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Flood Inundation Mapping of Buriganga River Floodplain using HEC-RAS 1D/2D Coupled Model

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Abstract

Bangladesh, as a low-lying country, is prone to flooding. Flooding has adverse effects on many social and economic aspects. This research has been constructed based on developing flood inundation maps in one of the main rivers of Bangladesh named “Buriganga”. The main purpose of these inundation maps is to depict the degree of flood damage based on flood depth classification. The inundation maps are based on different administrative Upazila. ArcGIS (Aeronautical Reconnaissance Coverage Geographic Information System) has been used for developing flood inundation maps. Results were obtained from the simulation of 1D/2D coupled hydrodynamic model in HEC-RAS (Hydrologic Engineering Center River Analysis System). Results acquired from the simulation were maximum flood depth, maximum flood flow velocity, and maximum inundation area for different historical flood events and return periods. The findings of the analysis showed that among all historical flood events, the event of 1988 was disastrous in nature. In 1988, the most and least affected areas during maximum inundation were Kadamtali Thana and Serajdikhan Thana. This study will aid in providing an overview of the degree of flood damage that has already occurred. Thus, it will help in planning different mitigation measures and managing future aspects of socio-economic vulnerability.

Keywords

ArcGIS, Flood Inundation Map, HEC-RAS

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1. Introduction

Bangladesh has two major distinctive features which are: a vast deltaic plain that is contingent to excessive flooding due to intense precipitation events in the monsoon season; and a small hilly region in the southeast and the northeast parts crossed by high-velocity rivers, carrying water all the way down to the Bay of Bengals, and depositing sediment throughout the river area [1]. The location of Bangladesh is on the Brahmaputra River Delta, also known as the Ganges Delta. Ganges delta is the largest river delta in the world which carries the combined water of several river streams, mainly the Brahmaputra River and the Ganges River [2]. In the Brahmaputra River, the greatest release happens during early rain events in June and July, though within the Ganges River, the most extreme release happens in August and September [3].

“The Buriganga River is the main river in Dhaka, the capital of Bangladesh. Old Dhaka was established as a provincial capital by the Mughal rulers on the northeastern bank of the Buriganga River during 1608-10” [4]. So, studying the characteristics of flood inundation in the Buriganga River is essential.

The objective of our research is to study how much area will be flooded and other flood analyses due to a given discharge and water level. For the very first time, HEC-RAS (Hydrologic Engineering Center River Analysis System) has been used employing a sophisticated 1D/2D coupled hydrodynamic model for the flood inundation analysis. Flood frequency analysis has been done for 30-, 50- and 100-year return periods, utilizing the Gumbel Distribution method. The fabrication of flood inundation maps for selected well-known historical flood events as well as for diverse future return periods has been studied. This research exclusively focuses on the Buriganga River’s floodplain, encompassing the regions of Dhaka, Narayanganj, and Munshiganj districts.

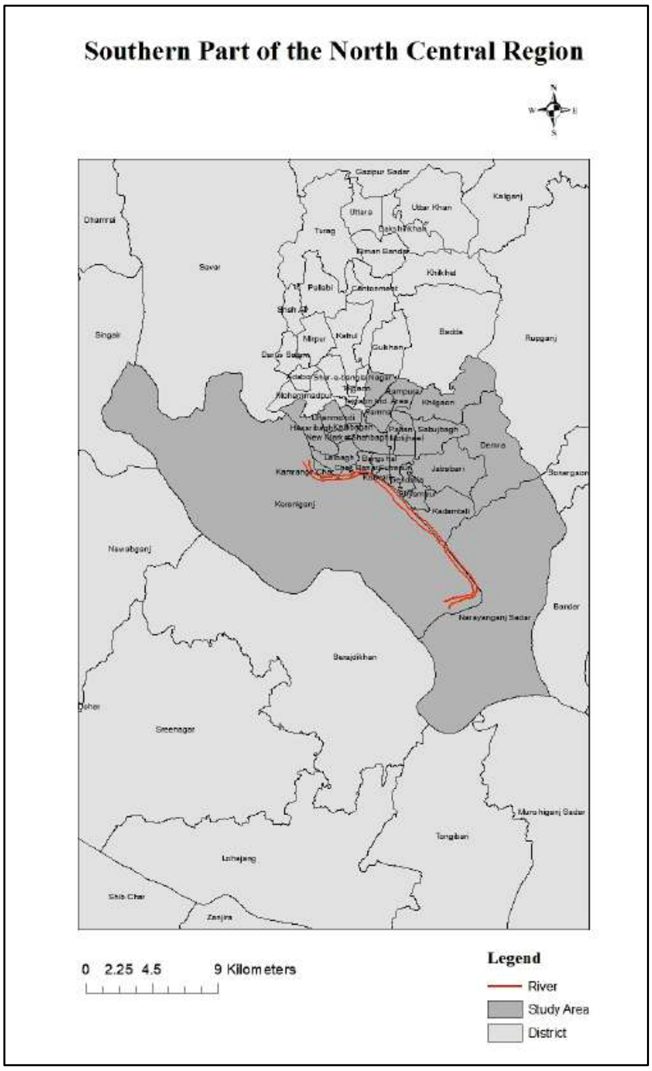

Fig. 1. Buriganga river system near Dhaka, Narayanganj, and Munshiganj districts of Bangladesh

