A DISSERTATION

on

FLOOD INUNDATION MODELING & MAPPING IN A REACH OF RIVER JAMUNA IN BANGLADESH

Submitted in partial fulfilment of the
Requirements for the award of the degree of
MASTER OF TECHNOLOGY

in

HYDROLOGY

Submitted By
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CANDIDATE'S DECLARATION

I hereby declare that the work carried out in this thesis titled **"Flood Inundation Modeling & Mapping in A Reach of River Jamuna in Bangladesh"** is presented on behalf of partial fulfillment of the requirement for the award of the degree of **Master of Technology** with specialization in **Watershed Management in Hydrology,** submitted to **DEPARTMENT OF HYDROLOGY, Indian Institute Of Technology, Roorkee, India,** under the supervision and guidance of **Dr. Manoj Kumar Jain, Professor,** DOH, IIT Roorkee, India.

I have not submitted the matter embodied in this thesis for the award of any other degree or diploma.

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Place: **Roorkee**

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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ABSTRACT

Bangladesh is a flood-susceptible country. Jamuna is one of the most flood vulnerable River in Bangladesh. Hydrodynamic modelling of about 172 Km River reach of Jamuna from Bahadurabad to Aricha has been undertaken as this river reach is vulnerable to recurring flooding every year. The extent of flooding and velocity with and without embankment condition have been studies by developing hydrodynamic model using HEC-RAS 1D & 2D. As the observed discharge data for gauging station was available for limited number of times but stage observations were available at 12 hourly interval, a stage discharge relationship at Bahadurabad gauging station has been developed to convert stage readings into corresponding discharge values required as upstream boundary for hydrodynamic model. Using the available 28 cross sections, 1D hydrodynamic model was developed using HEC-RAS. Twelve hourly flow Hydrograph and normal depth has been used as upstream and downstream boundary condition respectively. Unsteady flow state has considered in this simulation and the model was calibrated and validated using observed stage data at two locations in the study reach for the year 2009 and 2010 hydrological event correspondingly. The Manning's n value 0.026 and 0.027 for channel and both banks respectively was adjudged best to simulate observed water level data at Sirajganj and Aricha gauging sites. The NSE values obtained for both station is above 0.77 for calibration and validation period. The 2D hydrodynamic model was also setup both for with and without embankment scenario using the SRTM 30 m DEM which was resampled into 5 m grid cell size using ArcGIS. A simplified representation of Brahmaputra Right bank Embankment (BRE) was developed and interpolated at 5m grid resolution and fused with resampled DEM at 5 m resolution to generate terrain for setting up hydrodynamic model with BRE. Hourly flow hydrograph and normal depth were used as the upstream and downstream boundary conditions in the unsteady flow simulation. The results obtained for 2D hydrodynamic model indicate that 6, 11, 20, 37, and 26% area of the total flooded area was inundated with embankment condition by F0 (0 – 0.3 m), F1 (0.31 – 0.9 m), F2 (0.91 – 1.8 m), F3 (1.81 – 3.6 m), and F4 (> 3.6 m) flood depths, respectively. However without embankment 7, 13, 19, 39, and 23 % of the total flood area would be flooded with water depth class F0 (0 – 0.3 m), F1 (0.31 – 0.9 m), F2 (0.91 – 1.8 m), F3 (1.81 – 3.6 m), and F4 (> 3.6 m), respectively. In both scenarios (with and without BRE), velocity of water on floodplain remains below 0.5 m/s but the flow velocity is above 1m/s in the River reach and higher velocity of flow were simulated in middle path of the river where depth

of water is generally high. The spatial distribution of the simulated maximum flood area of inundation is about 14378 Km^2 and 12248 Km^2 out of 22167 Km^2 without and with embankment condition respectively. The results also shows that 64.5 and 55 % of the total study domain area are inundated by without and with embankment condition respectively. It also shows that about 2130 Km^2 area is protected due to embankment.

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LIST OF ABBREVIATION

BRE	Brahmaputra Right Embankment
BWDB	Bangladesh Water Development Board
CEGIS	Center for Environment and Geographic Information services
DEM	Digital Elevation Model
FAP	Flood Action Plan
FFWC	Flood Forecasting and Warning Centre
GBM	Ganges-Brahmaputra-Meghna
GIS	Geographic Information System
HEC-RAS	Hydrologic Engineering Center- River Analysis System
IWM	Institute of Water Modelling
NWMP	National Water Management Plan
NSE	Nash-Sutcliffe efficiency Co-efficient
RL	Reduce Level
RMSE	Root Mean Square Error
SRTM	Shuttle Radar Topography Mission

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Bangladesh is a flood-susceptible country. Floods have had an impact on the society from the time long past and recurring flooding is an existing old phenomenon in Bangladesh (Kundzewicz and Takeuchi, 1999). Sub-tropical climate prevails in the country with average annual precipitation of about 2300 mm, which varies from over 5,000 mm in the north-east to 1200 mm in the north-west part of Bangladesh. Bangladesh is surrounded by India in north, west and large extent in the east. The Bay of Bengal and Myanmar are located in south and south-east part of Bangladesh respectively. Bangladesh has 405 small and big rivers, among them 57 are trans-boundary Rivers. Fifty four rivers originate from India and 3 rivers initiate from Myanmar. Three main River the Ganges, the Meghna, and the Brahmaputra are also originate from India (FFWC, 2016). Bangladesh annually experiences the consequences of floods of the Ganges, the Brahmaputra,the Meghna (GBM) River basins due to low-lying estuary floodplain. The main causes of flood in Bangladesh are heavy rainfall and poor drainage due to low relief. The three colossal rivers, GBM enter in Bangladesh from India through North, Northeast and Northwest of the country respectively. High degree of floods attacks a consistent basis in the catchment of these GBM rivers in Bangladesh because of the passages of depression during the monsoon season (Kale, Hire and Baker, 1997).

The Brahmaputra River is one of the largest rivers in terms of both sediment and water discharge into Bangladesh. In Bangladesh, it is named as Jamuna River, which traverses a distance about 240 km and with an average width of 12 km. The river's longitudinal slope is varying from 85 to 65 mm/km. Around 20200 m^3/s is the annual average discharge of the Jamuna River. The sediment carried through the river at Bahadurabad is about 590,00,000 tons per year (Sarker, et al., 2011). Annual hydrograph of the Jamuna River comprises of low flows and high flows during winter and summer season respectively. Heavy monsoon rainfall and snowmelt in Himalayas are main reasons of high flows during summer time. The observed minimum discharge and peak flood discharge is about 2860 m^3/s and 1, 00,000 m^3/s respectively, with unlimited seasonal variations in terms of sediment loads and water levels. The river is recognized for braided pattern, mobile sandbars, shifting anabranches, with meta-stable islands and nodal reaches and severe bank erosion (Nakagawa *et al.*, 2013).

To protect areas along the river from flooding, the Brahmaputra Right Embankment (BRE) was constructed in year 1960. BRE provides flood protection to about 230,000 ha of land which is located on the west side of the Brahmaputra and Teesta River. The length of the BRE is 217 km from Kaunia in Rangpur to Bera in Pabna district. The average height is 4.5 m, crest width is 6m and slope 1:3 on both sides(World Bank, 1963).

This study is undertaken to examine the flood inundation protection offered by the BRE using HEC-RAS software package available as sources package to develop flood inundation map by using hydro-dynamic model.

1.2 Objective of the Study

The objectives of the study are as follows:

1) To calibrate and validate the hydrodynamic model HEC-RAS 1D for River reach to evaluate value of Manning's roughness coefficient 'n'
2) To simulate extent of flood inundation using HEC-RAS 2D with and without the flood embankment.

1.3 Structure of the Thesis

The dissertation has been prepared under five Chapters. Chapter 1 describes the background and objectives of the study. Chapter 2 outlines different definition of relevant topics, literatures, theories regarding this study and a brief review of previous studies related to this study area. Chapter 3 presents methodology adopted, data collection from various sources and its processing. The model setup is also discussed in this Chapter. Chapter 4 presents development of Stage-discharge relationship, calibration as well as validation 1-D hydrodynamic model. The results obtained using 2-D hydrodynamic simulation in terms of inundation extent, depth and velocity with and without embankment are also represented in this Chapter. Conclusion and recommendations for further study are presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 General

"A flood is an unusually high stage in a river - normally the level at which the river overflows its banks and inundates adjoining area"(Subramanya,2008). Bangladesh is the largest delta located at the confluence of the Ganges, the Meghna and the Brahmaputra. Flash floods, River floods, rainwater floods and coastal floods are four types floods predominantly occurs in Bangladesh (Haskoning, 2003). Flash floods occur generally in the East and Northeastern Hills regions at the beginning of the monsoon season. Major and minor rivers active flood plains are submerged due to river floods. Rainfall floods occur due to inadequate drainage throughout the country in the monsoon season. Floods occur in coastal area due to storm surge or tropical cyclone in pre- and post-monsoon seasons (Haskoning, 2003). Floods in Bangladesh have been classified based on the extent of inundation, respective return periods and level of physical damage into five categorize. A flood with inundation area exceeding 21%, 21%-26%, 26% - 34%, 34%-38.5% and more than 38.5% of the entire land area of Bangladesh is categories as normal, moderate, severe, catastrophic and exceptional, respectively (Mirza, 2002).

2.2 Floods in Bangladesh

Bangladesh is the country through which the third biggest freshwater discharges passage to oceans from the Ganges-Brahmaputra-Meghna (GBM) river system. The total area of the GBM catchment is over 1.7 million km^2 which is trans-boundary in nature. The GBM basin spread between Bhutan (3 percent), Bangladesh (7 percent), Nepal (9 percent), China (18 percent) and India (64 percent). The recorded peak flood discharges of Ganges, Brahmaputra and Meghna are 76,000 m^3/s (at Hardinge Bridge, 1987), 102,534m^3/s (at Bahadurabad, 1998), and 19800 m^3/s (Bhairabbazar, 1988), respectively (Mirza, 2003).

In the GBM system, five major floods events occurred in the Nineteen century and 16 such flood events occurred in the twenty century. About 35 to 75 percent of the land area of Bangladesh was inundated during many of these floods. The devastating flood of 1998 was the most acute on record and continued for about eight weeks and was the most severe in terms of the duration and depth. It caused severe damages to lives and properties and inundated about 68 per cent of the total land area of Bangladesh. This flood caused 1100 deaths, inundated about 100000 km^2 area, impacted the property of about 10000 households and affected 30 million people. It also destroyed 16000 km and 6000 km roads and embankments correspondingly and affected 6000 Km^2 of standing crops of land (World Bank, 2010).

The 2004 flood inundated about two thirds of the country. When rain pushed the river waters to the northwestern Bangladesh, a large number of villages were inundated in early October 2004 (Brouwer *et al.*, 2007). During the floods of June 2010, 49 district of Bangladesh and ten millions of people were inundated. More than 12000 Bangladeshi inhabitants were rendered homeless when hundreds of houses were damaged. Due to the floodwater, crops were destroyed and roads became inaccessible, food and drinking water was in short of supply(Alauddin, 2010).

2.3 Flood Management in Bangladesh

Flood management measures are targeted to reduce the damage and harmful effects of flood and to build environment for improved economic activity. Structural and non-structural measures are taken in Bangladesh. After massive floods of 1963, structural measures were initiated by executing flood control projects. Non Structural measures were launched in seventies. Flood is a normal phenomenon, which cannot be stopped. The flood control policies and measures should be focused to alleviation of flood hazard, rather than flood restrained. For proper disaster management, structural and non-structural measures should be integrated (Hossain, 2014).

