the study area. Few spots of Jamalpur and the whole Tangail district were seen at maximum depth for a 100-year return period. However, the maximum velocity of flooded water was observed within the main course of the Jamuna River. The hazard mapping based on the product of maximum velocity and depth can be useful to select crop types according to hazard zonation. But hazard mapping for a 2-year return period is more realistic to use as the surrounded area is flooded almost every year. For 2 years return period, Jamalpur and Tangail is safer than Sirajganj, Bogra & Ghaibanda district. From a 100-year return period hazard mapping from settlements, the floodplain near the bank is located in a high hazard zone but the right floodplain is very vulnerable to settlements as well as crops. For 2 years and 100 years, return period about 48% and 88% of the total agricultural were affected. For 2 years & 100 years, the return period of about 67% and 80% of the total settlements were inundated. The percentage of inundation settlements would be less if the total settlement beyond the study area were included.

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Conflicts of interest

The authors declare no conflict of interest.

Authors contribution statement

AH, ORS: Conceptualization; AH, MAA: Data curation; AH, ORS: Formal analysis; AH, MAA: Investigation; AH: Methodology; AH: Software; AH: Supervision; AH, MAA: Validation; AH, ORS, MAA: Visualization; AH: Roles/Writing – original draft; AH, ORS, MAA: Writing – review & editing.

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