2. Methodology

2.1 Study Area

The Buriganga river catchment, located between 23°38′ N latitude and 90°26′ E longitude, is used for this study. The boundary of the Buriganga River is considered from Bosila (where the river Turag ends at a distance of about 11 km downstream from Aminbazar bridge at Mirpur) to Hariharpara (where Buriganga meets with Dhaleswari downstream). This section of the river covers a distance of 16.5 km. Buriganga river has been chosen for developing flood inundation maps to develop an advanced alert system due to frequent flooding in this area. The hydrodynamic characteristics of the Buriganga River are influenced by the tropical changes in various climatic types prevalent in the study area. The time-dependent changes in various meteorological aspects such as rainfall level, time span, ambient temperature, atmospheric moisture, vapor release, and wind speed affect the discharge levels along the hydrological pathways. These changes ultimately have an impact on the quality of water in the river [5]. Fig. 1 depicts the study area of this research.

2.2 Data Collection

The study area’s cross-sectional, water-depth, discharge, and landscape profile data were acquired in accordance with the hydrodynamic and flood model specifications. Discharge records from 2005-2020 and water-level data from 1985-2020 were obtained from BWDB (Bangladesh Water Development Board) for stations of Mirpur, Dhaka Mil Barac and Hariharpara. Cross-section data (2019) of Buriganga River (RMBG1-RMBG6) was also collected from BWDB. The corresponding data of the digital Elevation Model (2021) and satellite images for the Southern portion of the North Central Region of Bangladesh (2021) were gathered from USGS/ Earth Explorer. For topography, Shuttle Radar Topography Mission (SRTM) data was used.

2.3 Data Map Preparation and Model Development

A stream centerline layer of Buriganga river reach was created first, and later riverbanks were defined. Flow paths from upstream to downstream were defined and digitized for left riverbank, central channel, and right riverbank. The Cross-section Cut Line theme represents the location, position and size of cross-sections. Cross Section Cut Line themes were extracted and later digitized using ArcGIS and HEC-RAS.

After exporting the data, the one-dimensional hydrodynamic model of the study area was developed. Around twenty-two numbers of river cross-sections were integrated for the development of the model. As a boundary condition, the stage hydrograph was considered for both upstream and downstream calculations.

2.4 Model Performance Evaluation

It is essential to conduct tests to determine the level of precision with which the model reproduces river processes. Mirpur was considered as the upstream station and Hariharpara as the downstream station. Dhaka Mill Barrack was considered to be an intermediate hydrologic station. Calibration was done in this study using Hariharpara. Later the Model data was tested with the observed data set. Validation was done in this study using the Hariharpara station. For calibration and validation, the 2016 and 2018 dataset was used respectively.

In this research, recognized quantitative statistical performance metrics, including Coefficient of Determination (R^2), Coefficient of Nash-Sutcliffe Efficiency (NSE), Percent BIAS (PBIAS), and RMSE-Observations Standard Deviation Ratio (RSR), were employed to evaluate the performance of the developed 1D/2D coupled hydrodynamic model for the Buriganga River. These metrics facilitated the comparison between simulated results and observed data.

2.5 Layering and Modification of Terrain Data

After connecting the terrain model with geometry and plan, it is possible to perform layering in RAS Mapper. The floodplain geometry can be visualized using this terrain. As a result, to capture the terrain's features accurately, the size of each grid cell must be sufficiently small. Previously, a digital terrain model of the research region was created using a new layer tool. This terrain model was employed to preprocess data for 2D flow regions, enabling computation of flood depths and inundation extents according to simulation outcomes. The BTM (Bangladesh Transverse Mercator) projection was adopted as an ESRI file to develop the terrain layer. All of the data were projected into the chosen coordinate system until projection was included. The initial terrain model insufficiently represented the ground surface. So, a new terrain in RAS-MAPPER was formed to improve the terrain data. The resample to the single terrain option was used to generate a single RAS terrain at the specified cell size. After that, cross-sections were used to create an interpolation surface terrain. “Merge input terrains to single raster” was used to bring in multiple tiles that are of the same cell size resolution to create a single continuous surface.