2.3.1 Flood Management by Structural Measures

Structural measures are implemented to control the physical progression of flooding and prevent inundation. Structural measures with suitable connected structures and appropriate water management practices generate condition favourable to rising productivity from land and other development activities. Reservoirs, Dams and Detention basin, Retention Pond are not realistic due to topographic situation in Bangladesh. Embankment, Levee, Dyke, Bund, Polder, or Flood wall to obstruct the flow of water from rivers to floodplain are most common options. Due to high cost, improvement of conveyance capacity is not a practicable option. Flood bye pass, afforestation, watershed management and flood diversion are not practiced. Erosion and

River maintenance are continued for big and medium Rivers.

Flood control embankment of length 13179 km (this include 4750km polder and 8429 km flood embankment), 621 km river re-excavation and 275 km river dredging are completed up to June 2017. Total 6.45 million ha area are under control from irrigation, flood control and drainage (FCD) (BWDB, 2017).

2.3.2 Flood Managements by Non-structural measures

Non-structural measures decrease hazards by administrative procedure. It does not resist or disturb process of flooding. Flood forecasting and warning center was founded in 1972 in Bangladesh. Flood forecasting and warning contributed to enhancement the capability of flood awareness and reduction of flood losses. Now FFWC are provided future 5 days forecasting and warning for about 54 location of 29 different rivers (BWDB, 2017). Other non-structural measures are Flood cum Cyclone Shelter, Flood proofing, flood fighting, evacuation and shelter management, flood insurance, flood plain mapping and changes in cropping pattern etc. (Hossain, 2014).

2.4 The Brahmaputra - Jamuna River System

The River Jamuna originates at the mouth of a glacier in the Kailas, south of the Gunkyud Lake in southwestern Tibet(Sarker, et al., 2011). The Brahmaputra valley is 640 km long and width ranges from 64 km to 90 km in Assam (India). The valley is confined within the Pataki hill ranges, the Himalayan mountain ranges, plains of Bangladesh, the lower (Assam) hill ranges are located by east, north, south and west respectively (Prasad and Mukherjee, 2014). The Brahmaputra crossing the spurs of the Meghalaya plateau turns south and come into Bangladesh with the name of Jamuna. Jamuna River from source to mouth in the Bay of Bengal is about 2,850 km long. Jamuna traverses 240 km within Bangladesh territory (up to Aricha). The Jamuna comes into Bangladesh east of Bhabanipur (India) and northeast of Kurigram district. It has four main tributaries the Dharla, Dudhkumar, Teesta and the Baral-Gumani-Hurasagar system. Old Brahmaputra River, New Dhaleswari River are main distributaries of Jamuna River, which come from the left bank of the Jamuna River 20 km north of Bahadurabad and south of Bangabandhu Bridge. The Brahmaputra River basin area is around 580,000 sq.km which place four countries China 50.5%, India 33.6%, Bangladesh 8.1% and Bhutan 7.8% (Prasad and Mukherjee, 2014)(Figure2.1).

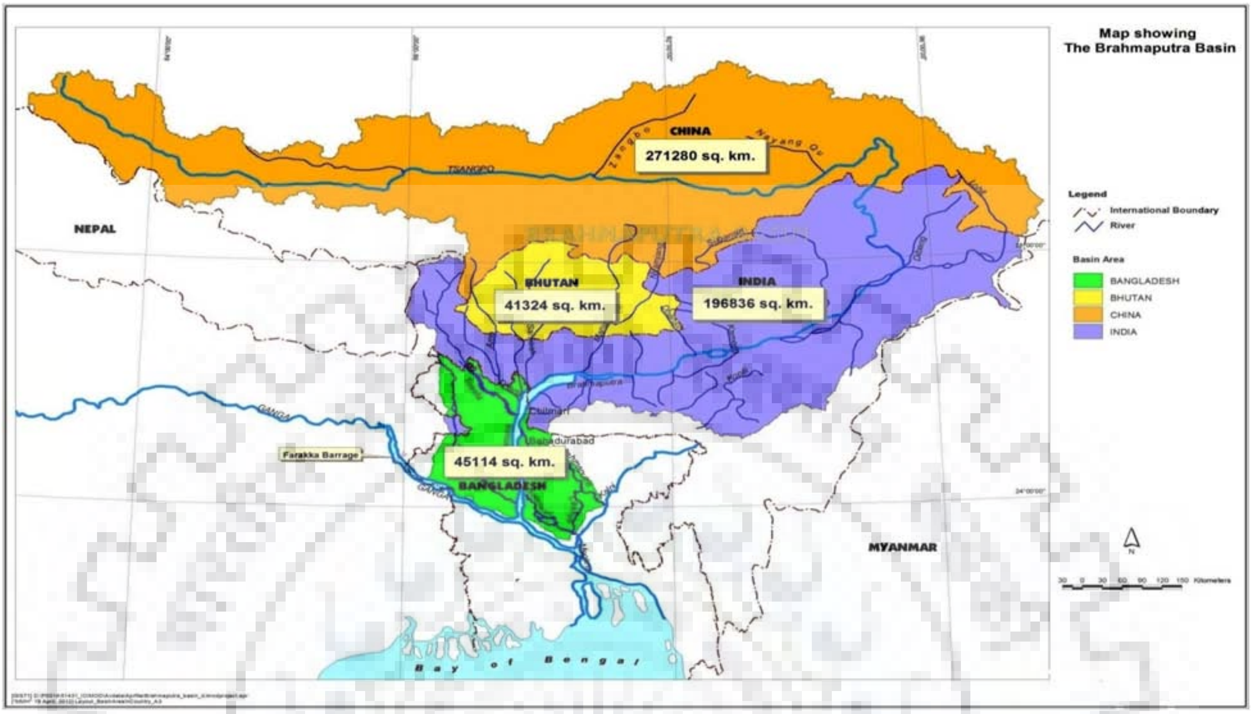

Figure 2.1: Brahmaputra River basin in different countries (Source: IWM, 2014)

2.5 Hydrodynamic Modelling System (HEC-RAS)

The US Army Corps of Engineer's River Analysis System software was developed in division of Institute of Water resources (IWR) at Hydrologic Engineering Centre. It is able to perform 1D steady flow; 1D and 2D unsteady flow; quasi Unsteady sediment transport modelling; full unsteady flow sediment transport modelling; River hydraulics calculations; water quality modelling and water temperature analysis (Brunner, 2016).

2.5.1 1D unsteady flow Hydrodynamics

HEC-RAS is proficient of simulating 1D unsteady flow modeling through a complete network of River. Dr. Robert L. Barkau's UNET model was used to solve the 1D unsteady flow equation (Barkau, 1992 and HEC, 1997). Initially subcritical flow was calculated on 1D unsteady flow component. The hydraulic computations for bridges, cross-sections, culverts, and other hydraulic structures that steady flow element were integrated with the unsteady flow component.

The laws of flow of water in a stream are: 1) conservation of mass (Continuity) and 2) conservation of momentum.

Continuity equation

Conservation of mass is known as the Continuity equation for 1D System. The Continuity equation can be described as

$$\frac{\partial C}{\partial t}+\frac{\partial V}{\partial x}+\frac{\partial P}{\partial t}-S=0 \quad (1)$$

Where x is distance, t is time, V is Flow, C is Cross-sectional area, P is storage and s is per unit distance lateral inflow.

Momentum equation

The momentum equation "states the rate of change in momentums is equal to the external force acting on the system". The Momentum equation can be written as

$$\frac{\partial V}{\partial t}+\frac{\partial VU}{\partial x}+ga\left(\frac{\partial h}{\partial x}+F\right)=0 \quad (2)$$

Where, F is friction slope, g is acceleration of gravity, h is water surface elevation, and U is velocity.

Equation 1 and 2 are non-linear. Solution of nonlinear algebraic equation can be obtained by using implicit finite difference scheme. Fread (1974,1976), Amain and Fang (1970), and others are using Newton-Raphson iteration technique to solve the nonlinear equations. The iterative technique can experience difficult convergence problems when river geometry was discontinuous. Preissmann and Chen established a technique for linearizing the equations to avoid nonlinear solution. These linearized equations which are capable of solving finite difference scheme are used in HEC-RAS.

2.5.2 2D unsteady flow Hydrodynamics

In three dimensions the motion of fluids is described by the Navier-Stokes equations. For flood and channel modelling, simplified Shallow Water (SW) equations are used. Uniform density, hydrostatics pressure, and incompressible flow are assumed and turbulent motion is estimated using eddy viscosity. Horizontal length scales is much greater than vertical length scales is also assumed. So hydrostatics pressure is greater than vertical velocity.

Unsteady, viscous and advection terms can be ignored and bottom friction and barometric pressure gradient (gravity) terms are principal terms in momentum equations for some shallow flows. Then momentum equation converts into two dimensional Diffusive Wave Approximation. Mass conservation and Diffusive Wave Approximation are combined together and recognized as Diffusive Wave Approximation of the Shallow Water (DSW) equations.

Mass Conservation

When flow is incompressible, mass conservation (continuity) equation on unsteady differential form is

$$\frac{\partial h}{\partial t} + \frac{\partial (zp)}{\partial x} + \frac{\partial (zq)}{\partial y} + s = 0$$

Where p, q are velocity components in Cartesians directions, h is water surface elevation, z is water depth, t is time and s is a source/ sink term.

In present condition remote sensing can deliver very high resolution topographic data. It is impossible to solve the equations on numerical method in some cases where data is too dense. To solve this problem HEC-RAS uses sub-grid bathymetry approach. In this method grid cell can be pre-computed cross-section area, hydraulic radius and volume from fine bathymetry. For this way fine bathymetry have available information to be solved on coarser numerical method through mass conservation.

Momentum Conservation

When vertical length scale is much smaller than horizontal length scales that implies vertical velocity is small and uses volume conservation. Pressure is almost hydrostatic which is justified by the Navier-Stokes vertical momentum equation. These equation is adequate when strong wind forcing, non-hydrostatic pressure and baroclinic pressure gradients is absent. Vertical derivatives and vertical velocity term can be disregarded. The Shallow water equation can be written as

$$\frac{\partial p}{\partial t} + p\frac{\partial p}{\partial x} + q\frac{\partial p}{\partial y} = -g\frac{\partial h}{\partial x} + q_t\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2}\right) - f_c\, p + cq$$

Where p and q are velocity component of x and y direction, g acceleration due to gravity, is $q_t$the coefficient of horizontal eddy viscosity, f_c is coefficient of bottom friction and c is Coriolis parameter(Brunner, 2016).

2.6 Application of HEC-RAS

(Patel *et al.*, 2017) assessed the flood inundation by applying coupled 1D/2D HEC-RAS model to Surat city in India. In their simulation they considered with and without Bank protection condition. The whole area of Surat city was divided into seven zones. In 1D modeling they used 2 hydraulic structures, 299 cross sections and 5 major bridges through the river of about 119.4 km length whereas 0.5 m contour topographic map was used to produce a 5m surface grid. They also considered 90 m and 30 m SRTM DEM for the Lower Tapi Basin and Surat city, respectively. They considered flow hydrograph (released from Ukai Dam) and Stage (tidal level at mouth of River Tapi) as upstream and downstream boundaries respectively during 2006 flood. Unsteady flow condition was applied for simulation and validated of the flood of year 2006. The simulated results indicate a maximum 75-77 % area was inundated at peak discharge about 25,770 m^3/s without Bank Protection condition. Furthermore, they evaluated under the bank protection work which was constructed after 2006 Flood. Simulation results indicate that major zone was safe except the west zone under 14430 m^3/s discharge.