2.6 2D Flow Area Computational Mesh and Lateral Structure

A 300 m × 300 m grid resolution polygon boundary was defined for the 2D flow area (regions where flow occurs on both sides of the Buriganga River). A Finite Volume solution scheme was used in the HEC-RAS 2D modeling capability.

Three lateral structures on both sides of the Buriganga River were included on the upstream and downstream portions. In this model, a close equivalent elevation was maintained for both bank elevation and levee height.

2.7 1D and 2D Coupled Model Generation

Stage hydrograph was used as a boundary condition. Calibrating the 2D flow domain for unsteady flow simulations included implementing boundary conditions using different time series datasets. Later, water surface profiles were generated for the year 1988. These data were exported in Geographic Information System (GIS) format data to create a floodplain map and the depth of the flooding map. The main focus of this study involves the development of a 1D/2D coupled model for the Buriganga River floodplain, utilizing HEC-RAS 5.0.7., a software developed by the United States of Army Corps of Engineers (USACE). The equations employed for this coupled modeling are presented below. The 2D Saint-Venant equation was effectively employed to solve HEC-RAS 5.0.7 [6].

$$\frac{\partial \zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=0 \tag{1}$$

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)=-\frac{n^2 pg\sqrt{p^2+q^2}}{h^2}-gh\frac{\partial \xi}{\partial x}+pf+\frac{\partial}{\rho\partial x}\left(h\tau_{xx}\right)+\frac{\partial}{\rho\partial y}\left(h\tau_{xy}\right) \tag{2}$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)=-\frac{n^2 qg\sqrt{p^2+q^2}}{h^2}-gh\frac{\partial \xi}{\partial x}+qf+\frac{\partial}{\rho\partial x}\left(h\tau_{yy}\right)+\frac{\partial}{\rho\partial y}\left(h\tau_{xy}\right) \tag{3}$$

Where h is the water depth (m), p and q are the specific flow in the x and y direction (m^2s^{-1}), ζ is the surface elevation (m), g is the acceleration due to gravity (ms^{-2}), n is the Manning resistance, ρ is the water density (kgm^{-3}), τ_{xx}, τ_{xy}, and τ_{yy} are the components of the effective shear stress and f is the Coriolis (s^{1}) [7].

2.8 Flood Inundation and Flood Flow Velocity

Flood inundation depths were within the study region sorted into five tires: F_0 (0-0.3 m), F_1 (0.3-0.9 m), F_2 (0.9-1.8 m), F_3 (1.8-3.6 m), and F_4 (> 3.6 m). Additionally, flood flow velocities were grouped into five categories: V_0 (0-0.15 ms^{-1}), V_1 (0.15-0.3 ms^{-1}), V_2 (0.3-0.45 ms^{-1}), V_3 (0.45-0.60 ms^{-1}), and V_4 (> 0.6 ms^{-1}) [8].

3. Results and Discussion

The model is calibrated using the 2016 dataset, and the model is validated using the 2018 dataset. As a boundary parameter, stage hydrographs were used. For both calibration and validation, the observed station's daily average water level data is compared to the model's simulated performance. Fig. 2 and Fig. 3 depict the stage hydrograph for Hariharpara station, which displays a comparison between the observed and simulated performances based on Manning's 'n' value of 0.027 for the main channel.

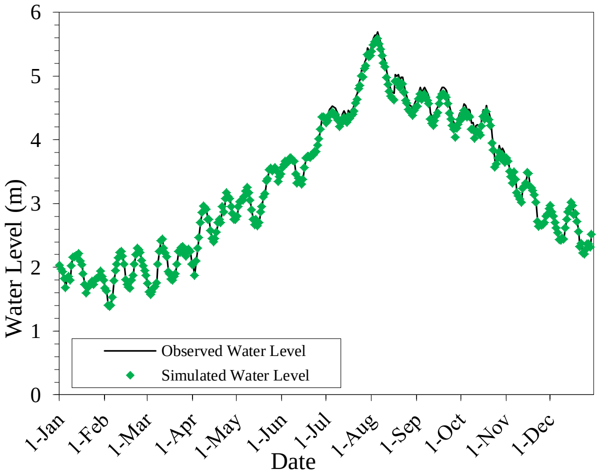

Fig. 2. Calibration hydrograph

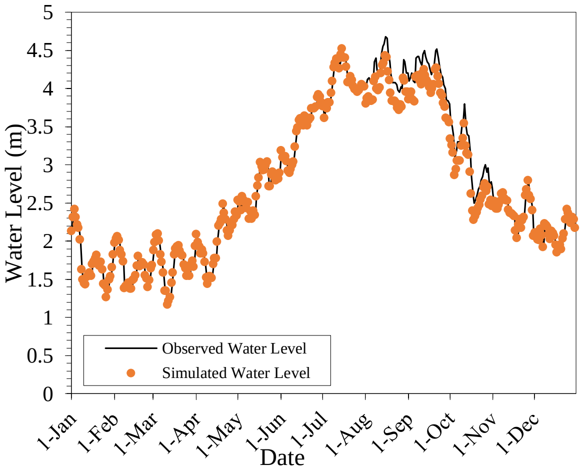

Fig. 3. Validation hydrograph

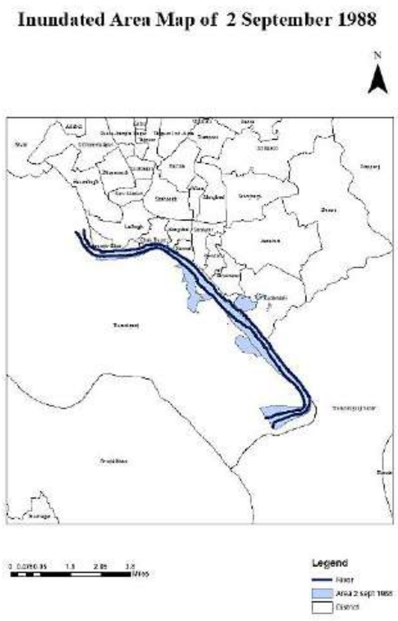

Fig. 4. Inundation area map 10 August 1988

Fig. 5. Inundation area map 2 September 1988

In unsteady calibration, the coefficients of determination R^2, PBIAS, and Nash Sutcliffe Efficiency (NSE) were determined to be 0.94, 2.5, and 0.87, respectively. These values indicate that the simulated value closely resembles the observed value. The coefficients of determination R^2, PBIAS, and Nash and Sutcliffe

Efficiency (NSE) have been found 0.89, 2.8, and 0.85, respectively, in unsteady validation, suggesting that the validated value is similar to the observed value.

3.1. Flood Inundation Map and Area Analysis

HEC-RAS conducts flood model simulations and displays them using RAS-Mapper without reliance on GIS assistance. Multiple shapefiles representing different flood extents were generated for various time periods. Subsequently, the exported shapefile in GIS facilitated the assessment of the inundated area, encompassing the main channel, for flood inundation evaluation. The computation of each flood depth class area aided in defining the categorization of flood depths.

Fig. 6. Inundation area map 4 September 1988

Fig. 7. Inundation area map 10 September 1988

Table 1. Inundation area of 10 August 1988

District Name	Thana Name	Land Type	Area (m^2)	Inundated Area (m^2)	%
Dhaka	Chak Bazar	Land	1633734.8	59512.7	3.64
Dhaka	Kadamtali	Land	8878120.3	333607.8	3.76
Dhaka	Kamrangir Char	Land	1610062.3	393245.1	24.42
Dhaka	Keraniganj	Land	190677011.9	4606361.6	2.42
Narayanganj	Narayanganj Sadar	Land	99854101.3	246414.2	0.25

Table 2. Inundation area of 2 September 1988

District Name	Thana Name	Land Type	Area (m^2)	Inundated Area (m^2)	%
Dhaka	Chak Bazar	Land	1633734.83	82645.09	5.06
Dhaka	Kadamtali	Land	8878120.28	1033962.51	11.65
Dhaka	Kamrangir Char	Land	1610062.33	454299.50	28.22
Dhaka	Keraniganj	Land	190677011.86	8645965.83	4.53
Dhaka	Shyampur	Land	2293924.06	33679.84	1.47
Narayanganj	Narayanganj Sadar	Land	99854101.29	268688.34	0.27

In 1988, four consecutive days were observed in the study region for the review of inundation scenarios from May to September. 10 August, 2 September, 4 September, and 10 September are the dates for observation. Fig. 4 – Fig. 7 display a model-simulated inundation flood map for those precise dates, and Table 1 – Table 4 indicate the amount of inundation areas. On 10 August, the maximum and minimum inundation area percentages were approximately 24.42 percent and 0.25 percent, 28.22 percent and 0.27 percent on 2 September, 61.95 percent and 0.41 percent on 4 September, 64.95 percent and 0.02 percent on 10 September and 59.38 percent and 0.02 percent on 13 September.