In other study (Rahman and Ali, 2016) developed flood inundation map and flood depth map of the River Jamuna by using HEC-RAS 1D with HEC-GeoRAS. They calibrated and validated HEC-RAS 1D model during monsoon season 2004 and 2005 respectively. They calculated the parentages of area inundated as 59, 57, 55, 51, 46 and 26% by 100, 50, 25,10 and 2 year return period floods respectively. They also found that about 33-42% of the total flood area had been inundated with flood depth between 1.2 to 3.6 m.

In another study, (Quirogaa *et al.*, 2016)evaluated the Bolivian Amazonia Llanos de Moxos plains flood which had inundated by the River Mamore. They had simulated 2014 February flood event and used HEC-RAS 2D. They used SRTM 90 m DEM and considered two boundary condition one was discharge at upstream another was normal depth at downstream. They also assessed most of the flood area flow velocity below 0.25 m/s. West side of the River Mamore had estimated longer flood duration, bigger flood extent and deeper water depth. On other east side the two locations had overflowed which was located 10 km south west and 32 km North of Trinidad city. They also assessed first ten days' flood increased quickly and most severe for evacuation. San Javier had flooded five days and north and south of Trinidad flooded twelve and seven days respectively after overflowing the River Mamore. San Javier had categorized high hazards according to flood depth. Trinidad had characterized medium and low hazard and north side flood depth deeper than south side. So south side of Trinidad might be the evacuation route.

CHAPTER 3
MATERIAL AND METHOD

3.1 General

In order to set up the mathematical model different kind of data for recent and previous years have been collected and compiled. These data need further analysis and explanation of the model results for accurate evaluation of hydrological condition in the study area. According to the Modelling desires, a major amount of data includes discharge, water level, cross-section, land use, Embankment alignment and top RL and Digital Elevation Model (DEM) etc. have been collected. This chapter outlines a brief description about the collected data and model setup.

3.2 Selection of Study Area

The study area is a reach of Brahmaputra-Jamuna River from Bahadurabad to Aricha. The study area reach length is about 172 KM. In this reach length, Jamuna meet with Ganga at Aricha. The study area is shown in Fig 3.1. The area is located between Gaibandha, Bogura, Sirajganj and Pabna Administrative District as western side and Jamalpur, Tangail, Chauhali Upazilla on Sirajganj and Manikganj Administrative District on eastern side. Brahmaputra Right Embankment (BRE) is located western side of Jamuna River Right Bank. But in the eastern side there are no continuous flood embankment, some portion have embankment and maximum portion have no embankment. Some village roads are used as flood embankment.

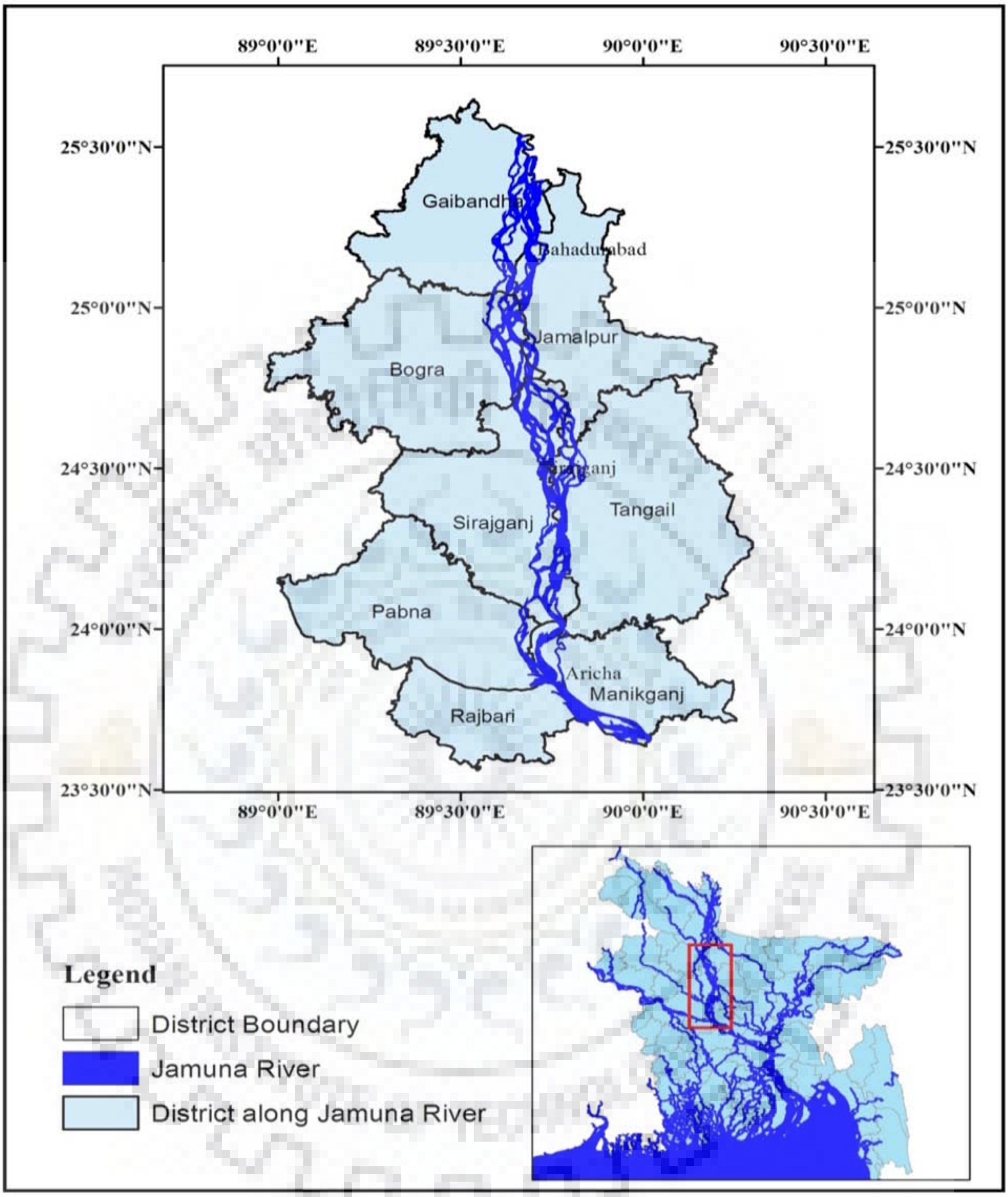

Figure 3.1: Location Map of the study area and study reach

3.3 Methodology

Modeling is an iterative method to simulate the physical process. Model enhancements are based on the quality availability of data and, hydrological perceptions and choices of the study. The general methodological framework adopted in the present study is presented in

Figure 3.2. A brief description of the methodology and approaches adopted are narrated in this section to attain the study objectives.

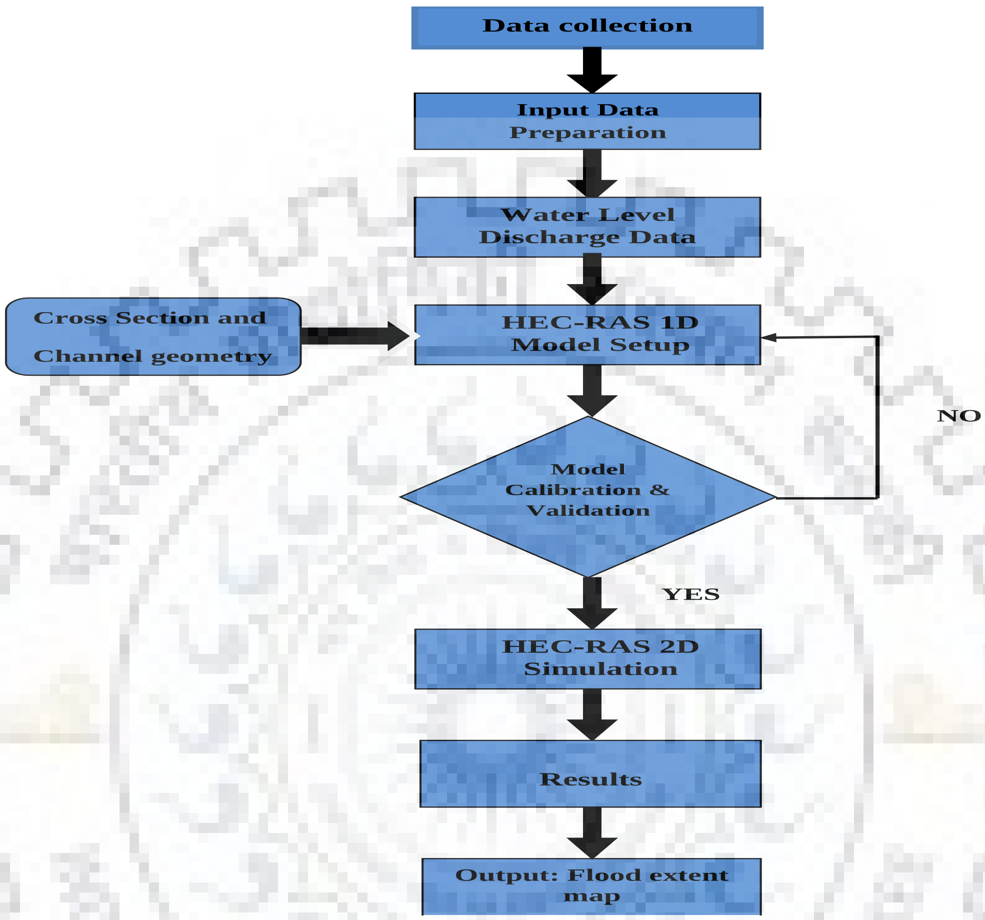

Figure 3.2: Flow chart of methodology applied in the study

3.4 Data Collection

To understand the existing physical process, quality data are required for reliable model setup and model result. To develop a hydrodynamic model for simulation of flood scenario in the Brahmaputra-Jamuna River, various data have been collected from different sources. A brief description of data is given below:

3.4.1 Digital Elevation Model

Three dimension of terrain surface is called Digital Elevation Model (DEM). This data is required to develop HEC-RAS 2D Model. DEM data gives the elevation on earth surface and related features on it. The Shuttle Radar Topography Mission (SRTM) is a global elevation data set which is very standard due to homogeneity, availability and consistent accuracy to other global elevation data. DEM data has been collected as a global elevation dataset downloaded from the United State Geological Survey (USGS) website. In this study, SRTM DEM data at resolution of 1 arc-second global (30m x 30m) has been downloaded and used.

3.4.2 Water Level and Discharge Data

Water level data at different locations are essential for defining water level of different flood events. Water level data is explored to get idea about the amount of water flow in particular locations and it is also used to calibrate the model. Discharge data are required to investigate the hydrological features of the river and to deliver boundary condition in the hydrodynamic model. Historical water level and discharge data at Bahadurabad, Sirajganj, Aricha and Bahadurabad station of Brahmaputra-Jamuna River have been collected from Bangladesh Water Development Board (BWDB). The type of data and duration of collected data are listed below.