Table 3. Inundation area of 4 September 1988

District Name	**Thana Name**	**Land Type**	**Area (m^2)**	**Inundated Area (m^2)**	**%**
Dhaka	Chak Bazar	Land	1633734.83	83268.33	5.10
Dhaka	Demra	Land	22376005.78	1069371.50	4.7/
Dhaka	Jatrabari	Land	12264492.94	50097.36	0.41
Dhaka	Kadamtali	Land	8878120.28	5499970.38	61.9497
Dhaka	Kamrangir Char	Land	1610062.33	501412.77	31.14
Dhaka	Keraniganj	Land	190677011.90	26545358.24	13.92
Dhaka	Lalbagh	Land	4256260.10	196271.60	4.61
Dhaka	Shyampur	Land	2293924.06	100300.23	4.37
Narayanganj	Narayanganj Sadar	Land	99854101.29	2330552.31	2.33

Table 4. Inundation area of 10 September 1988

District Name	**Thana Name**	**Land Type**	**Area (m^2)**	**Inundated Area (m^2)**	**%**
Dhaka	Chak Bazar	Land	1633734.83	81337.26	4.98
Dhaka	Demra	Land	22376005.78	1634737.67	6.86
Dhaka	Jatrabari	Land	12264492.94	110919.90	0.90
Dhaka	Kadamtali	Land	8878120.28	5766192.29	64.95
Dhaka	Kamrangir Char	Land	1610062.33	487638.70	30.29
Dhaka	Keraniganj	Land	190677011.9	30892845.32	16.20
Dhaka	Lalbagh	Land	4256260.1	224400.07	4.80
Dhaka	Shyampur	Land	2293924.06	23973.05	1.05
Munshiganj	Seajdikhan	Land	173749913.96	36967.77	0.02
Narayanganj	Narayanganj Sadar	Land	99854101.29	5575465.08	5.58

3.2. Flood Inundation Depth Analysis

Fig. 8 – Fig. 11 show the flood inundation depth of the study region in 1988 (10 August, 2 September, 4 September, and 10 September). RAS-Mapper has been used to build the depth map, which is then exported as raster files into GIS.

These Figures reveal that the F_1 flood depth zone exhibits significantly greater coverage compared to other depth categories during the Monsoon periods. Conversely, the F_4 flood depth class had a smaller area. Each of the flood depth categories, including F_1, F_2, F_3, and F_4, have also been observed to increase with the passage of time until September.

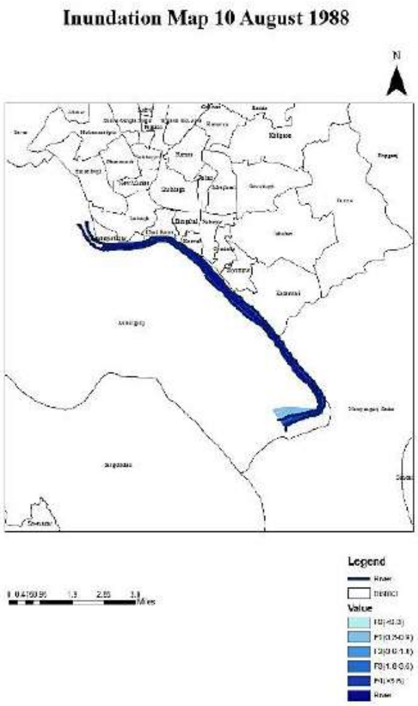

Fig. 8. Inundation depth map 10 August 1988

Fig. 9. Inundation depth map 2 September 1988

Fig. 10. Inundation depth map 4 September 1988

Fig. 11. Inundation depth map 10 September 1988

3.3. Flood Inundation Velocity Analysis

The flood velocity data for the studied region was exported as a RASTER format and subsequently underwent additional processing to generate maps that visually depict the geographical change in flood flow rate across the overall study area. The flood depth is classified into five classes denoted as V_0, V_1, V_2, V_3, and V_4, each representing defined intervals: 0-0.15 ms^{-1}, 0.15-0.30 ms^{-1}, 0.30-0.45 ms^{-1}, 0.45-0.60 ms^{-1}, and >0.60 ms^{-1}, respectively. Fig. 12 shows a map depicting the spatial variation of flood flow velocities for the highest inundation conditions in 1988.

3.4. Analysis of Future Flood Inundation Depth

Fig. 13 – Fig. 16 display flood inundation maps for the base time, 2047s, 2067s, and 2117s. Flood depths are categorized into five groups in these inundation maps as adapted for historical flood depth mapping. When comparing flood depth maps from various time periods, it reveals a notable escalation in flood depth, evolving from the initial reference point to the year 2117. This transition is visually depicted by the increasing intensity of the blue shades in the flood depth mapping, signifying the progressive nature of this change over time.