Data Type	Station Name	RiverName	Duration	Source
WL Data	Bahadurabad	Brahmaputra-Jamuna	2006-2012	BWDB
WL Data	Sirajganj	Brahmaputra-Jamuna	2006-2010	BWDB
WL Data	Aricha	Brahmaputra-Jamuna	2006-2010	BWDB
Discharge	Bahadurabad	Brahmaputra-Jamuna	1996-2016	BWDB

Table 3.1: Summary of the water level and Discharge data

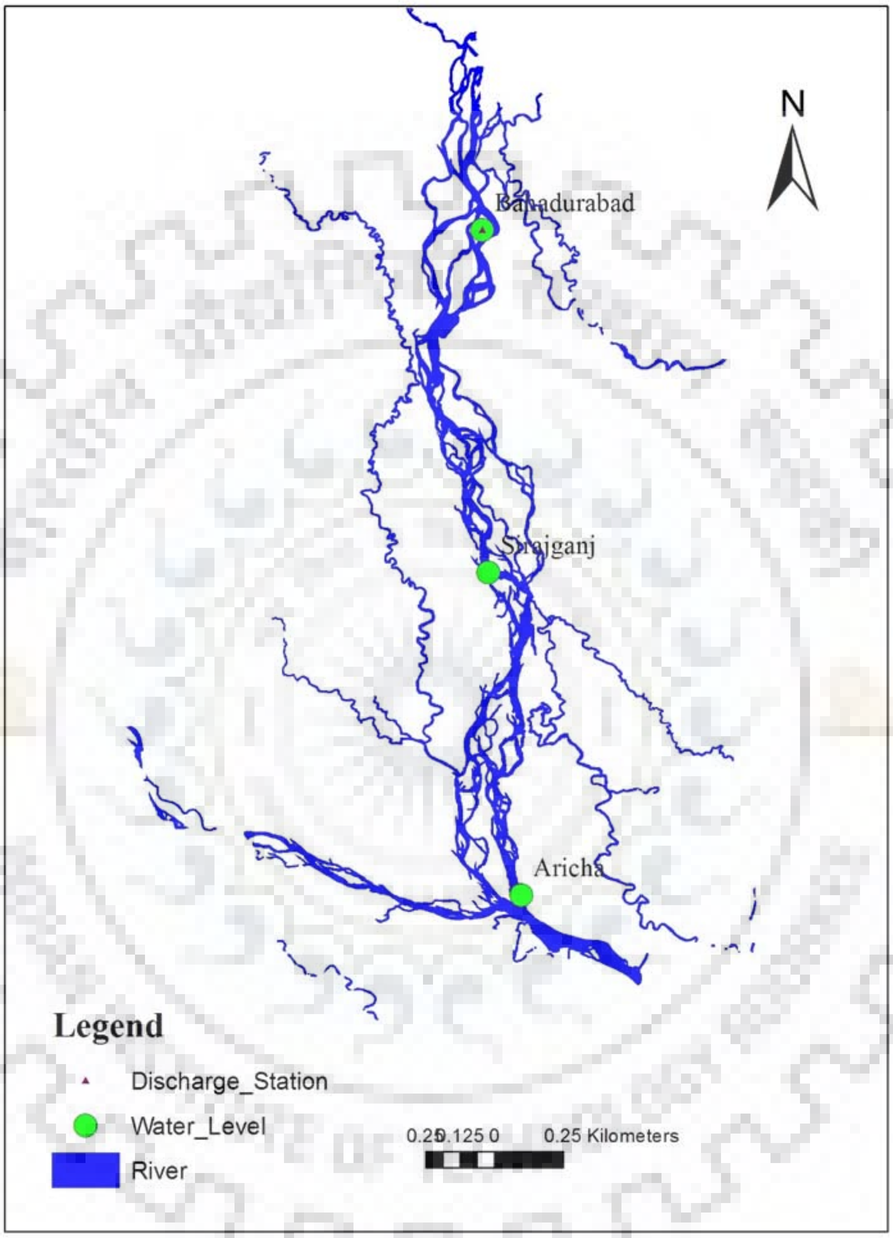

Figure 3.3: Locations of water level and Discharge stations on study reach

3.4.3 Land Use Data

Land use data has been collected from http://www.waterbase.org/ website. The roughness factor is estimated based on water base land use map which is reclassify by using ArcGIS

The Land use/ cover pattern map is reclassified into four categories as agriculture, forest, river, and sand.

3.4.4 Embankment Data

Brahmaputra Right Embankment (BRE) alignment and top Reduce Level (RL) of the embankment data has been collected from Institute of Water modelling (IWM).

3.5 Model Setup

The HEC-RAS, a hydrodynamic model has been setup both for one dimensional and two dimensional domains to study hydrodynamics of floods and also to perform scenario analysis of the generate flood inundation, with and without the BRE. Using this modeling software, a mathematical model for generating inundation map has been developed. Various key steps during processing the model are described below.

3.5.1 Hydrodynamic model: HEC-RAS

A local flood model of the study area has been developed using the HEC-RAS developed by the Hydrologic Engineering Center, U.S. Army Corps of Engineers. Setup for 1D and 2D is described in details below:

3.5.2 HEC-RAS 1D setup

The 1D hydrodynamic model of the study areas has been developed for the study reach of the mighty Brahmaputra-Jamuna River in Bangladesh. The total length of river stretch considered in the model setup is around 172 km. for setting up of the model, 28 nos. of measured cross-sections of the river have been used. There are 2 nos. of open boundaries in the model, where boundary input data are collected from BWDB and some are generated through simulation of Brahmaputra River reach. The HEC-RAS one-dimensional Model has been calibrated for hydrological event of 2009 and validated for hydrological event of 2010.

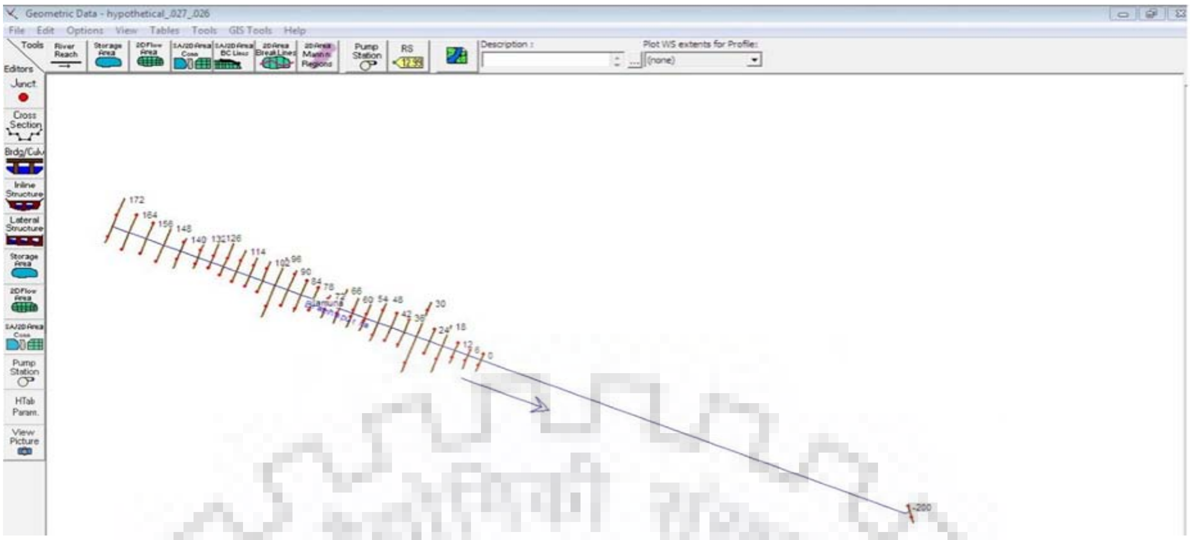

Figure 3.4: HEC-RAS 1D model schematic description of study area

Boundary Conditions

Two boundary condition are considered for simulation in HEC-RAS 1D hydrodynamic model, one is upstream boundary and the other is downstream boundary condition.

- Upstream boundary condition: Discharge at the upstream boundary
- Downstream boundary condition: Normal Depth at downstream boundary

For upstream boundary, upstream inflow available at 12 hourly interval flood hydrograph for the year 2009 has been used. For downstream boundary, the normal depth (friction slope) at outflow boundary has been considered (USACE, 2016).

3.5.3 HEC-RAS 2D setup

In this study, the digital elevation model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM) has been used. Available six tiles of DEM have been mosaicked to fuse them in a single DEM file using the ArcGIS10.3. Then the mosaic DEM has been projected to UTM zone 45N in ArcGIS. After that the DEM has been resampled from 30 m× 30m to 5 m× 5m grid cell size. Then using RAS-Mapper of HEC-RAS 5.0.7, terrain model from processed DEM has been created for setting up 2D HEC-RAS. In RAS-mapper, embankment alignment has been digitized (shown in Fig. 3.5) and cross sections of the Embankment have been created. After that cross sections of the embankment have been edited according to top Reduce Level (RL). Between two cross section, several cross-sections have been generated by interpolation at 50m distance using XS interpolation tool on the Geometric data editor.

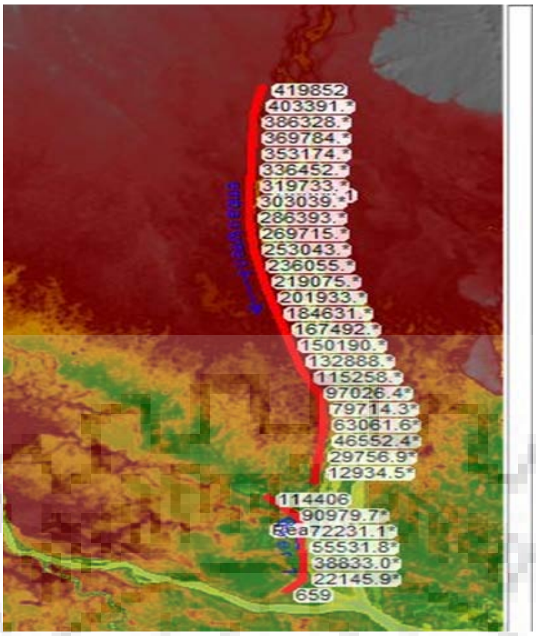

Figure 3.5: Embankment alignment showing in Geometry editor

The embankment model has been exported as a terrain model. For this procedure the "Create GeoTIFF from XS's option which is available from the data file on the left in RAS Mapper has been used. Right click Above name of geometry file and select Export Layer… Create GeoTIFF from XS's. In this occasion use only 'Channel Only' option and select the cell size as 5 (Kiers, 2015).

The modification of the original terrain model with the Channel Only terrain to create a terrain model that includes all features represented in the terrain. From RAS Mapper, use the menu option 'New terrain' and add the different terrain as 'Channel Only' have higher priority for these method and moved to top of the list. In this procedure modification of original terrain has been done.

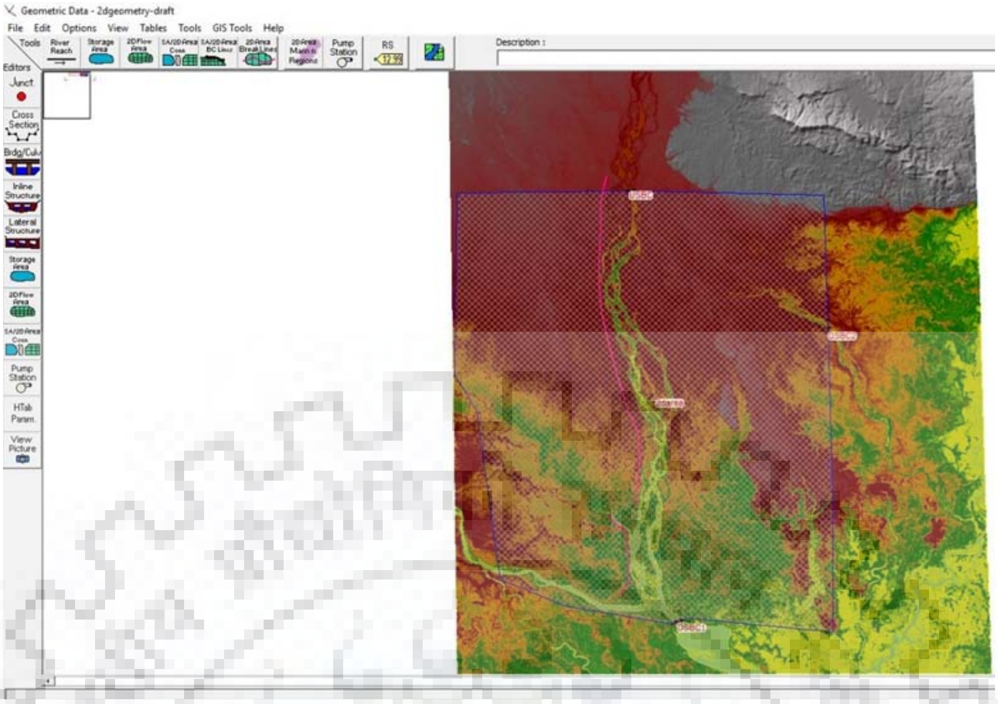

Figure 3.6: Schematic description of geometry of study area HEC-RAS 2D model

The geometry comprises 2d computation area along the study reach of River Jamuna. This computation domain is defined by a close polygon and computation cell are generated inside the polygon. The sides of polygon cells have been limited to 3 to 8 faces due to efficiency and saving memory space. In this particular computation, mesh sixe of 250m× 250 m and total grid cell as 354362 and 354047 with embankment and without embankment respectively have been created. Three boundary condition have been used in this study. One is upstream boundary condition and two downstream boundary conditions. Upstream boundary condition is flow hydrograph and downstream boundary condition is normal depth. During with embankment simulation a break line along the embankment alignment has been used to break the flow. The roughness factor is estimated based on land use map of the study domain which is reclassify by using ArcGIS. The Land use/ cover pattern map is reclassified into four categories named as agriculture, forest, river, sand. Manning's n value has been assigned to each landuse category as agriculture (0.045), Forest (0.07), sand (0.03) and River (.026) based on the recommendations by Chow (1959) and calibrated value obtained for channel reach in 1D simulation of this study, respectively.

The model simulation have been performed under unsteady flow condition using diffusive wave equations in 2D hydrodynamic modelling. Hydraulic property tables have been computed before starting calculations(USACE, 2016).Elevation-volume relationships are calculated for each cell and elevation-hydraulic properties (wetted perimeter, area) relationships are computed for every computation cell face. The calculation have been performed iteratively with maximum allowed iteration as 20 and computation time 15s. The flood inundation (depth), Water surface elevation (WSE) and velocity information for the discretized 2D domain have been obtained during simulation.

Boundary Conditions

Three boundary conditions are considered to simulate HEC-RAS 2D, one is upstream boundary and two downstream boundary conditions.

- Flow hydrograph at the upstream boundary
- Normal Depth at downstream boundary

Here hourly discharge hydrograph generated using HEC-RAS 1D model set up during the year 2012 flood event have been used as upstream boundary condition. Two downstream boundary conditions have been used one for each branching of the river at downstream end. Normal depth (friction slope) as outflow boundary has been used for both.

CHAPTER 4
RESULT AND DISCUSSION

4.1 General

In this Chapter, results obtained for HEC-RAS 1D & 2D model simulation are discussed. In particular, Maximum flood inundation depth, water surface elevation and velocity maps have been developed with and without embankment condition to understand the flood propagation in the Brahmaputra-Jamuna River reach in Bangladesh.

4.2 Stage-discharge relationship

At the Bahadurabad discharge station, 20 years of discharge data with corresponding water level data are available for 1221 number of observations. Using available stage and corresponding discharge observations, a stage-discharge relationship at Bahadurabad station has been developed and the same is shown in Fig. 4.1 as arithmetic scale and in Fig. 4.2 in logarithmic scale.

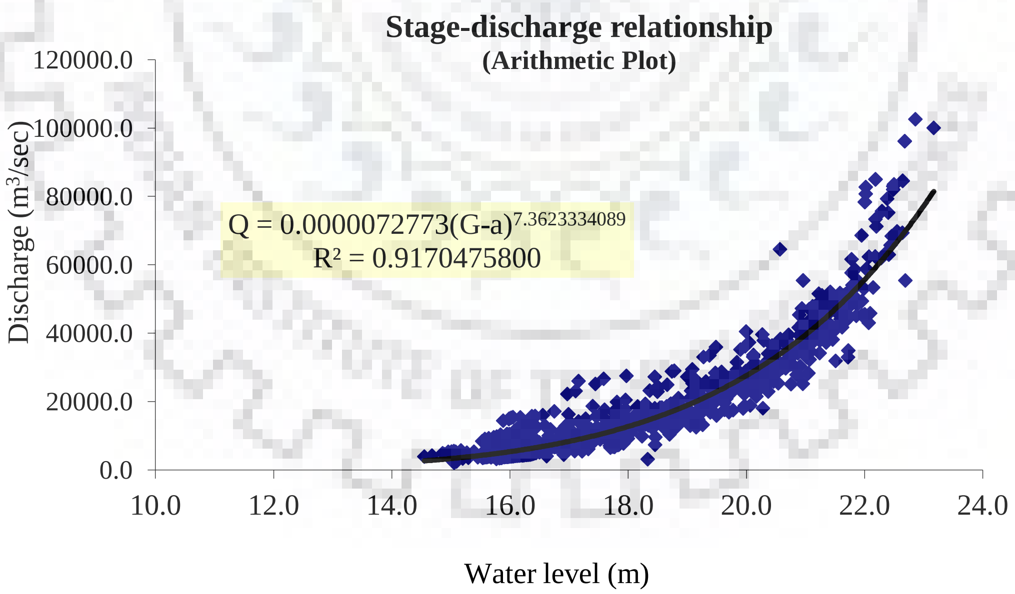

Figure 4.1: Stage-discharge relationship (Arithmetic Plot)

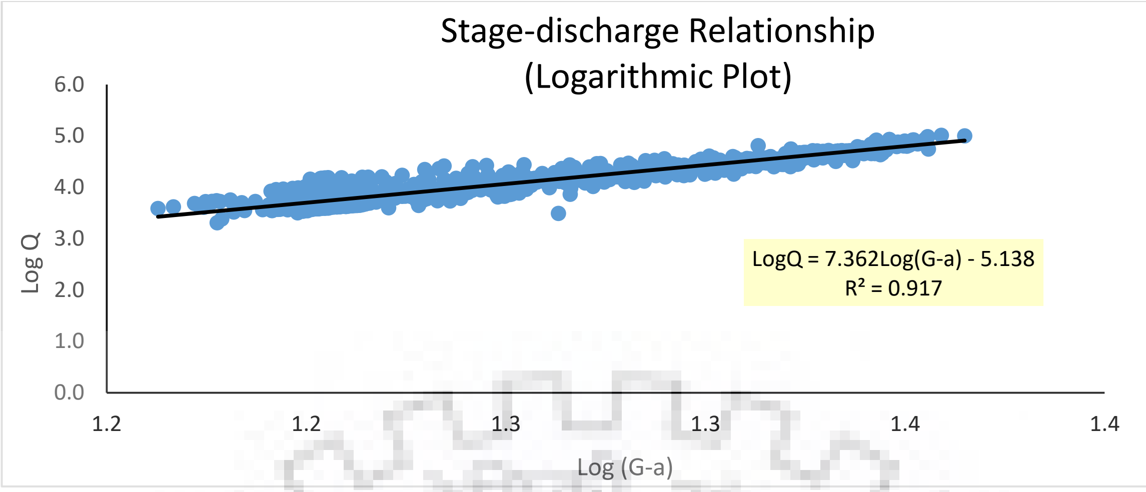

Figure 4.2: Stage-discharge relationship (Logarithmic Plot)

This equation $Q = 0.0000072773(G-a)^{7.3623334089}$ is the stage discharge relationship at Bahadurabad discharge station. In this equation Q is denoted as discharge and G is denoted as stage. In this equation, the stage corresponding to zero discharge constant is -2.58 m. The developed equation has been used to convert observed stage values at 12 hourly interval to corresponding 12 hourly discharge values for used in model simulation.

4.3 Calibration of HEC-RAS 1D Model

The only parameter Manning's roughness factor 'n' value is evaluated through calibration. The 2009 hydrological event is used for calibration of the model. In the present study, universal expansion and contraction loss coefficient are considered 0.3 and 0.1 respectively. Unsteady flow analysis has been performed in this study. For upstream boundary, 12 hourly inflow discharge hydrograph has been used. Normal depth is used here as downstream boundary condition. Available 12 hourly observed water level data at Sirajganj and Aricha observed station have been used to compare with model simulated output for calibration and validation of the developed 1D hydrodynamic model.

In this study, a 1D reach on Jamuna River is considered. The reach is 172 km long with width varying between 3 km to 12 km during its course. Initial value of Manning's roughness has been taken as 0.025 which is a fairly representative value for silt-bed Rivers like Brahmaputra based on previous study by (Woldemichael *et al.*, 2010). The value of Manning's n is then fined tuned by simulating observed stage hydrographs for calibration period 2009 using different n values by trial and error by minimizing root mean square error between observed and model simulated stage hydrograph. It is shown that the trend and shape of the simulated and observed stage hydrograph are nearly alike. By trial and error process, n = 0.026 for channel and n = 0.027 for left bank and right bank has been adjudged as best. Overall, Correlation co-efficient (R^2), Nash-Sutcliffe efficiency Co-efficient (NSE) and RMSE values obtained are presented in Table 4.1.

The output of the HEC-RAS 1D model is shown against observed water level data in Figure 4.3 at Sirajganj and Figure 4.4 at Aricha Station, where river water level measurement gauge is used as ground instrumentation of BWDB for the year 2009. For the Brahmaputra-Jamuna River, the HEC-RAS 1D model simulated water level are in close proximity with corresponding observed water level values for most of high water levels. Some discrepancies could be observed at low water levels where model simulated results are lower than the corresponding water level observations. Overall, the model simulated results have been adjudged to represent flow conditions well. These discrepancies could be attributed to the availability of limited cross-sectional information and braided nature of the lower river reaches of Jamuna River system.