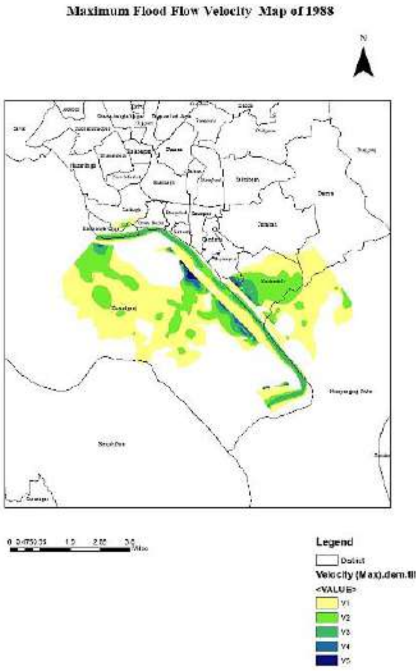

Fig. 12. Maximum flood flow velocity map of 1988

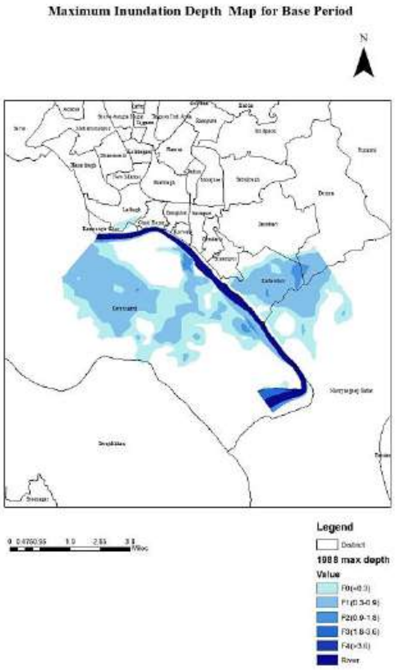

Fig. 13. Maximum inundation depth map for base period

Fig. 14. Maximum inundation map for 30 years return period

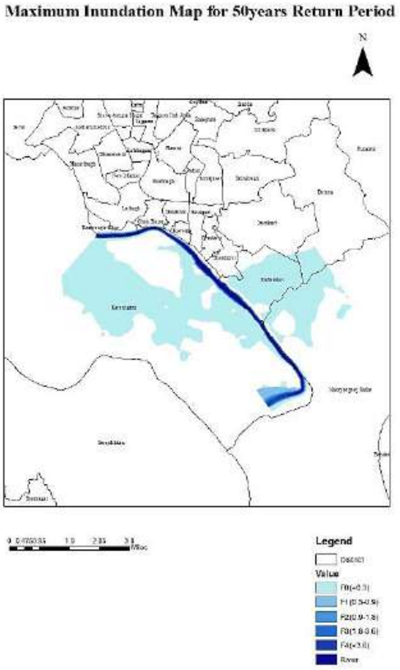

Fig. 15. Maximum inundation map for 50 years return period

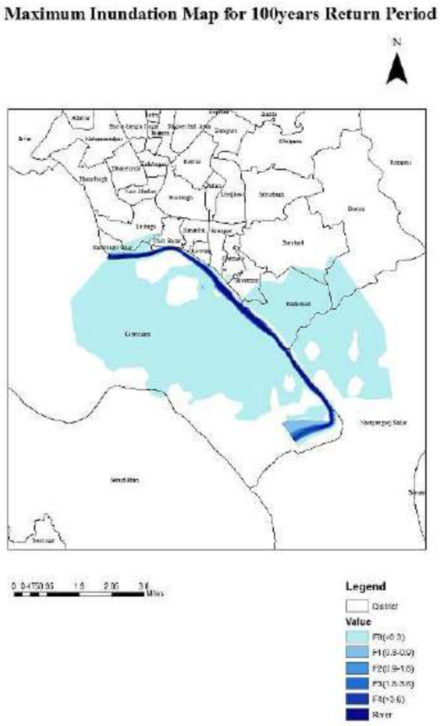

Fig. 16. Maximum inundation map for 100 years return period

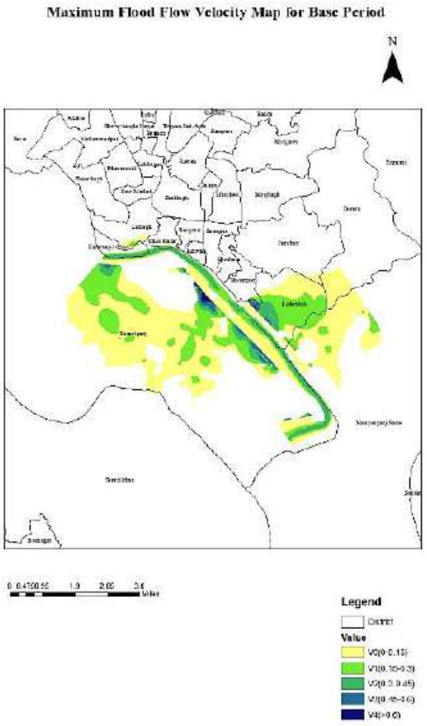

Fig. 17. Maximum flood flow velocity map for base period

3.5. Analysis of Future Flow Velocity

The RASTER file containing flood flow velocity data from the study region was processed further to generate maps that depict the spatial distribution of flood flow velocity across the floodplain. These maps cover the base time as well as the years 2047, 2067, and 2117.

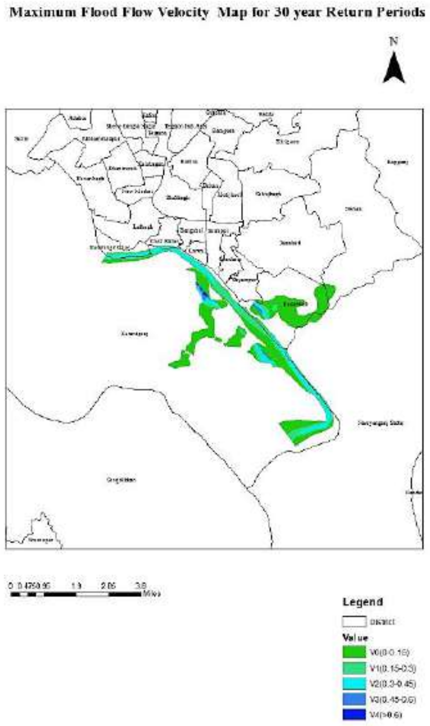

Fig. 18. Maximum flood flow velocity map for 30 years return period

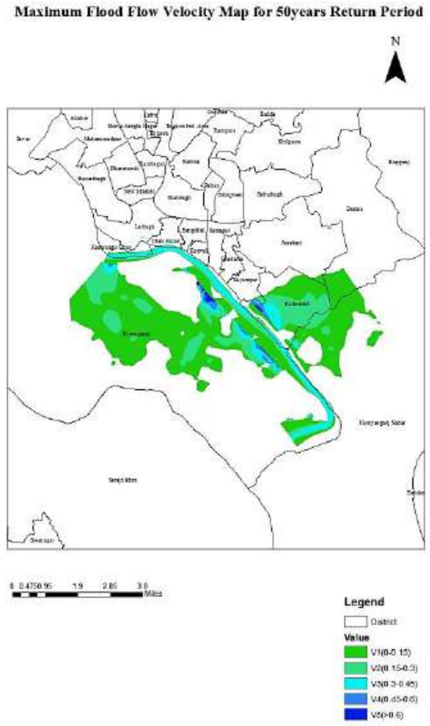

Fig. 19. Maximum flood flow velocity map for 50 years return period

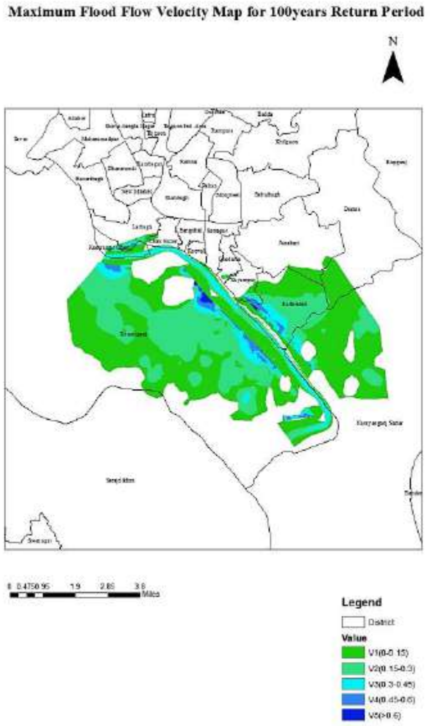

Fig. 20. Maximum flood flow velocity map for 100 years return period

Fig. 21. Flood inundated area of 30 years return period

3.6. Analysis of Future Flood Inundated Area

The figures represented in Fig. 21 – Fig. 23 illustrate the maps displaying the extent of flood inundation for both base and projected future time periods. The potential percentage of inundated area is shown in Table 5 – Table 7. In the 2047s, 2067s, and 2117s, the highest inundated area percentages are about 38.99 percent, 76.25 percent, and 90.05 percent, respectively.