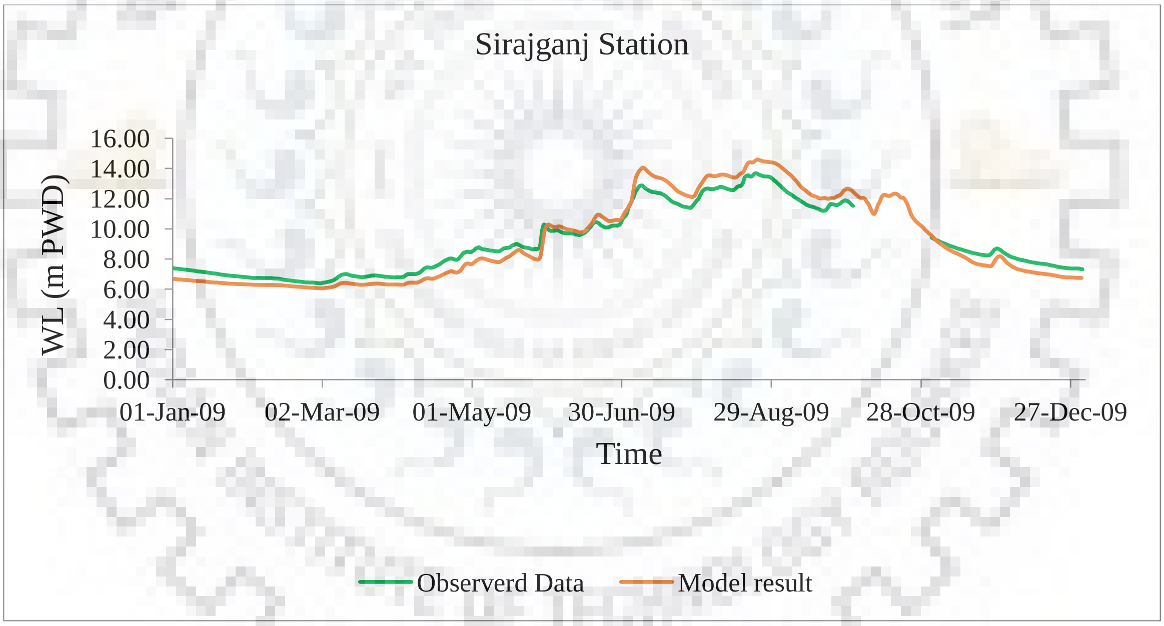

Figure 4.3: Calibrated Observed versus simulated Water Level using HEC-RAS1D Model and Comparison at Sirajganj Station for the Year 2009

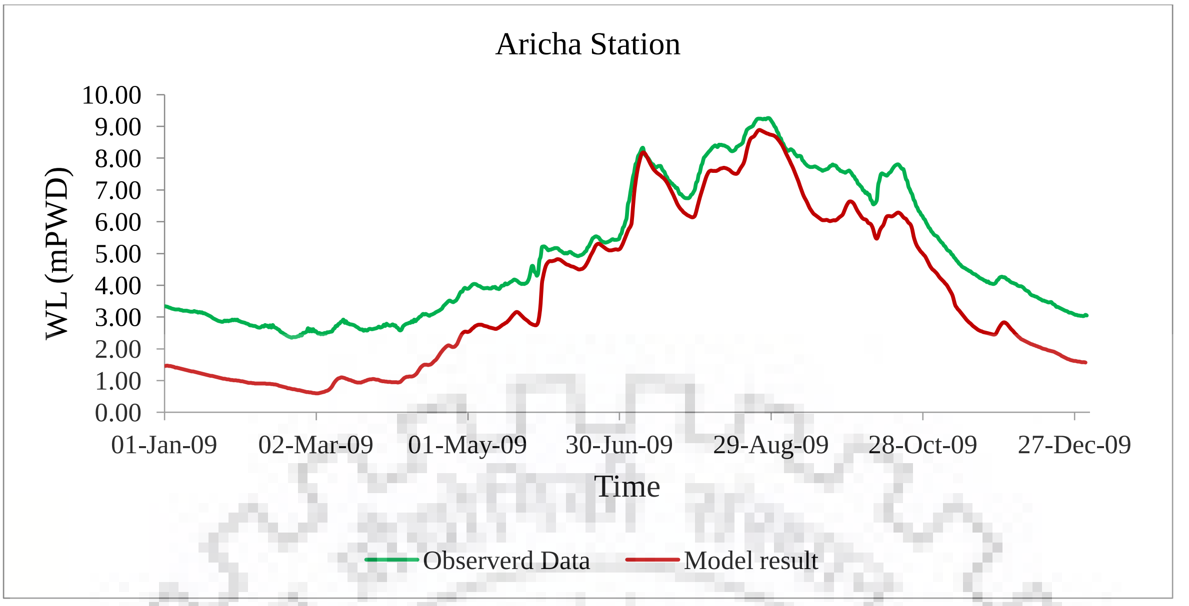

Figure 4.4: Calibrated Observed versus simulated Water Level using HEC-RAS1D Model and Comparison at Aricha Station for the Year 2009

Table 4.1: Statistical analysis for calibration period at Sirajganj and Aricha Station on study reach on Brahmaputra-Jamuna River.

Statistical Parameter	Sirajganj	Aricha
Correlation Co-efficient(R^2)	0.9948	0.9884
Nash–Sutcliffe Efficiency Co-eff. (NSE)	0.9444	0.7727
Root Mean Square Error(RMSE)	0.6650	1.3466

4.4 Validation of HEC-RAS 1D Model

Model validation demonstrates the capability of the model to produce accurate predictions for period outside the calibration period (Refsgaard and Knudsen, 1996). Model validation for this study is used to determine the effectiveness of the calibrated parameter in predicting the water level at different location of Bramhaputra-Jamuna River the period 2010. Figure 4.5 shows the observed and simulated water level for validation period at Sirajganj station and Fig. 4.6 at Aricha station. Close match between simulated water level and corresponding observed water level at both the stations and the model performance statistics shown in Table 4.2 demonstrate that the model could perform equally well during validation period.

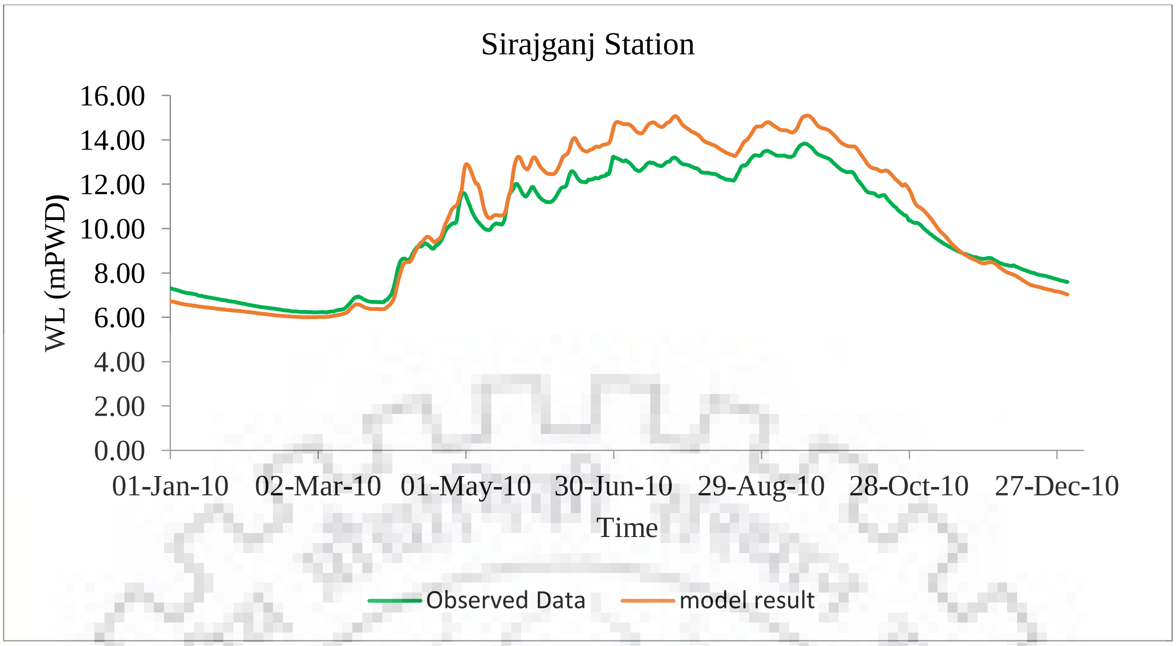

Figure 4.5: Validated observed versus simulated Water Level using HEC-RAS1D Model and Comparison at Sirajganj Station for the Year 2010

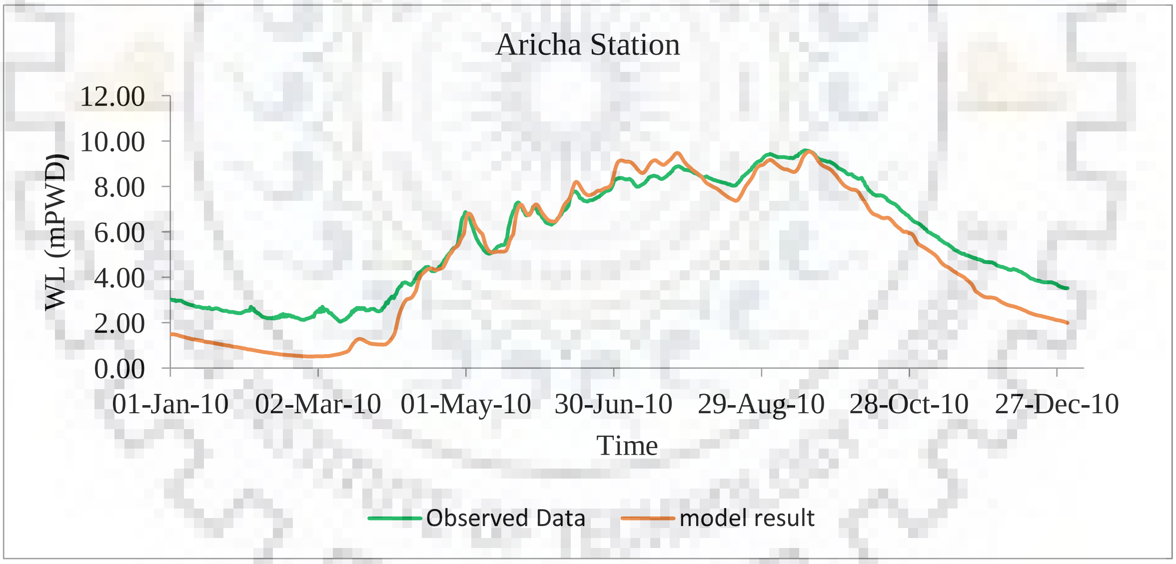

Figure 4.6: Validated observed versus simulated Water Level using HEC-RAS1D Model and Comparison at Aricha Station for the Year 2010

Table 4.2: Statistical analysis for validation period at Sirajganj and Aricha Station on study reaches on Brahmaputra-Jamuna River.

Statistical Parameter	Sirajganj	Aricha
Correlation Co-efficient (R^2)	0.9952	0.9867
Nash–Sutcliffe Efficiency Co-eff. (NSE)	0.9117	0.8895
Root Mean Square Error(RMSE)	0.9915	1.0551

4.5 Simulation of Flooding Scenario without Embankment

Using the HEC-RAS 2D setup described earlier, flood scenario has been simulated using unsteady flow condition and 2012 year event without embankment. The 2012 year hydrological event is used in HEC-RAS 2D setup with terrain without embankment. The model simulations has been performed under unsteady flow condition. Hourly flow hydrograph is used as upstream boundary condition and normal depth is used as downstream boundary condition. Hourly hydrograph is generated at 171.5 km location using HEC-RAS 1D model setup. The peak discharge is 80,698 m^3/s in year 2012 flow hydrograph. The normal depth is considered 0.000065 which is bed slop of the river at the downstream end of the study domain. The Land use/ cover pattern map is reclassified into four categories as agriculture, forest, river, sand and Manning's n value have been assigned using tables recommendations by Chow (1959) for agriculture (0.045), Forest (0.07), sand (0.03) and River (.026) respectively. The simulation has been done by using diffusive wave equation with maximum 20 iteration and run time 15s.The maximum flood depth and velocity has been exported from RAS Mapper and different maps have been prepared by using Arc-GIS. The maximum flood inundation depth classified according to NWMP is shown in Fig. 4.7.