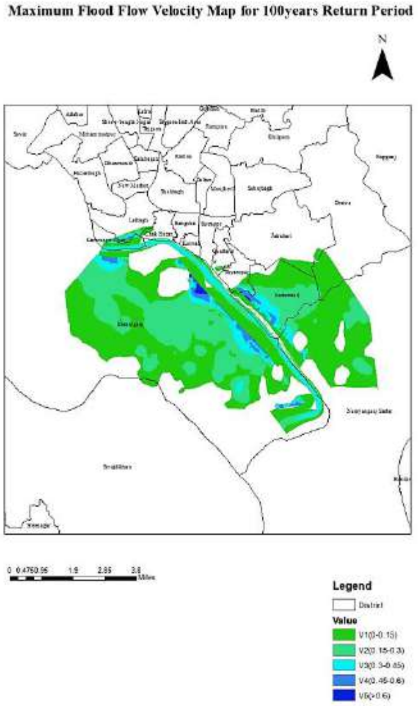

Fig. 22. Flood inundated area of 50 years return period

Fig. 23. Flood inundated area of 100 years return period

Table 5. Maximum inundated area for 30 years return period

District Name	Thana Name	Land Type	Area (m^2)	Inundated Area (m^2)	%
Dhaka	Chak Bazar	Land	1633734.83	82560.65	5.05
Dhaka	Demra	Land	22376005.78	256342.98	1.15
Dhaka	Jatrabari	Land	12264492.94	2623.34	0.02
Dhaka	Kadamtali	Land	8878120.28	3461392.42	38.99
Dhaka	Kamrangir Char	Land	1610062.33	454075.82	28.20
Dhaka	Keraniganj	Land	190677011.90	11030041.75	5.79
Dhaka	Shyampur	Land	2293924.06	51045.68	2.23
Narayanganj	Narayanganj Sadar	Land	99854101.29	538445.54	0.54

Table 6. Maximum inundated area for 50 years return period

District Name	Thana Name	Land Type	Area (m^2)	Inundated Area (m^2)	%
Dhaka	Chak Bazar	Land	1633734.83	83241.33	5.10
Dhaka	Demra	Land	22376005.78	1615985.79	7.22
Dhaka	Jatrabari	Land	12264492.94	158910.37	1.30
Dhaka	Kadamtali	Land	8878120.28	6769489.87	76.25
Dhaka	Kamrangir Char	Land	1610062.33	461336.21	28.65
Dhaka	Keraniganj	Land	190677011.90	32973878.80	17.30
Dhaka	Lalbagh	Land	4256260.10	7264.85	0.17
Dhaka	Shyampur	Land	2293924.06	115466.33	5.03
Narayanganj	Narayanganj Sadar	Land	99854101.29	6718774.90	6.73

Table 7. Maximum inundated area for 100 years return period

District Name	Thana Name	Land Type	Area (m^2)	Inundated Area (m^2)	%
Dhaka	Chak Bazar	Land	1633734.83	83622.70	13.04
Dhaka	Demra	Land	22376005.78	1675398.43	8.64
Dhaka	Gendaria	Land	1547054.48	68436.63	4.42
Dhaka	Jatrabari	Land	12264492.94	763556.87	6.23
Dhaka	Kadamtali	Land	8878120.28	7995446.73	90.05
Dhaka	Kamrangir Char	Land	1610062.33	923697.88	57.37
Dhaka	Keraniganj	Land	190677011.90	52013832.73	27.28
Dhaka	Kotwali	Land	760703.07	16618.75	2.18
Dhaka	Lalbagh	Land	4256260.10	475507.42	11.17
Dhaka	Shyampur	Land	2293924.06	526527.97	22.95
Dhaka	Sutrapur	Land	2191581.00	670038.00	0.31
Munshiganj	Seajdikhan	Land	173749913.96	210958.37	0.12
Narayanganj	Narayanganj Sadar	Land	99854101.29	14425796.06	14.45

4. Conclusion

In this study, a thorough analysis portrays the severe impacts of the highest flood depth, flow rate, flood inundation area, and percentage of Upazila inundated for each Upazila within the studied area. The development of a Buriganga River floodplain inundation model employed a 1D/2D couple approach. For 2D flood areas, floodplains have been considered, and the flow conditions of Buriganga River have been considered as 1D flow. Calibration and validation utilized the water-level data from the upstream station

(Dhaka Mill Barrack). Results exhibited strong agreement between observed and simulated water-level data, employing a Manning's roughness coefficient '*n*' value of 0.027, yielding correlation coefficients R^2 of 0.94 and 0.89, respectively. From these maps, it has been found that during maximum inundation, Kadamtali Thana was the most affected, with 79.65% affected area, and Serajdikhan Thana was least affected, with 0.033%. Maybe because of the higher elevation, Serajdikhan Thana was the least affected. By the Gumbel Distribution method, flood frequency analysis was done for 30-, 50- and 100-year return periods. Notably, the inundation mapping in this study specifically addresses the water overtopping, excluding flooding due to embankment breaches or other factors, which could be explored in further studies.

This flood inundation modeling process can reliably be used as a helpful tool for managing risks of floods, future assessment of socio-economic vulnerability, and for decision making as well for future development within the floodplain of the Buriganga river basin.

However, this study has some limitations which can be addressed in our future research. The resolution of the digital spatial database can be increased for the real replication of the topography and better performance of the model. The flood hazard maps can be studied by this model. A comprehensive evaluation of the socio-economic, natural, physical, and institutional vulnerability would offer a more rational assessment of the study area's sensitivity, adaptability, and exposure. Notably, this study overlooks factors like rainfall, evaporation, and percolation, which can be integrated into subsequent research. Furthermore, for future research, the inclusion of risk assessment based on hazard and vulnerability indexes could provide valuable insights.

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