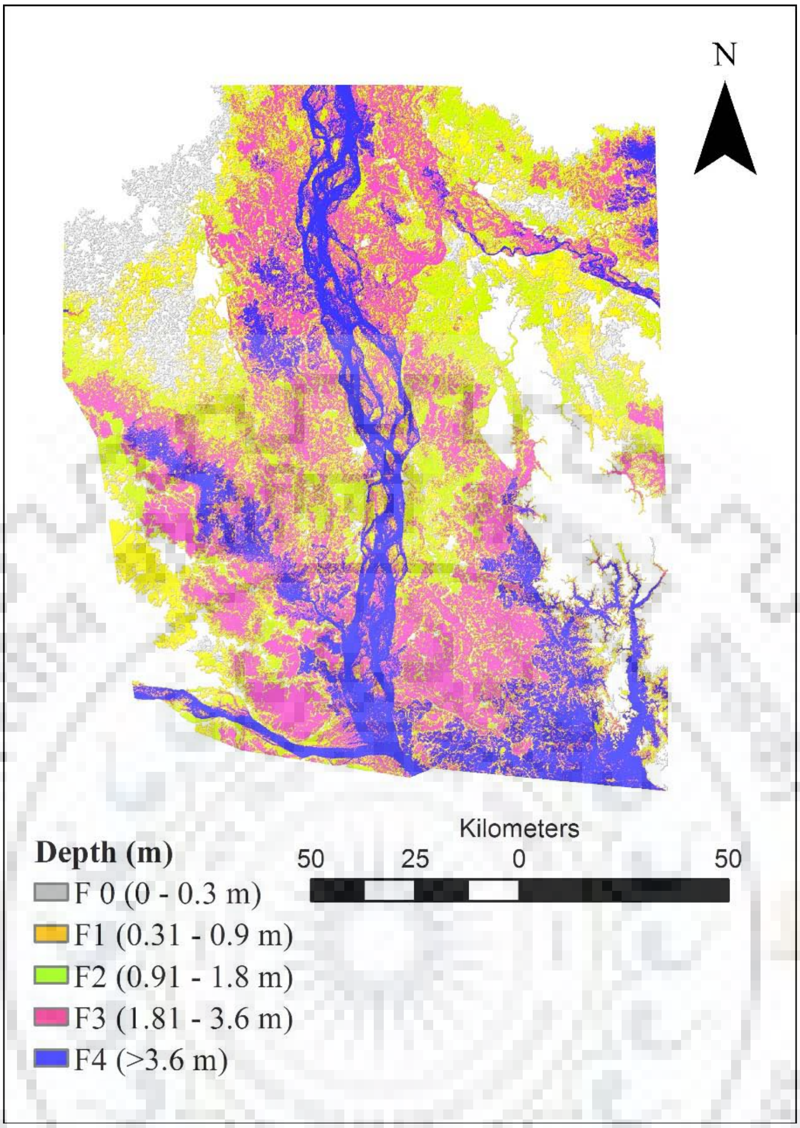

Figure 4.7: Maximum water depth Map without Embankment condition

The classification indicates that 7,13,19,39, and 23% area of the total flood area are inundated by F0 (0 - 0.3 m), F1 (0.31 - 0.9 m), F2 (0.91 - 1.8 m),F3 (1.81 - 3.6 m), and F4 (> 3.6 m) flood depth respectively. The flood depth between 1.81 to 3.6 m is about 39% inundated area of total flooded area which is maximum.

Figures 4.8 shows that the maximum overland flow velocity of water for without embankment condition. The velocity is classified into five classes viz (0-0.5) m/s, (0.5-1) m/s, (1-.1.5) m/s, (1.5-3) m/s, and (>3) m/s. Below 0.5 m/s velocity is observed in the floodplain. In river and low land, the velocity is between 0.5 to 1 m/s. Above 1m/s velocity is observed in the deepest portions in the middle of the river portion only.

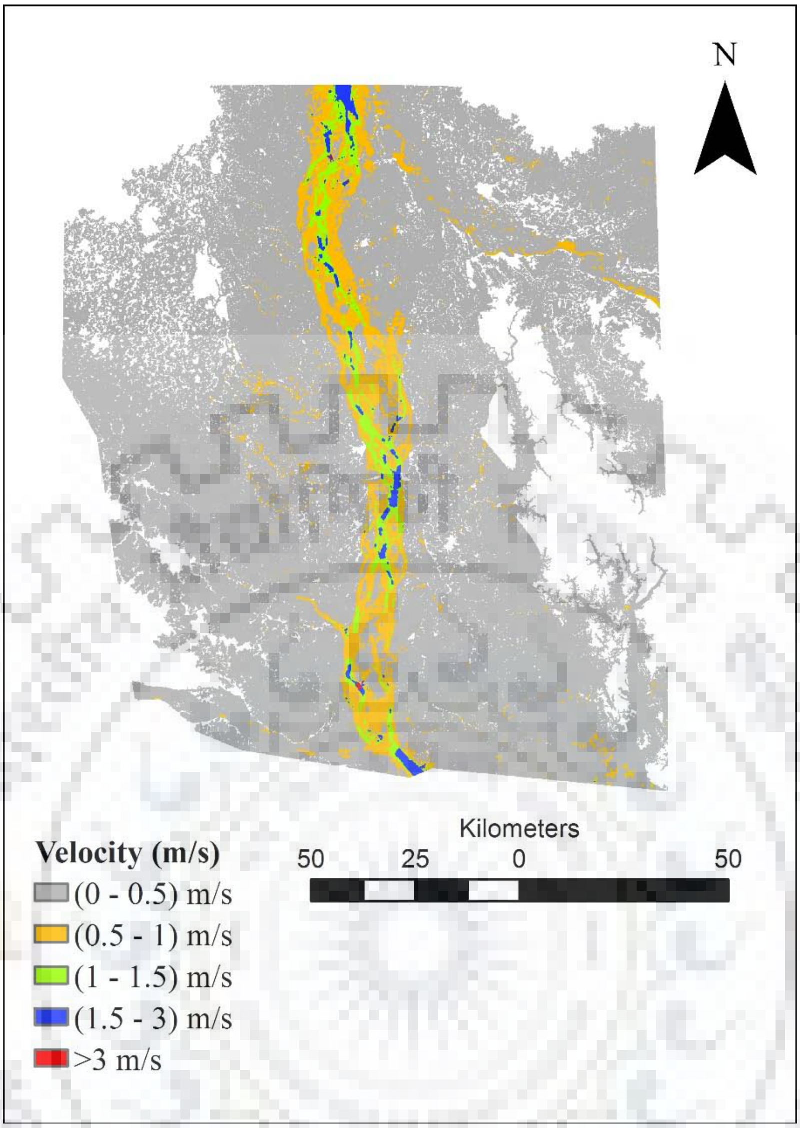

Figure 4.8: Maximum velocity Map without Embankment condition

4.6 Simulation of Flooding Scenario with Embankment

The 2012 year hydrological event is also used in HEC-RAS 2D setup with terrain containing embankment. The model simulations have been performed under same conditions as described for terrain without embankment. Figure 4.9 shows inundated areas with different discharge for terrain area with embankment condition. In Fig. 4.9 snapshots of extent of inundated areas are shown as ‘a’, ‘b’ and ‘c’ at peak discharges of 11173 m3/s, 45824 m3/s, and 61607 m3/s respectively. The symbol a, b, and c also represents the time which is 23 April 12:00 PM, 19 June 17:00 PM and 27 June 18:00 PM respectively on the flood hydrograph shown in upper pane of Fig. 4.9. The bank full discharge is about 11173 m3/s, after that water moves to the floodplain which is shown at ‘a’. At 45824 m3/s discharge water moves to the floodplain and also enters into the joining river which is shows at ‘b’. Embankment is able to protect the local habitat at higher discharge as shown in ‘b’ and ‘c’ snapshots.

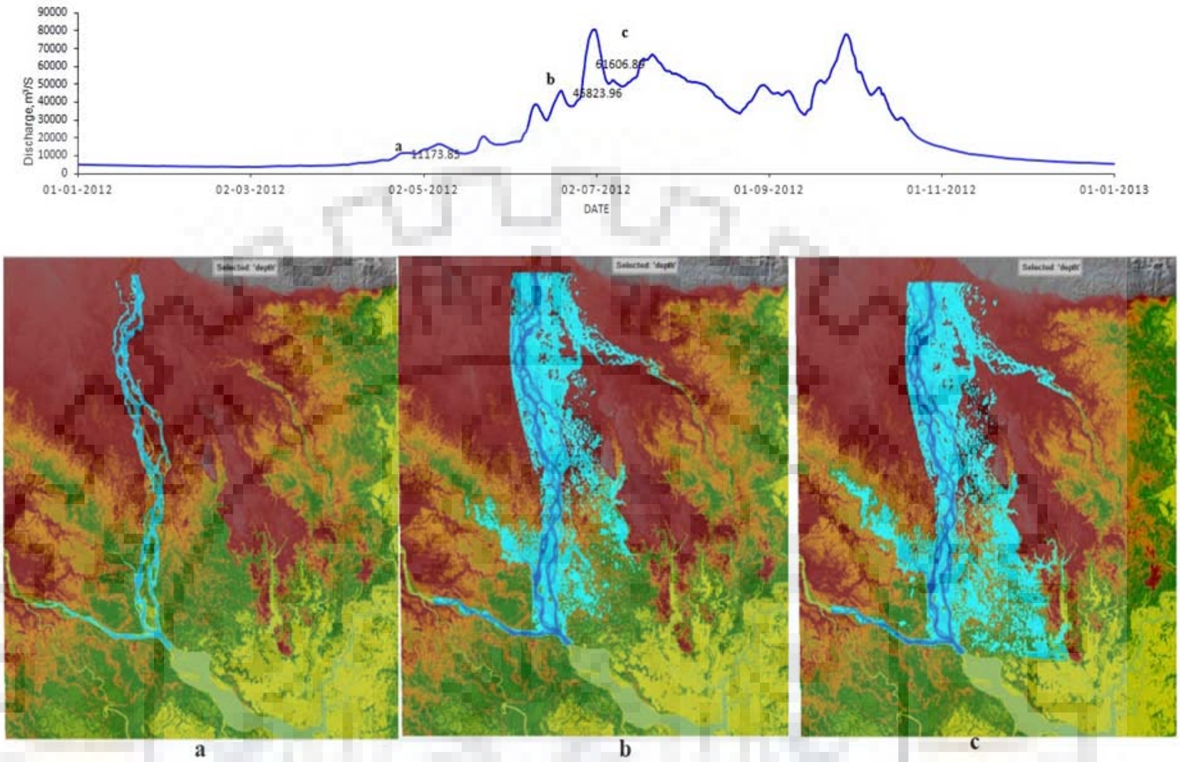

Figure 4.9: Comparison of inundation at different discharge

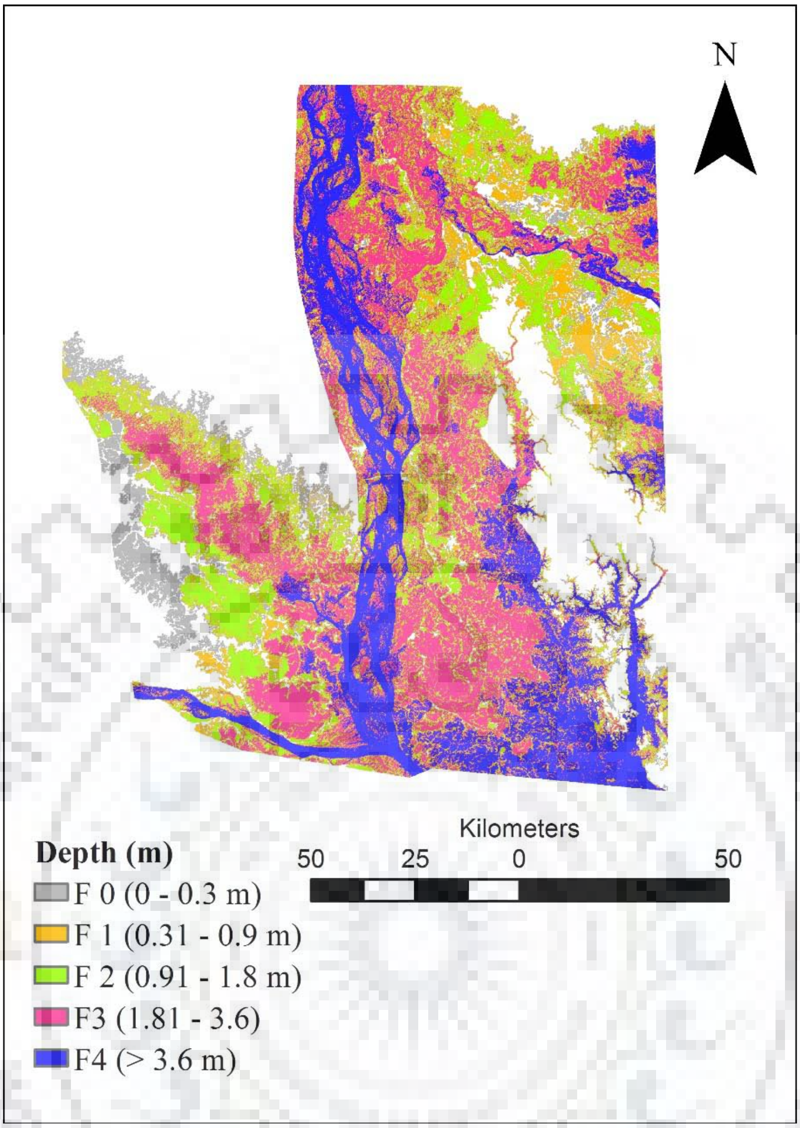

Figure 4.10: Maximum water depth Map with Embankment condition

The spatial distribution of the simulated maximum flood depth have been classified according to National Water Management Plan (NWMP) Guideline. In NWMP guidelines, the flood depth is classified into five classes viz F0 (0 - 0.3 m), F1 (0.31 - 0.9), F2(0.91 - 1.8 m) F3(1.81 - 3.6 m) and F4 (> 3.6 m) based on the inundation depth. F0, F1, F2, F3, and F4 are identified as very high land, high land, medium high land, low land, and very low land respectively. The maximum flood map with embankment is classified according to NWMP. The classification indicates that 6, 11, 20, 37, and 26% area of the total flood area are inundated by depth class F0, F1, F2, F3, and F4 respectively. The flood depth between 1.81 to 3.6 m is about 37% inundated area of total flooded area which is maximum. The classified maximum flood depth map is shown in Fig. 4.10. It is important to note that the flood embankment has been found effective in protecting a vast area from fury of floods.

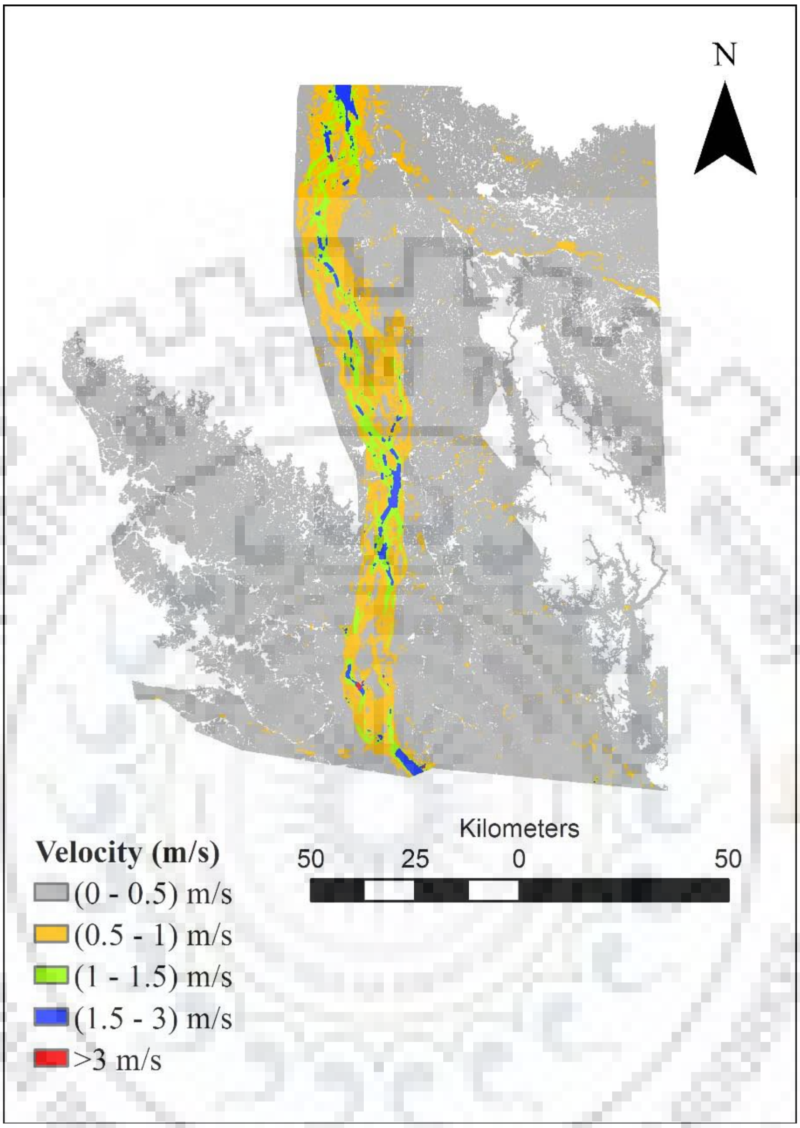

Figure 4.11: Maximum velocity Map with Embankment condition

Figure 4.11 shows the model simulated maximum flow velocity with embankment condition. The velocity is classified into five classes viz (0-.5) m/s, (.5-1) m/s, (1-.1.5) m/s, (1.5-3) m/s, and (>3) m/s. Below 0.5 m/s velocity is observed in the floodplain area. Above 1m/s velocity is observed in the river portion only.

4.7 Comparison Area of inundation with and without Embankment Scenario

Using the HEC-RAS 2D setup described earlier, flood scenario has been simulated using under unsteady flow condition and 2012 year event with and without embankment. In present simulation the study domain area is about 22167 Km^2. The spatial distribution of the simulated maximum flood area of inundation is about 14378 Km^2 and 12248 Km^2 without and with embankment condition respectively. The results also shows that 64.5 and 55 % of the total study domain area are inundated by without and with embankment condition respectively. The area computation without embankment indicates that 961, 1935, 2670, 5541 and 3272 Km^2 area are inundated by F0 (0 - 0.3 m), F1 (0.31 - 0.9), F2(0.91 - 1.8 m) F3(1.81 - 3.6 m) and F4 (> 3.6 m) flood depth respectively. The area computation with embankment indicates that 789, 1322, 2458, 4533 and 3146 Km^2 area are inundated by depth class F0, F1, F2,F3and F4 respectively. It also shows that about 2130 Km^2 area is protected due to embankment.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 General

Bangladesh is a flood-susceptible country. Around 20% area of the country is affected by flooding in every year. Structural measures have been used for controlling the flood and protecting the agricultural land by executing FCD projects. In the present study, flooding scenario in the reach of River Jamuna have been studied using 1D and 2D hydrodynamic model HEC-RAS. The results attained from this study can be summarized as follows:

5.2 Conclusions

The conclusions of this study can be summarize as follows-

- In this study a stage discharge relationships has been developed by using 1221 no observed discharge and corresponding water level data at Bahadurabad station. The stage discharge relationship equation at Bahadurabad station is Q= 0.0000072773(G-a) $^{7.3623334089}$. The zero discharge constant ‘a’ value is -2.58.
- The manning’s n value has been evaluated from HEC-RAS 1D model Setup. The model is calibrated during the 2009-year event and under unsteady flow condition. The calibration has been performed by simulating water level at two downstream sites at Sirajganj and Aricha Stations. Correlation co-efficient (R^2), Nash-Sutcliffe efficiency Co-efficient (NSE) and Root Mean Square Error (RMSE) values obtained between observed simulated water level at Sirajganj station are 0.9948, 0.94 and 0.66 respectively during calibration. R^2, NSE and RMSE at Aricha Station are also 0.9884, 0.77 and 1.34 respectively during calibration period. The manning’s n has been evaluated as 0.026 for channel area and 0.027 for left and right bank area.
- The calibrated model has been validated using independent observed data for the year 2010 event. R^2, NSE and RMSE at Sirajganj Station are also 0.9852, 0.91 and 0.99 respectively during this period. R^2, NSE and RMSE at Aricha Station are also 0.9867, 0.89 and 1.05 respectively during validation period.
- In present study hydrodynamic model HEC-RAS 2D has been developed to simulated the flooding scenario with and without embankment condition. The

model simulations has been performed using unsteady flow analysis using flood event of 2012. The 2D model assessed the flood depth, velocity and water surface elevation for both with and without embankment condition. Area inundated with flood depth (0 - 0.3 m), (0.31 - 0.9 m), (0.91 - 1.8 m), (1.81 - 3.6 m), and (> 3.6 m) are 6, 11, 20, 37, and 26% of total flood area, respectively with embankment condition. Maximum velocity simulated in the floodplain remains below 0.5 m/s. however, in the river section and low lands, the velocity is between 0.5 to 1 m/s. Above 1m/s velocity is observed in the deepest part of the river near the centre of river.

- Simulation results without embankment condition indicates that 7, 13, 19, 39, and 23% area of total flood area would have been inundated with (0 - 0.3 m), (0.31 - 0.9 m), (0.91 - 1.8 m), (1.81 - 3.6 m), and (> 3.6 m) flood depth respectively. Maximum simulated velocity in the floodplain remains below 0.5 m/s. In river and low lands the velocity is between 0.5 to 1 m/s. Above 1m/s velocity is observed in the deepest river portion only.
- In present HEC-RAS 2D simulation the study domain area is about 22167 Km^2. The spatial distribution of the simulated maximum flood area of inundation is about 14378 Km^2 and 12248 Km^2 without and with embankment condition respectively. The results also shows that 64.5 and 55 % of the total study domain area are inundated by without and with embankment condition respectively. The area computation without embankment indicates that 961, 1935, 2670, 5541 and 3272 Km^2 area are inundated by F0 (0 - 0.3 m), F1 (0.31 - 0.9), F2(0.91 - 1.8 m) F3(1.81 - 3.6 m) and F4 (> 3.6 m) flood depth respectively. The area computation with embankment indicates that 789, 1322, 2458, 4533 and 3146 Km^2 area are inundated by depth class F0, F1, F2, F3 and F4 respectively. It also shows that about 2130 Km^2 area is protected due to embankment.

5.3 Limitations and Recommendations for Future Work

In this study flood inundation extent, velocity is assessed by using hydrodynamic model HEC-RAS. Due to crude terrain information, the study results may not reflection the real situation. Use of more detailed terrain information may improve results further in future studies. The recommendations can be written as follows-

- DEM plays important role to improve the proficiency of model. It is highly recommended that high resolution DEM which adequately replicate the actual topography may be used to enhanced performance of the model.

- Bathymetry of the river should be included for comprehensive study.
- More cross section details of BRE should be incorporated to enrich the results.
- All tributaries (Baral, Gumani, Bangali, Hurasagar) and distributary (Dhaleswari) should be involved in the model set up to improve the results.
- Bangabandhu Bridge across the Jamuna River is not considered in this study for getting better results it should be included.
- In some year, Embankment breach has happened, in future study, breach simulation may also be attempted.

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